IEEE PULSED POWER AND PLASMA SCIENCE CONFERENCE 2019

23-28 June 2019

Orlando, Florida

PULSED POWER AND TRANSIENT PLASMA PLASMA AND PULSED POWER WITH BIOMEDICAL, DEFENSE, ENERGY, AND ENVIRONMENTAL APPLICATIONS

Martin Gundersen[1]
1. University of Southern California

This talk will review a university program that overlaps pulsed power and plasma science, and will describe applications to industrial, environmental, biomedical and defense problems. It will present some background for the development of the research, and the ideas underlying transient plasma, or plasma in a formative phase, which is key to some of these studies. Transient plasma can produce volume ignition of various fuels and engines with lower energy cost, for example, considerably reduced delay to ignition in pulse detonation engines, higher peak pressure for internal combustion engines, and improved energy efficiencies in emissions abatement. Biomedical applications include studies of nanosecond pulsed electric fields for the induction of programmed cell death in cancer cells in vitro and in vivo which have led to animal studies conducted with catheter-based pulsed power delivery systems, and the formation of commercial entities translating the research to medical applications. Finally, a project (tenuously connected to pulsed power) to foster and encourage interest in science and engineering and improve perceptions of science in society through movies will be described.

FRACTIONAL MODELS IN SOLVING MAXWELL EQUATIONS AND APPLICATIONS

Lay Kee Ang[1], Yee Sin ANG[1], Muhammad Zubair[2]
1. Singapore University of Technology and Design
2. Information Technology University, Pakistan

In numerical modeling, it is common to solve coupled differential equations in one-, two- or three- dimensions (1D, 2D, or 3D) with corresponding boundary conditions. For some complicated objects, the dimension may be strictly 1D, 2D or 3D, where the normal computational approach may be expensive. By using fractional models that had been developed mathematicians, the complicated object is projected into a "fractional" dimension in order to solve the relevant equations in this non-integer dimension with the assumption that the effects at smaller scales can be ignored. In this talk, we will present some recent results of using such "fractional" models on Maxwell-equation based problems such as fractional Child-Langmuir law for high current cathode, Fractional Mott-Gurney law for space charge limited current transport in organic diode, Fractional Fowler Nordheim law for field emission from rough surface, Fractional Fresnel coefficients for laser absorption/reflection on a rough metal surface and Fractional capacitance of a planar capacitor. These new fractional models will provide useful fractional parameters that can be characterized by experimental measurement. Smooth transition between the fractional models and the traditional models is demonstrated. The calculated results will be compared with available experimental results or numerical results obtained from commercial solvers and the comparison shows good agreement.

CONSISTENT BGK MODEL FOR HIGH ENERGY DENSITY PLASMA MIXTURES

Jeffrey Haack[1], Cory Hauck[2], Kristian Beckwith[3], Michael Murillo[4]
1. Los Alamos National Laboratory
2. Oak Ridge National Laboratory
3. Sandia National Laboratories
4. Michigan State University

We derive a conservative multispecies BGK model that follows the spirit of the original, single species BGK model by ensuring pairwise conservation of momentum and kinetic energy and that the model satisfies Boltzmann's H-Theorem. The derivation emphasizes the connection to the Boltzmann operator, which allows for direct inclusion of information from a molecular dynamics validated effective Boltzmann model. We also develop a complete hydrodynamic closure via the Chapman-Enskog expansion, including a general procedure to generate symmetric diffusion coefficients based on this model. We further extend the model to include the effect of degeneracy on the electron plasma species. We employ this model to investigate kinetic effects on interfacial mixing of the shell-fuel interface in inertial confinement fusion, as well as experiments performed on the Z pulsed power facility.

Sandia National Laboratories is a multimission laboratory managed and operated by National

Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell

International Inc. for the U.S. Department of Energy's National Nuclear Security Administration

under contract DE-NA0003525. SAND Number: SAND2019-1735 A

This work was supported by the US Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001).

THERMODIFFUSION OF PLASMA MIXTURES FROM MOLECULAR DYNAMICS SIMULATIONS

Abdourahmane Diaw[1]
1. Los Alamos National Lab

Modeling of ionic thermal diffusion in hot and dense plasma mixtures has been of longstanding interest in astrophysics and in inertial confinement fusion. Here we first review the kinetic theory approaches to calculating plasma thermal diffusion. We then present the first highly-converged molecular dynamics (MD) calculations of the thermal diffusion coefficient in a mixture of deuterium and tritium across coupling regimes. The non-equilibrium classical MD simulations are performed with interparticle interactions modeled by a pure Coulomb potential where Ewald summation is used to handle the long-ranged interactions. The species thermal diffusion is estimated using the Green-Kubo approach with an integral of the cross correlation function of the species current and the heat flux, a quantity calculated in the equilibrium MD simulations. Extensive comparisons between our MD data and the kinetic theory formulas show very good agreement in the weakly coupled regime. However, in the strongly coupled regime, we observed a discrepancy between the two methods with MD (unlike kinetic theory) giving effectively non-zero values of the thermal diffusion.

SPEED-LIMITED PARTICLE-IN-CELL FOR FAST SIMULATION OF SLOW-PLASMA PROBLEMS

Andrew Chap[1], Thomas Jenkins[1], Greg Werner[2], John Cary[1]
1. Tech-X Corporation
2. University of Colorado

Speed-limited particle-in-cell simulation (SLPIC) is a method of increasing the time-step in a PIC simulation by slowing down the fastest particles in such a way that the end state of the simulation is unaffected, while significantly reducing the number of time-steps required to reach this end state. SLPIC is useful when the simulation requires a kinetic treatment of fast particles (e.g. electrons) while the physics of interest occurs on the time-scale of slow particles (e.g. ions).

In a SLPIC simulation, the true velocities and weights of particles are tracked, but particles are moved through the simulation at a lower speed specified by the ”speed-limiting” function, and weighted to the grid with a reduced weight. By moving fast particles at a lower velocity, the time-step of the simulation can be significantly increased relative to that of a PIC simulation.

We show that for steady-state problems, SLPIC can achieve the same accuracy as PIC with a computational speed-up that is bounded by $\sqrt{\frac{m_{\mathrm{ion}}}{m_{\mathrm{electron}}}}$. For an argon-electron plasma sheath simulation, a speed-up factor of approximately 200 for reaching steady-state is demonstrated.

The trade-off of the large SLPIC time-step is an increased algorithmic complexity, since the equations of motion and grid-weighting are each modified by the velocity-dependent speed-limiting function. We discuss ways of dealing with these complexities and their effect on accuracy in certain cases, as well as the implications of choosing various speed-limiting functions.

To demonstrate the limits of SLPIC in dynamic problems we simulate the interaction of a wave with speed-limited particles and show that SLPIC is accurate only when the speed-limit is sufficiently higher than the wave velocity. This implies that SLPIC is useful for problems where the wave speed is slower than the fastest particles, for example, in ion-acoustic Landau damping.

TRANSITION OF LOW-TEMPERATURE PLASMA SIMILARITY LAWS FROM LOW TO HIGH IONIZATION DEGREE REGIMES*

Yangyang Fu[1], Janez Krek[2], Deqi Wen[1], Peng Zhang[1], John Verboncoeur[1]
1. Michigan State University
2. Michigan State University, CMSE

Similarity laws are often employed when the characteristics of two or more discharge systems are compared. The classical similarity laws were previously validated and applied for weakly ionized plasma discharges [1, 2]. However, similarity relations are not valid for all plasma regimes [3, 4]. Especially for strongly ionized regimes, scaling laws are not well understood. In this study, we evaluate the transition characteristics of low-temperature plasma similarity laws from low to high ionization degree regimes. The similarity relations of plasma density and ionization degree in geometrically similar gaps are presented. It is found that deviations of classical scaling laws occur as the ionization degree increases from low to high. For low pressures, the similarity laws hold until a higher ionization degree than for high pressures. The time-dependent scaling of the charged species and the electron energy distributions in two geometrically similar systems are also compared.

[1] Y. P. Raizer, *Gas Discharge Physics* (New York: Springer, 1991)

[2] Y. Fu, P. Zhang, J. Krek, and J. P. Verboncoeur, *Appl. Phys. Lett.* 114, 014102, 2019.

[3] A. Venkattraman and A. A. Alexeenko, *Phys. Plasmas* 19, 123515, 2012.

[4] Y. Fu, G. M. Parsey, J. P. Verboncoeur, and A. J. Christlieb, *Phys. Plasmas* 24, 113518, 2017.

*This work was supported by the Air Force Office of Scientific Research (FA9550-18-1-0062, FA9550-18-1-0061) and the Department of Energy (DE-SC0001939).

FULL-WAVE SIMULATIONS OF A COMBINED PLASMA IMPEDANCE PROBE - PLASMA WAVE RECEIVER SYSTEM FOR PLASMA MEASUREMENTS IN THE IONOSPHERE.

Edmund Spencer[1], Robert Arslanbekov[2], Vladimir Kolobov, Christopher Burns[1]
1. University of South Alabama
2. CFDRC Corporation

An electrically short dipole antenna (1-2 m) mounted on the payload of a sounding rocket is commonly used as a probe to measure plasma properties in the earth's ionosphere. The complete measurement system consisting of the dipole and associated circuitry is called a plasma impedance probe (PIP). Here we report on the behavior and impedance characteristics of an electrically long dipole antenna (18-20 m, obtained through a plasma fluid finite difference time domain (PF-FDTD) simulation. The motivation for this study is to design a combined impedance probe - plasma wave receiver system. In order for plasma waves to be efficiently received, the dipole antenna must be optimized to receive signals usually in the electron cyclotron resonance range. However, it is found that the overall antenna behavior changes when the cyclotron and antenna resonances are moved closer to each other. In the case of our simulations, the plasma cyclotron resonance frequency is shifted lower by 20

NUMERICAL STUDY OF A COAXIAL ELECTRON SHEATH

Andrew Fierro[1], Benjamin Yee[1], Matthew Hopkins[1], Allen Robinson[1], George Laity[1]
1. Sandia National Laboratories

A particle-in-cell (PIC), direct simulation Monte Carlo (DSMC) simulation is presented for a coaxial low-temperature plasma. Depending on the ratio of the area of the electron collector (A_e) to ion collector (A_w), different sheath structures may form[1]. In the case of the $A_e/A_w < \sqrt{2.3 m_e/m_i}$ where m_e is and m_i are the electron and ion mass respectively, an electron sheath will be observed. Here, a collisionless electron presheath is studied in a coaxial configuration. The center conductor is held at a positive bias and the outer conductor is fixed at ground potential. A clear electron sheath configuration is found in the model when the ratio of inner conductor area to outer conductor area meets the electron sheath criteria. It was observed that the azimuthal velocity distribution function experiences a loss as electrons with near zero velocity are lost to the center electrode. Radial velocity distribution functions are mostly Maxwellian except near the positively biased electrode where a drifted Maxwellian is observed. The analysis of the electron sheath has important applications in probe theory, probe diagnostics, and electron beam devices[2]. This coaxial electron sheath problem demonstrates a fluid-like bulk plasma region and a kinetic sheath region. As such, this is an ideal problem for analyzing the transition region between the fluid and kinetic regime.

[1]S. Baalrud, et al., Phys. Plasmas, 14, 042109, 2007

[2]N. Hershkowitz, et al., US Patent num. 7398592B2, 2009.

This work was supported by the Laboratory Directed Research and Development (LDRD) program and Sandia National Laboratories under project 209240. Sandia National Laboratories is a multi- mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

THE MICHELLE CODE: LATEST FEATURES AND ADVANCED APPLICATIONS

John Petillo[1], Alex Burke[1], Aaron Jensen[2], Serguei Ovtchinnikov[1], Eric Nelson[1], George Stantchev[3], Simon Cooke[3], Kevin Jensen[3], Ben Held[4], Alan Nichols[4]

1. Leidos

2. Leidos Corporation

3. Naval Research Laboratory

4. National Instruments

Beam optics for sources, transport and depressed electron collectors for RF component design and performance are predicted using simulation codes with ever more fidelity. To meet these modern day challenges, the MICHELLE charged particle beam optics code [1,2] has a new official release of Version 7 (2019), which contains a host of improvements including the physics solvers, user environments, user interface, interfacing with 3rd party codes and data, and the installation package. The physics solvers include new advances in thermionic emission, and modifications to the algorithms. The user environments include the previously-reported AFRL Galaxy Simulation Builder, but also improvements in the Analyst-MP environment. There are now options to use a wider variety of computation mesh grid generators, along with some advanced meshing techniques. This is taken advantage of with the ability to run MICHELLE under SolidWorks for device design, and for subsequent parametric optimization. The new software installers support UNIX & Windows, up through Windows 10.

This paper reports on the latest MICHELLE release and also will highlight the use of the new capability on advanced techniques for thermionic emission as well as extreme mesh examples of field emission arrays, illustrating how this capability can be used by the device designer.

1. John Petillo, et al., IEEE Trans. Plasma Sci., vol. 30, no. 3, June 2002, pp. 1238-1264.

2. John Petillo, et al., IEEE Trans. Electron Devices Sci., vol. 52, no. 5, May 2005, pp. 742-748.

3. Stellar Science Ltd Co. Galaxy Simulation Builder (GSB) User Guide, Version 6.6. High Power Electromagnetic Division, Air Force Research Lab, Kirtland, NM, 2017.

----

* Work supported by the ONR, NRL and Leidos

BROADBAND BOUNDARY MODEL FOR INJECTION AND ABSORPTION OF EM-WAVES WITH THE HIGDON OPERATOR METHOD

Larry Ludeking[1]
1. OrbitalATK of NGC

The injection and absorption of waves entering or escaping open boundaries in EM-PIC simulations is of interest provided the numerical reflections are low, and the boundary is stable. The Higdon [1] operator method provides the basis of a multi-phase velocity matching algorithm. The potential for high order implementation provides for (a) injection of low reflection incident waves into the interior of the simulation environment, (b) near perfect absorption of scattered outgoing waves, and (c) is insensitive in EM-PIC to particles traversing the boundary edge. This method has been applied with substantial success in several wave equation environments. These include dispersive electromagnetic wave modeling, as well as the shallow water equations and acoustic phenomena.

The general Higdon operator of order J may be described as follows for wave propagation along the x axis, as the product of multiple uni-directional wave equations, each product uses a potentially unique value of phase velocity. For J=1, this reduces to the standard 1-dimensional wave equation in which the sign of the phase velocity indicate either a forward or backward traveling wave. As J, the number of product terms, increases it is necessary to capture information that is more remote spatially and temporally from the boundary edge. Givoli and Neta [1] suggested the method of recasting the solution in terms of auxiliary functions of arbitrarily high order. We will report on our implementation of this method for 1st and 2nd order FD approximations and the effectiveness on broadband transmission.

1. Dan Givoli and Ben Neta, “High-Order Higdon Non-Reflecting Boundary Conditions for the Shallow Water Equations”, NAVAL POSTGRADUATE SCHOOL, Monterey, CA, NPS-MA-02-001, April 2002.

ELASTOSTATICS IN BEAM OPTICS ANALYZER

Thuc Bui[1], R. Lawrence Ives[1], David Marsden[1]
1. Calabazas Creek Research, Inc.

Calabazas Creek Research (CCR) developed and has maintained and continuously added new capabilities to Beam Optics Analyzer (BOA). It provides several finite element field solvers for electrostatics, heat transfer, magnetostatics and Helmholtz fields. It can track particles relativistically in either static or harmonic fields with space charge effects. It provides sophisticated emission models for field and thermionic emission. Its Mesher generates unstructured mesh with fine-grained control.

Using the power density generated by electrons depositing their energies on terminal electrodes, BOA can simulate the temperature profile of the device. This however does not provide a complete design loop. It would be ideal and much more efficient to compute the thermal stresses and predict the hot dimension of the electrodes on the same model and the same simulation platform. This would make a simulation tool, such as BOA, a complete multiphysics platform.

In a multiphysics platform, the same CAD model should be used for all analysis types from beam simulation to heat transfer and stress analysis. Parts required in one analysis type could be redundant in another. Thus, the analysts should be able to enable/disable parts as needed. Changing material in one part in one analysis type should be automatically carried over to other analysis types. BOA currently includes all the above convenient features for its particle beam and heat transfer analyses.

In the present work we extend BOA's capability to include stress analysis. We will demonstrate seamless integration of the elastostatics field solver with beam simulation and heat transfer analysis. Integration of stress analysis into BOA provides a convenient, one-stop, multiphysics, simulation tool. It provides one package that can perform particle simulation, thermal and stress analysis using the same CAD model. We will present the finite element elastostatics formulation, particle, thermal and stress simulation results of a gridded triode gun.

PERFORMANCE PORTABLE FINITE VOLUME MAGNETOHYDRODYNAMICS FOR THE EXASCALE ERA

Forrest Glines[1], Philipp Grete[2], Brian O'Shea[2]
1. Sandia National Laboratory
2. Michigan State University

Computational plasma models such as magnetohydrodynamics (MHD) and particle-in-cell (PIC) are essential tools in modern plasma physics. They can be used to complement physical experiments, inform future avenues of research, and provide insight into plasma phenomena that are difficult to create and control in a laboratory. The more detailed and physically realistic simulations can require the computational resources of entire supercomputers. As larger computing resources become available, we are able to conduct more refined plasma simulations, which can deepen our understanding of the behavior of plasmas. However, constraints in computer chip manufacturing are leading the next generation of supercomputers to employ a variety of novel architectures, usually with many more processing units. Until recently, each new architecture can require a separate, non-trivial rewrite of a simulation code. A current goal in computational science is the creation of programming paradigms for writing performance portable code: code that can run efficiently at high performance on many different supercomputer architectures. To explore the development of performance portable plasma simulation codes, we are currently modifying a CPU-only finite volume astrophysical MHD code to run efficiently on both CPUs and GPUs, using Kokkos, a performance portability library. I will present the strategies we used for implementing MHD using Kokkos and the challenges we encountered while attempting to achieve maximum performance on different platforms. In addition, I will discuss performance results for multiple architectures compared against the original code. The strategies, challenges, and results presented will allow other research groups to straightforwardly adopt this approach to prepare their own codes for the exascale era. (SAND No: SAND2019-2048 A)

OPTIMIZATION OF A FOLDED WAVEGUIDE TRAVELING WAVE TUBE USING IMPEDANCE MATRICES

Aaron Jensen[1], John Petillo[1], Serguei Ovtchinnikov[1], David Chernin[1], Alex Burke[1]
1. Leidos

RF device design and performance are predicted using simulation. Fast design tools such as those that model beam dynamics in one dimension may be sufficient for initial design work or for RF devices where performance is not critical. However, in many cases these tools do not have the fidelity to meet performance objectives. Particle-In-Cell codes such as MAGIC can be used to model the complete device physics in 3D using Maxwell's equations but these simulation tools are computationally intensive and time consuming. The GPU code NEPTUNE [1] is a faster alternative to MAGIC but its computational time is still not insignificant. An alternative approach is presented using impedance matrices and Tesla-Z [2]. In this approach the impedance matrix for a folded waveguide traveling wave tube (FWTWT) is calculated using the Analyst 3D field solver. The impedance matrix is used in Tesla-Z [2] to predict tube performance. This approach is faster than PIC simulation, where the 3D fields are taken into account through the computation of the Z-matrix as opposed to a simplified or analytic model, and the particle dynamics are modeled in 2D. Ultimately, the Tesla-Z matrix approach is used within the Galaxy Simulation Builder (GSB) framework to optimize the FWTWT using the DAKOTA optimization library. The approach and optimization results are presented.

1. S. J. Cooke, I. A. Chernyavskiy, G. M. Stanchev, B. Levush and T. M. Antonsen, ”GPU-accelerated 3D large-signal device simulation using the particle-in-cell code ‘Neptune’,” IVEC 2012, Monterey, CA, 2012, pp. 21-22.

2. I. A. Chernyavskiy T.M. Antonsen, Jr., J.C. Rodgers, A.N. Vlasov, D. Chernin, and, B. Levush, “Modeling Vacuum Electronic Devices Using Generalized Impedance Matrices,” IEEE Transactions on Electron Devices, Vol. 64, No. 2, pp. 536-542, Feb. 2017.

IMPORTING CAD-GENERATED DEVICE GEOMETRY TO THE NEPTUNE EM-PIC SIMULATION CODE

Simon Cooke[1], George Stantchev[1]
1. Naval Research Laboratory

The 3D Electromagnetic Particle-in-Cell (EM-PIC) method is well known as a powerful simulation technique for modeling electron beam and/or plasma interactions with strong electromagnetic fields inside complex device structures. One of the first tasks for users of PIC codes is to precisely define the 3D device geometry for their simulation. To simplify this task for users of NRL's Neptune code, we have created a new approach to import geometric models from commonly used Computer-Aided Design (CAD) tools.

There are two primary approaches commonly used to define 3D geometry: (1) CAD modeling tools, and (2) Constructive Solid Geometry (CSG) methods. Conventional CAD tools represent and manipulate solid object surfaces using a boundary representation composed of 2D surface patches. CSG methods build complex geometry from a set of simple volumetric shapes (primitives, such as spheres or cylinders) composed using Boolean operations and geometric transformations.

In Neptune, we implement the CSG approach using a mathematical representation of shapes as implicit functions in 3D that produce positive values inside the structure, zero on the boundary and negative values outside. A function is then mapped onto the Cartesian simulation grid using an accurate "cut-cell" algorithm that determines intersections of the grid with the zero-valued surface-contour of the 3D function. A full scripting language is available to construct shapes/functions of arbitrary complexity using simple operations, however for sufficiently complex geometries this becomes a challenging programming exercise, in which case importing CAD models would be a more convenient approach.

We describe our new method, in which we transform the CAD model (using its surface triangulation) into Neptune's function representation. This enables the imported geometry to be used as a new primitive shape in the CSG model and further combined with other shapes, providing considerable flexibility to the user.

———-

Supported by the US Office of Naval Research

SMART MODELLING OF MICROWAVE TUBE USING DEEP LEARNING

Nalini Pareek[1], Purushotthaman N.[1], Anirban Bera[1]
1. CSIR CEERI

High power Microwave tubes have been considered as an offshoot of the advancement in pulsed power technology and plasma sciences [1]. The umbrella of high power microwave tubes itself consist of various devices,that cater to many strategically important applications such as space missions, fusion experiments , radars etc. The classical approach of designing such microwave generating sources has been dominated by the codes based on analytical or numerical methods; The final set of equations used in the codes are simplified based on certain assumptions, in order to downsize the complexity of the equations ,and also to reduce the computational expense. This however takes a toll on the level of accuracy of the design. The process further slows down when physical or geometric parameters have to be repeatedly adjusted during the design cycle. Thus the conventional methods bring uncertainties in the design methodology. Moreover, as new technologies and devices continue to evolve, we need not only new models but also modeling algorithms such that model development becomes fast and more accurate, which are in fact contradictory set of requirements from the currently available CAD tools. The aim of this work is to be able to model as well as handle these uncertainties at the design stage itself by using ANN (Artificial Neural Network) [2] based Data Driven Model.The ANN model can learn device data through an automated training process, and the trained neural networks are then used as fast and accurate models or efficient high-level circuit and system design. These models have the ability to capture multidimensional arbitrary nonlinear relationships, thus making neural networks a useful choice for device modeling.

1] Barker et al. “High Power Microwave Sources and Technologies”, IEEE Press, ISBN No. 0780360060, 2001

[2] Zhang, Q. G. (2000). Neural Networks for RF and Microwave Design. Norwood: Artech House.

INCREASING THE PULSE REPETITION RATE FOR SOLID STATE THYRATRON REPLACEMENTS

John Waldron[1]
1. Silicon Power

Silicon Power reports increased pulse repetition rate capability for Solid State Thyratron Replacements (SSTR) utilizing enhanced SolidTRON technology. Varying amounts of minority carrier lifetime killing in our semiconductors has enabled demonstration of 300ns wide capacitive discharge pulses up to 10kA/cm2 at pulse repetition rates up to 50kHz at a junction temperature of 110°C.

While Silicon Power has found success in displacing some Thyratrons, the higher pulse repetition rates enjoyed by Thyratrons and Ignitrons had been a challenge to overcome. Finally, a well-documented procedure produces quantifiable tradeoffs for frequency capability versus conduction losses.

The superior conduction efficiency and low leakage currents of SolidTRON products permits modest lifetime killing to increase operational pulse repetition rates without suffering detrimental increases in energy losses. Specifically, at 110°C a 20x improvement in frequency capability is achieved with a modest 75% increase in conduction losses (at 1kA/cm2). More importantly, comparing the peak current achieved in identical setups between as-fabricated devices and those with the highest frequency capability differ by only 1.5%.

Additionally, these gains are achieved without a complicated gating scheme. The improved pulse repetition rate was demonstrated using a simple pulse transformer; where galvanic isolation is provided with magnetic coupling. The modest minority carrier lifetime killing allows the device to self-commutate without gate assisted turn-off.

This paper includes plots of the effects of lifetime killing on the minimum period required between pulses, the impact of conduction losses as a function of current density, and leakage currents at junction temperatures ranging from 25°C to 110°C.

DESIGN AND EVALUATION OF SIC GTO MODULE FOR PULSED POWER APPLICATION

Lei Gao[1], Yinghao Meng[1], Kun Zhou[2]
1. Microsystem & Terahertz Research Center, Institute of Electronic Engineering, China Academy of Engineering Physics
2. Microsystem & Terahertz Research Center,Institute of Electronic Engineering, China Academy of Engineering Physics

High voltage power modules are developing towards higher voltage, higher current, smaller volume, resulting in the increase in the power density and operating temperature. As the wide bandgap material, Silicon Carbide (SiC) is regarded as the next generation ideal material for power devices, and has shown superior properties enabling power devices to meet the requriements of high voltage large current, high temperature, and hign frequency in both power electronics and pulsed power applications. In this work, all solid-state SiC power module integrating two paralleled SiC GTOs is presented for pulsed power application. Based on preliminary evaluations of the single GTO device, the full module can achieve the pulsed current capability over 10 kA. The FRD is also co-packaged to enable reverse current conduction capability. Current distribution and discharging properties of the module is also discussed in detail. Thermal-mechanical properties of the module was investigated with temperature and stress distribution. The design shows advantages in handling large pulsed current and also decreasing thermal stress to enable realiability.

HIGH SENSITIVITY HEH MONITOR

Viliam Senaj[1], David Cabrerizo Pastor[1], Thomas Kramer[1]
1. CERN

The LHC beam dumping system serves to safely abort 2 counter rotating proton beams each with energy of up to 360 MJ and its reliable operation is crucial for the accelerator safety. The system comprises 50 fast pulsed magnets and their associated pulse generators to fast extract and paint both beams on the surface of two 8 m long graphite blocks. The pulse generators operate at up to 29 kV and comprise 800 HV GTOs and 480 HV triggering IGBTs to deliver altogether more than 1 MA. All generators are installed underground in the galleries parallel to and shielded from LHC tunnel but some high energy hadrons (HEH) leak from the tunnel into the galleries via interconnecting cable ducts and can provoke Single Event Burnout (SEB) of HV semiconductors. This can lead to system malfunction and possible damage of the accelerator. In order to reduce the likelihood of SEB, the choice of HV semiconductors was based on their SEB cross-section and cable ducts shielding was improved by filling empty gaps with iron rods. To keep the probability of SEB failure low enough ($<$ 0.1 per year), the requested HEH fluency in the galleries needs to be less than 5e4 HEH/cm2.year. The presently used HEH monitors are not sensitive enough subsequently the development of a new high sensitivity HEH monitor was necessary. It is based on protected SEB phenomenon in HV Si diodes. Depending on number of used diodes, it can be up to thousand fold more sensitive compared to present memory upset based instruments. It will allow confirming HEH fluency estimations used in failure rate evaluation and taking the most appropriate mitigation measures if necessary. The HEH monitor sensitivity measurement is ongoing under various conditions (cosmic rays at low and high altitudes, protons, neutrons, temperature variation).

PACKAGING AND EVALUATION OF 100 KV PHOTOCONDUCTIVE SWITCHES

Jared Culpepper[1], Adrian Miller[1], Andreas Neuber[1], James Dickens[1]
1. Texas Tech University

In practice, it is challenging to integrate a Photoconductive Semiconductor Switch (PCSS) capable of switching on the order of 100 kV into a package with small parasitic inductance such that the sub-nanosecond rise time of the PCSS is still achievable at current amplitudes of hundreds of amperes. The lateral geometry PCSS is built on a 2.5 cm x 1.3 cm GaAs sample with a gap distance of 2 cm to achieve rise-times less than one nanosecond. Another challenging aspect of a practical GaAs PCSS is the filamentary nature of the current which leads to shortening of the device lifetime. This is addressed by using an appropriate electrode profile at the contacts to produce a mostly uniform electric field between the electrodes, thereby decreasing field enhancement points and filament "hot-spots." Fully 3D, transient electric field simulations of the switches, also incorporating the field dependent conductivity of the GaAs material, enable optimization of the switch package while keeping the electric field stress at acceptable levels during the fast, 10 μs application of the charging voltage. The switches are packaged such that the semiconductor is encapsulated in EFI dielectric to mitigate breakdown driven by the electric field across the GaAs surface. High-gain lock-on conduction mode is utilized so that the triggering system does not require high laser power to switch the PCSSs into their on-state. The high voltage design of the PCSS package is presented and initial switching results are discussed.

EVALUATION METHODS FOR ELECTRODE EROSION UNDER HIGH CURRENT, HIGH ENERGY TRANSIENT ARCS

Jiawei Wu[1], Ruoyu Han[2]

1. Global Energy Interconnection Development and Cooperation Organization
2. Beijing Institute of Technology

Electrode erosion caused by arcs is a common phenomenon in closing switches. Severe electrode erosion will influence the performance of a switch. Besides, erosion products can also damage the insulation, causing surface flashover, etc. Numerous research has been conducted on electrode erosion phenomenon for different applications, such as electrical discharge machining (EDM), pulsed power technology, etc. In general, existing research on electrode erosion mainly concentrates on some certain aspects associated with the application background. Therefore, it should be essential to establish a universal evaluation framework for electrode erosion, combining advantages of the research of both pulsed power technology and EDM. Through the framework, it becomes possible to estimate electrode surface morphology quantitatively and build connections between electrical discharges and surface conditions, which will be meaningful for material selection, electrical and mechanical design in practical engineering.

According to the previous research, typical methods utilized for electrode erosion estimation including self-breakdown voltage statistics, mass/volume measurement, simple erosion parameters based on microscope pictures, roughness parameters based on profiles, and erosion products analyses. In fact, there exist two categories of approaches to studying electrode erosion. The first category concerns phenomena during the dynamic electrical discharge process, including operating characteristics, circuit parameters, and plasma parameters. Jitter, self-breakdown voltage, transferred charge, images of the discharge channel, and emission spectra can be obtained. The second category relates to some "static" features, such as the change of mass, volume, macro-morphology, micro-morphology, and chemical components, which can be regarded as the consequences of electrical discharges. Obviously, dynamic electrical discharges and static erosion consequences interact with each other. Therefore, the framework should contain essential items in both categories and be divided into four aspects.

1) Operating characteristics, including statistical results of jitter, self-breakdown voltage, transferred charge, failure rate, and lifetime.

2) Macro-morphology estimations, including photographs, weighing, 2-D profiles, and 2-D roughness parameters.

3) Micro-morphology estimations, including microscope observations, 3-D surface reconstruction, and 3-D roughness parameters.

4) Erosion products analyses, including X-ray Fluorescence (XRF) analysis, X-ray Photoelectron Spectrometer (XPS) analysis, and emission spectra analysis.

To verify this method, two pairs of electrodes made of 90WCu and 90WNiFe respectively were tested under repetitive high current, high energy transient arcs. Then they were evaluated in this framework. In addition to this, several problems of this topic are also proposed and discussed. It is hoped that this study will aid in better understanding of the phenomenon of electrode erosion and act as a reference for related applications related to power equipment, EDM, pulsed power technology, etc.

SIMULATION OF POST-BREAKDOWN TRANSIENT RESISTANCE OF A PLASMA CLOSING SWITCH FILLED WITH AIR, N2, CO2, AND AN AR/O2 MIXTURE

Yuan Yao[1], Igor Timoshkin[1], Scott MacGregor[1], Mark Wilson[1], Martin Given[2], Tao Wang

1. University of Strathclyde

2. University Strathclyde

Gas-filled plasma closing switches (PCS)s are an important element in pulsed power systems designed to generate high voltage, high power impulses. In practical applications, it is desirable to minimise the resistance of the PCS, to reduce the power loss in the switching system and to produce fast-rising (ns and sub-ns) HV impulses. Despite the significant number of publications in this field, it is still problematic to predict the time-varying resistance of plasma channels for different gases and for different circuit parameters.

The post-breakdown behaviour of the time-dependent resistance of the plasma channel(s) resistance in a customised PCS geometry has been studied in this paper.

of Experimentally-registered current and voltage waveforms were used to obtain the transient resistance of plasma channel(s) in the PCS, which was filled with different gases: dry air, CO2, N2 and a 90%/10% Ar/O2 mixture. Also, Braginskii's and Kushner's analytical models were used in the analysis of the transient resistance: the analytically-obtained transient resistances have been compared with the experimental results generated in the present work. This will help to determine the accuracy of the different analytical methods, which in turn will help in optimisation of the operational performance of PCSs filled with environmentally-friendly gases.

EXPERIMENTAL STUDY OF GRAPHITE ELECTRODE EROSION UNDER PREMIXED ATMOSPHERE IN SPARK GAP SWITCH

Hongyu Dai[1], Lee Li[1], Shuai Ren[1]
1. Huazhong University of Science and Technology

The spark gap switch with graphite electrodes is widely used in the high-power laser system. Affected by the heat flux of the high-current arc, the graphite will sublimate in a short time. The sublimation characteristic determines the lifetime of the graphite electrode. To study the effects of gas composition on the erosion rate, three kinds of mixture gas are chosen to work as the discharge atmosphere. All of them contain 20% oxygen, and other parts are nitrogen, helium, and argon respectively. In theory, the sublimation of the electrode is transferred into the gas state of carbon oxide and the solid state of simple substance carbon, but the too much solid state will damage the insulating property. The paper aims to research the effect of the atmospheres on the evolution of graphite. The current integral method is adopted to calculate the transfer charge of the pulsed arc, which is a basis for the measurement of arc power. Meanwhile, the concentration of gas products in the switch chamber is measured by a flue gas analyzer. It is found that, compared with the usual nitrogen-oxygen atmosphere, the discharge with inert gas can significantly reduce the ablation of the electrode. Especially in the case of the mixture of argon and oxygen, the sublimation of graphite electrode decreases significantly. The higher oxidation efficiency can directly reduce the mass of solid residue. In the inert gas atmosphere, the oxide proportion is higher, and more sublimation carbon translates into gaseous. The premixed gas with argon and oxygen is better than traditional gas in the switch chamber. In the method of optimizing premix gas, the electrode erosion rate can be reduced, which is beneficial to the lifetime of the electrode.

FEEDBACK FROM CELLS: HOW CANCER CELLS COULD MAKE COLD ATMOSPHERIC PLASMA JET SELECTIVE DURING TREATMENT

Li Lin[1], Dayun Yan[1], Michael Keidar[2]
1. The George Washington University
2. George washington University

Currently, the plasma-based cancer treatment and the mechanism of plasma jet interacts with the target are hot topics. During the cell treatment, the cell feedback makes plasma jet inconsistent among different type of cells even with all other setups are the same. Therefore, such cell feedback on plasma jet cannot be neglected. In this work, we discovered how cancer cells change the plasma parameters at steady state during in-vitro treatments. Comparing with MDA-MB-231 (breast adenocarcinoma), PA-TU-8988T (pancreatic adenocarcinoma), and U87MG (glioblastoma), B16F10 (murine melanoma) make the lowest electron density in the helium plasma jet. When the jet is pointing at the edge of the cell colony, B16 also makes the most asymmetric self-organization patterns. Capacitance imaging of cell colonies indicates that the capacitance of the B16 colony is the highest one among these cell lines and also the permittivity. A finite element study of target permittivity shows that a dielectric target without ground electrode behind can decrease the electric field of streamer head in plasma jet when the permittivity is high. This agrees with the observation of this work. However, a dielectric target with a ground electrode behind results in an opposite permittivity effect which agrees with the previous simulations. The observation of this work reveals how the cancer cells can change the plasma jet due to their permittivity, which helps to determine the selectivity of plasma treatment.

COLLECTIVE EFFECTS OF NANOSECOND PULSED ELECTRIC FIELDS ON CELLS ORGANIZED IN A MONOLAYER

Juergen Kolb[1], Fukun Shi[2], Christina Wolff[2], Anna Steuer[2]
1. Leibniz Institute for Plasma Science and Technology e.V.
2. Leibniz Institute for Plasma Science and Technology

Basic research on the underlying mechanisms of pulsed electric field effects of sub-microsecond duration on mammalian cells has mostly focused on the study of individual cells in suspension. However, for cells that are organized in a tissue, connections and communication between cells are crucial. Accordingly, we investigated besides intracellular effects also extracellular effects and in particular the response on tight junctions and cell-cell communication and how both affect the development of cells in a tissue, such as their potential to metastasize. Distinct effects could be found that are primarily caused by a transient disassembly of respective membrane proteins that are only compensated by repair mechanisms over the course of one hour [1,2,3]. Conversely, these changes have an immediate effect on intracellular biomolecular pathways, elastic properties of cells and on the permeability of tissues. Some of these effects can be enhanced by combining the treatment with pulsed electric fields and exposures to non-thermal plasmas. Overall this allows for new possibilities for tumour treatment and potentially also tissue regeneration.

[1] F. Shi et al., IEEE Trans. Biomed. Eng. (2019) in print. doi:10.1109/TBME.2018.2882299

[2] A. Steuer et al., PloS one 13 (2018) e0204916. doi:10.1371/journal.pone.0204916

[3] A. Steuer et al., European Biophysics J. 46 (2017) 567. doi:10.1007/s00249-017-1205-y

EVALUATION OF MAGNETIC STIMULATION FOR CELL MEMBRANE PORATION

Qin Hu[1], Ravi Joshi[2]
1. Central Michigan University
2. Texas Tech University

Exposure of biological cells and tissues to magnetic fields has not been studied much, and most of the research to date has focused on electrical stimulation. However, an even newer modality that might hold promise, is based on interactions of magnetic fields with living cells and tissues. Progress in experimental techniques has resulted in the burgeoning development of new approaches to target and observe effects of magnetic fields at the intracellular and molecular levels [1, 2]. Time-varying magnetic fields can also produce electric fields (and change transmembrane potentials) based on Faraday's law of induction. n neural tissues. Also, while medical applications based on electric fields require direct application via electrodes inserted into tissue, pulsed magnetic fields would allow treatment without invasive electrodes. This advantage could lead to an expansion of bioelectric treatments by allowing clinicians to affect any target within the body in a contactless manner.

An analysis into the time-dependent development of electric fields at cell membranes due to an externally applied magnetic field will be discussed. The parameter space for the magnetic stimulation for bringing about membrane poration will be discussed. Our results will focus on the time-dependent magnetic vector potential, and the resulting transmembrane potential, and poration based on the Smoluchowski equation.

[1]. M. H. Cho, E. J. Lee, M. Son, J. H. Lee, D. Yoo, J. W. Kim, S. W. Park, J. S. Shin, and J. Cheon, Nat. Mater., vol. 11, pp. 1038–1043, 2012. [2]. S. Qin, H. Yin, C. Yang, Y. Dou, Z. Liu, P. Zhang, H. Yu, Y. Huang, J. Feng, J. Hao, J. Hao, L. Deng, X. Yan, X. Dong, Z. Zhao, T. Jiang, H. W. Wang, S. J. Luo, and C. Xie, Nat. Mater., vol. 15, pp. 217–226, 2016.

CELL PERMEABILIZATION AND EXOGENOUS MOLECULE DELIVERY VIA MICROWAVE TREATMENT

Evelina Loghin[1], Allen Garner[2], Travis Crawford[2], Vasile Neculaes[3]
1. GE Global Research
2. Purdue University
3. GE

Typical techniques to artificially introducing nucleic acids (DNA or RNA) into cells can be divided into three categories: viral, chemical, and physical. The application space targets usually production of recombinant proteins, the study of the function and regulation of genes, the production of transgenic organisms, and as a method for gene therapy in clinical workflows. Physical means, such as electroporation (via electric pulse treatment) or sonoporation (via ultrasound treatment), can avoid some of the adverse side effects potentially triggered by viral and chemical means, but may less efficient and induce deleterious effects on cell function or surrounding tissue. For instance, electroporation can cause pain to surrounding tissue for in vivo treatments and may reduce cell viability during either in vitro or in vivo treatments. Some cells, such as stem and neuronal cells, remain difficult to transfect by any means. Thus, a physical method that can improve transfection efficiency while eliminating many of the side effects of chemical or viral techniques, particularly for these difficult to transfect cells, would significantly improve workflows requiring nucleic acid delivery into cells.

This paper presents experimental results for plasmid and siRNA delivery to CHO cells using 2.45 GHz microwave exposures in a single mode cavity, and potential mechanistic pathways for molecule uptake. While plasmid delivery efficiency is minimal, siRNA results are promising. This could indicate that microwave exposures may permeabilize the plasma membrane, but not the nuclear membrane.

MICROORGANISM INACTIVATION WITH ELECTRIC PULSES AND DRUGS

Agni Dhanabal[1], Anand Vadlamani[1], David Detwiler, Allen Garner[1]
1. Purdue University

Overuse of antibiotics in agriculture and healthcare has reduced the effectiveness of commonly used drugs for treating infections, motivating the development of methods to overcome antibiotic resistance to inactivate microorganisms. This study combines 300 ns electric pulses (EPs) with clinical and subclinical doses of drugs used to treat two common infectious bacteria, S. *aureus* and E. *coli*. We applied 20, 30 and 40 kV/cm, 300 ns EPs at 1 Hz with the number of EPs chosen to deliver the same energy density to 0.2, 2, and 20 μg/mL of tobramycin for 10 minutes of total drug exposure time. Applying 30 and 40 kV/cm EPs alone caused 2 to 4 log reduction; adding tobramycin induced a 7 to 9 log reduction. While this synergy occurred for smaller dosages with some antibiotics, it generally increased with larger doses. Minimal inactivation occurred with antibiotics alone over these timescales since these treatments typically require hours or days to effect cell kill off. These results indicate that combining EPs with drugs may potentially increase the effectiveness of drugs for treating local bacterial infections.

MODELING OF FLUXES AND SURFACE COVERAGE OF PLASMA-PRODUCED SPECIES ON ARTIFICIAL BONE SCAFFOLDING

Juliusz Kruszelnicki[1], Runchu Ma[1], Mark Kushner[1]
1. University of Michigan

Porous ceramics are used as scaffolding for tissue engineering and bone regeneration. Plasma treatment of porous calcium hydroxyapatite increases cell attachment and adhesion, improving performance as a bone substitute.[1] The mechanisms producing improvement are not well known, but surface coverage of chemisorbed O, OH and N have been correlated with increased wettability, possibly leading to increased cell proliferation. These plasma processes are typically performed at low pressure. Using atmospheric pressure plasmas (APPs) would lower cost, but are challenged to produce uniform plasmas inside the pores.

APPs propagating through pores tens of microns in size in ceramics were computationally investigated using the 2D modeling platform, nonPDPSIM.[2] Plasma was produced in a co-planar dielectric barrier discharge (DBD) by negative ns voltage pulses. The bottom dielectric had chains of pores with 100% interconnectivity. Discharges in air and He/O_2 mixtures were studied while varying the width and angle of the pore-chain.

Plasma propagating from the DBD into the pores initially produces a Townsend-like discharge and surface charging. The surface charging is sensitive to the angle of the pore-chain and can produce restrike-like discharges propagating back towards the plasma. The alignment of the pore-chain with the applied electric fields impacts plasma properties. Surface ionization waves (SIWs) along the curved surfaces of pores most readily form when the pore-chain has a large angle. The high electron temperatures at the head of the SIWs produce higher radical fluxes onto pore surfaces which are progressively less uniform as the pore-chain angle increases. Narrower openings between pores produce less uniform fluxes as propagation of the plasma is inhibited.

Work supported by the National Science Foundation and the DOE Office of Fusion Energy Science.

[1] Y. Moriguchi et al., PLoS ONE 13, 3 (2018).

[2] S. Norberg et al., Plasma Sources Sci. Technol. 24, 035002 (2015).

PLASMA POLYMERIZATION OF N,N-DIMETHYLACRYLAMIDE: CELL-REPELLENT OR CELL-ADHESIVE COATINGS?

Tim Egghe[1], Pieter Cools[2], Joachim Van Guyse[1], Mahtab Asadian[1], Dmitry Khalenkow[1], Anton Nikiforov[1], Heidi Declercq[1], Andre G. Skirtach[1], Rino Morent[1], Richard Hoogenboom[1], Nathalie De Geyter[1]
1. Ghent University
2. University Ghent

Several precursors for plasma polymerization have been studied at length, including carboxylic acids, amines, siloxanes and ethers. This is in stark contrast with amide-based precursors, for which only a limited amount of studies are available [1-5], which notably differs with the abundance of biomedical research focussing on amide-based surface modification using wet chemistry [6-8]. This indicates that plasma polymerization of amide-based precursors has still unexplored potential, even more so because the previously performed chemical analyses were not extensive and the stability examinations were limited to only 3 hours of water incubation. Therefore, the plasma polymerization of a novel amide precursor (*N,N*-dimethylacrylamide) was explored in this study. The effects of varying discharge power on the plasma active species (OES), hydrophilicity (WCA), chemical composition (FT-IR, Raman spectroscopy, XPS) and stability (up to 1 week of water incubation, with AFM scratch tests) were examined. Additionally, the interactivity between cells (MC3T3) and the deposited coatings were studied in-vitro through life/dead fluorescent imaging and MTS assays. In contrast to the unstable coatings obtained at lower powers, the stable coatings showed a reduced preservation of the precursor structure and therefore a lower hydrophilicity. The plasma fragmentation resulted in coatings with a complex N-rich chemistry that could be directly linked to the observed plasma species. XPS C_{60} depth profiling indicated a difference between the top layer and bulk of the plasma polymer due to spontaneous oxidation and/or post-plasma deposition. Stable coatings were found to have cell-interactive behavior, showing a cell viability of up to 71% as compared to tissue culture plates after 1 day of cell culture.

[1]: Cheng et al., DOI:10.1021/la050417o. [2]: Chu et al., DOI:10.1016/j.surfcoat.2007.08.076.

[3]: Griesser et al., DOI:10.1163/156856294X00194. [4]: Pan et al., DOI:10.1021/bm0000642.

[5]: Bullet et al., DOI:10.1002/sia.2318. [6]: Morgese et al., DOI:10.1016/j.eurpolymj.2016.11.003.

[7]: Lin et al., DOI:10.1021/bm200368p. [8]: Liu et al., DOI:10.1021/bm201814p.

MEASUREMENTS ON COMBINED 12.5/17.5 KV PROTOTYPE INDUCTIVE ADDER FOR THE CLIC DR KICKERS

Janne Holma[1], Mike Barnes[1]
1. CERN

The CLIC study is investigating the technical feasibility of an electron-positron collider with high luminosity and a nominal centre-of-mass energy of 3 TeV. The pre-damping rings and damping rings (DRs) will produce ultra-low emittance beam with high bunch charge. To avoid beam emittance increase, the DR kicker systems must provide extremely stable field pulses during injection and extraction of bunches. The DR extraction kicker system consists of a stripline kicker and two pulse modulators. The present specification for the modulators calls for pulses with 160 ns or 900 ns flattop duration of nominally +/-12.5 kV and 305 A, with ripple of not more than +/-0.02 % (+/-2.5 V). In addition, there is a proposal to use the same modulators and striplines for dumping the beam, with +/-17.5 kV stripline pulse voltage. An inductive adder is a very promising approach to meeting the CLIC DR extraction kicker specifications because analogue modulation methods can be applied to adjust the shape of the flattop of the output waveform. Two full-scale, 12.5 kV, 20-layer, prototype inductive adder have been designed, built and tested at CERN. One of these has also been tested with eight additional layers, to facilitate two operation modes: 12.5 kV pulses for extraction kicker operation and 17.5 kV for dump kicker operation. An automated control system for droop and ripple compensation, based on Labview software, has been designed and implemented for the prototype modulators. The results of laboratory tests of full-scale prototypes, during normal operation and with typical fault scenarios, are presented. The paper also includes comparisons of results from different measurement techniques of fast, up to two microseconds duration, high-voltage pulses and an analysis of the limits of these techniques.

PULSED RESONANT CHARGING POWER SUPPLY FOR THE SPALLATION NEUTRON SOURCE EXTRACTION KICKER PFN SYSTEM

Robert Saethre[1], Ben Morris[2]
1. Oak Ridge National Lab
2. ORNL

Pulsed Resonant Charging Power Supply for the Spallation Neutron Source

Extraction Kicker PFN System

R. Saethre, B. Morris, Oak Ridge National Laboratory

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) uses fourteen pulsed modulators in the extraction system to deflect the proton beam from the accumulation ring to the target. The SNS is executing the Proton Power Upgrade (PPU) project to increase the beam energy from 1.0 to 1.3 GeV, which requires an increase in the extraction kicker magnetic field intensity. Each pulse modulator consists of a pulse forming network (PFN), located in a service building external to the ring tunnel, along with a charging power supply and related controls and interlocks. Increasing the magnet current by charging the PFN to a 20% higher voltage will provide the required deflection. The existing capacitor charging power supply is incapable of charging the PFN to higher voltages between 60 Hz pulses, and therefore a new resonant charging scheme has been developed to charge to the required voltage within the available time. This paper describes the resonant charging power supply design and presents test results from a prototype operating on a full system test stand.

CONTROLLED RECTIFIER FOR IMPROVED HARMONIC PERFORMANCE OF A PULSE STEP MODULATED HIGH VOLTAGE POWER SUPPLY

Amit Patel[1]
1. ITER-India,Institite for Plasma Research

Harnessing Nuclear Fusion reaction as a source of energy is important for mankind as it can potentially provide an environmentally benign way to produce energy from an almost inexhaustible resource, viz., Deuterium from water. Research in magnetic confinement fusion uses high power Radio Frequency sources and accelerated Neutral Particles to heat plasma to fusion temperature. These devices use High Voltage Power Supplies that need to supply power in the range of 1-10 MW and at output voltage of several tens of KVs. Pulse Step Modulation technique is used to generate High Voltage from a series connection of a large number of low voltage switched power modules, all fed by a Multisecondary transformer. This makes the HVPS capable of generating low ripple output with μS order transient response time and low let through energy in case of load fault. However, power quality and reliability of these systems still needs improvement for future use in industrial environment. In a conventional diode rectifiers based switched power supply module, current drawn from multi-secondary transformer is highly distorted which ultimately affects the transformer performance. Because of same, higher capacity may be explored or better thermal management. Apart from power quality, certain applications demands a stable and programmable dc link in switched power supply module. As a mitigating action, a novel concept of replacing diode rectifiers by Front End Converter is attempted for first time. Article mainly discuss a HVPS with conventional diode rectifiers and possibility of replacing a diode rectifiers by Front End converter. Article also discuss a development of laboratory scale 6 kW Front End Rectifier supported by simulation as well as experimental results.

A COMPACT SOLID STATE TRIGGER GENERATOR UTILIZING A FERRITE LOADED AIR CORE TRANSFORMER*

Joshua Gilbrech[1], Susan Heidger[2], James Schrock[3], Jerald Parker[4], ROBERT RICHTER-SAND[1]
1. Leidos
2. U.S. Air Force Research Laboratory
3. AFRL
4. Leidos, Inc.

As pulse modulators are increasingly built more compact, so do the ancillary supporting electronics systems have to decrease in size. The trigger system presented, utilizes a 10kV 10kA capable solid state switch to conduct energy through a ferrite loaded air core transformer. The final output is capable of reaching 60-70kV in less than 100nS, with extremely low jitter with reliable (or consistent) performance. Depending upon the charging supply this system is capable of repetition rates of 88 Hz in continuous or burst mode operation. Higher voltages or faster rise-times are also supported based on lower repetition rates limited by the size and capability of the compact 10 kV power supply.

* Work is sponsored by Air Force Research Laboratory (AFRL)/RDH, Kirtland Air Force Base, under FA9451-17-D-0070

DESIGN OF SOLID-STATE MARX MODULATOR WITH FAST RISING TIME AND SHORT PULSE WIDTH

Jung Soo Bae[1], Hyoung Suk Kim[2], Chan Hun Yu[2], Kim Shin[1], Sung-Roc Jang[3]
1. University of Science & Technology
2. KOREA ELECTROTECHNOLOGY RESEARCH INSTITUTE
3. KERI

This paper describes the design of the solid-state Marx modulator with fast-rising time and short pulse width for various applications such as accelerator and plasma application. By stacking of SiC-MOSFETs, the designed specifications are satisfied as 10 kV, under 50 ns of pulse width, under 15 ns of rising time. The designed circuit consists of the ON switches for applying pulse to the load and the OFF switches for pull-down the pulse that is closely related to the rising and falling time of output pulse, respectively. Compared to conventional Marx generator using diode, the OFF switch connected in parallel with load provides discharging path for the stored energy on the parasitic capacitance and allows short pulse width owing to fast falling time. In order to provide complementary driving signal and power for ON/OFF switches, the simple control algorithm with minimum component count and reliable drive circuit against to the noise is proposed. Besides the circuit design, compact configuration for minimizing the inductance and synchronizing all the signal is essential to shorten the rising, falling and pulse width. Based on the proposed circuit, the detailed design and implementation of ns Marx modulator is presented such as the layout of Marx cell for minimizing inductance, the artwork of PCB for synchronizing fast gate signal, and resonant converter based charging circuit for compact arrangement.

In addition to the experiment with resistor load for verifying the performance of developed modulator, the results of application study including PAW (plasma activated water) application as well as the kicker system for accelerator will be introduced in the following paper.

100KW PEAK RACKMOUNT MARX WITH DYNAMIC PULSE-TO-PULSE WAVEFORM CONTROL

Kelli Noel[1], Magne Stangenes[2], Paul Holen[2], Michael Valbuena[2],
Christopher Yeckel[2], Sherry Hitchcock[2]
1. University of Missouri
2. Stangenes Industries

Stangenes Industries has designed and delivered a 5U 19” rackmount modulator for driving high impedance capacitive loads such as an electron gun. An FPGA controls the delays between successive triggering of 18 Marx stages to match the modulator output to loads of various impedances. With a single HV supply providing a fixed charge voltage the modulator can generate output voltages from 5KV to 50KV with 0.1KV of output resolution commanded pulse-to-pulse. The pulse width is adjustable between 0.5μs and 5μs in steps of 0.1μs and the pulse delay from trigger signal is adjustable from 0μs to 3μs in steps of 0.1μs, also commanded pulse-to-pulse.

The system is operated remotely by a client-computer via an ethernet protocol which also displays real-time diagnostic data. The modulator is equipped to count and recover from vacuum arcs and maintains a time-stamped fault log. Fast signals such as the trigger, faults, interlocks and waveform select are hardwired through low-latency optically isolated circuits. All the components: power supply, Marx, pulse-transformer, 40W DC filament, current/voltage diagnostics and controls are contained within the box which is powered by a single phase 120/240V wall plug. The system is entirely air cooled with no insulating oil.

This paper described the modulator as tested into an electron-gun. Waveform tuning procedures as well as heat data are presented. The system is capable of operation at a repetition rate of 1000HZ and a modulator average output power of 300W. The internal components are modular with emphasis placed on rapid MTTR for enhanced serviceability.

STUDY OF COCKCROFT-WALTON MULTIPLIERS DRIVEN BY AC SOURCES WITH LIMITED CURRENT

Jacob Williams[1], S. D. Kovaleski, Enbo Yang
1. University of Missouri Electrical Engineering and Computer Science

Cockcroft-Walton (CW) multipliers are common and simple DC high voltage sources; however, almost all literature on CW design assumes an ideal AC current source drives the multiplier. Our work on piezoelectric transformer driven CW multipliers for use in compact x-ray sources prompted a study of CW operation with limited supply current. Limiting the AC source current supplying a CW has been shown to significantly reduce its output voltage. Using SPICE, differing degrees of current limiting, varying stage capacitance, and variable loads all had a significant impact on total output voltage from a CW. CW multipliers are known to have an optimal number of stages to produce the highest output voltage, which is no different for multipliers with current limited sources. However, the optimum number of stages is dependent upon the current limiting and tends toward lower numbers of stages for reduced drive current. Varying stage capacitance also has a significant impact on output voltage, which is dependent on supply current. Both uniform stage capacitance and variable stage capacitance have been investigated, with marginal improvements found for the variable capacitance case. From simulation, the output voltage is shown to increase as the load increases, with the amount of increase dependent on the supplied current.

Work supported by the Advance Research Projects Agency-Energy

CHARACTERISTIC ANALYSIS OF METAL OXIDE RESISTOR UNDER IMPULSE OF DIFFERENT WAVE-HEAD TIME

Wei Zhang[1]

1. Xi'an Jiaotong University

ABSTRACT: This paper determines the waveform parameters of metal oxide varistor (MOV) test platform according to the IEC standards and the waveform characteristics of very fast transient overvoltage (VFTO) measured in gas-insulated metal-enclosed switchgear (GIS). The standard lightning impulse test circuit with 8 us wave-head time, the steep wave impulse test circuit with 100ns wave-head time and the very fast transient overvoltage impulse test circuit with 20ns wave-head time are designed and constructed respectively. Several typical MOVs used in 10kV and ultra-high voltage arresters are selected as samples. The volt-ampere characteristics of MOVs under the above three different wave-head time impulses are studied experimentally. The experimental results show that the residual voltage of MOV increases by 14.7% to 18.2% under the action of 20ns very fast transient overvoltage impulse compared with the standard lightning wave and the steep wave with the same amplitude. Under the action of standard lightning impulse with 8us wave-head time and the steep wave impulse with 100ns wave-head time of different amplitude, the voltage of MOV reaches its peak value earlier than current, showing the characteristics of inductance. Under the action of 20ns very fast transient overvoltage impulse, MOV has an obvious impedance transition voltage U0. Under U0 voltage, MOV shows resistance characteristics. When the peak voltage is less than U0, MOV shows capacitive impedance characteristics. When the peak voltage is greater than U0, MOV shows inductive impedance characteristics. U0/U1mA has little relationship with the shape and size of MOV.

ANALYSIS OF COMMERCIAL OFF-THE-SHELF 1200 V SILICON CARBIDE MOSFETS UNDER SHORT CIRCUIT CONDITIONS

Jonathan Forbes[1], Fernando Salcedo[1], Cedrick Tchoupe-Nono[2], Stephen Bayne[3]
1. Texas Tech University
2. Texas Tech University Center for Pulsed Power and Power Electronics
3. Center for Pulsed Power and Power Electronics, Department of Electrical and Computer Engineering, Texas Tech University

Silicon carbide (SiC) power semiconductor devices are experiencing an increasingly widespread adoption in many power electronics and pulsed power applications such as high-power DC-DC converters and inverters, battery chargers, industrial motor drives, as well as high-power solid-state pulse generators such as a Marx generator or a linear transformer driver (LTD). The wide-bandgap (WBG) and thermal properties of SiC provide inherent advantages over silicon power devices especially in high power density applications. These advantages include higher blocking voltages, increased switching speeds, physically smaller implementations of power electronics and pulsed power circuits, improved system efficiencies, and higher operating temperatures. To improve the overall confidence in the ability of SiC devices to reliably replace equivalent silicon solutions, independent reliability testing and analysis must be conducted. In this research, a short circuit test board was developed to analyze the short circuit ruggedness of 1200 V MOSFETs. Using the test board, commercially available 1200 V / 10 A SiC MOSFETs from 3 different manufacturers were subjected to both single and repetitive short circuit events, and the short circuit ruggedness of each device was measured and analyzed. The purpose of this research is to independently measure and report on the short circuit capabilities of commercially off-the-shelf 1200 V SiC MOSFETs.

THE CURRENT STATE OF CUSTOM PULSE POWER CORES SUPPLIED BY METGLAS INC.

Eric Theisen[1], John Webb[2]
1. Eric
2. Metglas

Metglas Inc. has a long history and large experience base in manufacturing Pulse Power Cores with amorphous metals for industrial and research applications. There are a wide variety of alloys for use as core materials which enables designs based on flux swing, core loss and rise/switching time requirements. The change in flux density can vary from 1.1 – 3.4 T depending on alloy selection. Custom cores range in size from grams to tons. Custom shapes, fabrication hardware, testing and handling devices are made as needed. Polyester film is the standard material used for interlaminar insulation but other coatings can also be used. Heat treatment, winding and other proprietary processing techniques result in products that meet requirements that might not be achieved using more conventional materials and these methods will be discussed.

TRANSIENT LOADING OF ULTRACAPACITORS*

Charles Nybeck[1], David Wetz[1], David Dodson[1], Alexander Johnston[1], John Heinzel[2], Joshua Ruddy[1]
1. University of Texas at Arlington
2. Naval Surface Warfare Center - Philadelphia Division

Ultracapacitors are of increasing interest in the high voltage coummunity due to thier ability to source high transient power while also offering a modest energy density. A market study of commerically available ultracapacitors finds a number of different models available with slightly different internal resistance, energy density, and power density parameters, among others. Hybrid ultracapacitor technologies, such as lithium-ion capacitors, have also been developed that have much higher energy density with nearly the same power density. In the work presented here, a few different commercially avaialble off the shelf ultracapacitors and lithium-ion capacitors have been procured and evaluated into a low impedance load, few hundred micro-Ohms, in a transient manner. The design of experiments as well as the impedaance and power density results obtained will be presented.

----

* Work supported by the US Office of Naval Research (ONR) under grant N00014-17-1-3015

INVESTIGATION INTO THE RELIABILITY OF COMMERCIAL 1.2-KV SIC MPS DIODES UNDER SURGE CURRENT AND AVALANCHE EVENTS

Fernando Salcedo, Jonathan Forbes, Stephen Bayne, Ranbir Singh

With the prospect of wide-bandgap (WBG) devices such as SiC (silicon carbide) taking the forefront to replace Si (silicon) in commercial applications, analysis must be done on surge current and avalanche energy reliability to verify the viability of replacing Si with SiC in terms of long-term reliability. Properties of SiC theoretically show superior thermal conductivity, and higher breakdown field, giving SiC devices the edge in power applications where temperature and voltage hold-off are vital. Power converters and inverters are often exposed to these events due to a load short circuit or transients before reaching steady-state. It is common for power semiconductor devices such as MOSFETs (metal-oxide-semiconductor field-effect transistors) or diodes to experience a short duration of overcurrent or overvoltage in these power switching applications. The surge current can potentially damage devices if not properly rated. Extended duration of overvoltage leads to avalanche breakdown, ending in catastrophic failure of the device. This paper investigates the surge current and avalanche breakdown capabilities of commercial SiC MPS diodes rated for 1.2 kV reverse voltage and 20 A continuous forward current. The diodes are rated for 164 A of non-repetitive surge current and 220 mJ of total avalanche energy. A testbed is designed and developed to test the reliability of commercial WBG diodes in surge and avalanche events. Each device is initially characterized, exposed to testing conditions, and then characterized again to monitor signs of degradation. Analysis of the data collected during and after testing was conducted to determine the reliability in commercial applications.

Keywords – SiC; WBG; wide-bandgap; MPS; merged pin; surge current; in-rush current; avalanche energy, pulsed power; reliability testing; power electronics

MODELING ELECTRICAL DISCHARGE TUBE USING COMSOL MULTIPHYSICS: DIAMOND-LIKE CARBON (DLC) THIN FILMS

Arezou Zarei[1], Masoud Alimohamadi[2]
1. Department of physics, Shahrood University of technology, Semnan, Iran
2. Department of physics, Farhangian University, Tehran,Iran

This paper presents a 2D fluid model of direct current (DC) glow discharge by Comsol multiphysics. The DC discharge consists of two graphite electrodes, one powered and one grounded (the cathode). Argon gas was considered due to the simplest mechanisms to implement at low pressures. Simulation is carried out in argon for the whole length of discharge (from the anode to cathode) at P=2.3$\times$10-2 mbar and L$<$5 cm. The film thickness was calculated as well as the plasma temperature, electric potential, and the electron density. Convection of electrons due to the fluid model is neglected.

Keywords: electrical discharge tube; Comsol multiphysics; Diamond-like carbon; DC glow discharge; thin films

IMPLICATIONS OF SURFACE ROUGHNESS ON MICROSCALE GAS BREAKDOWN THEORY

Jacqueline Malayter[1], Russell Brayfield[1], Amanda Loveless[1], Allen Garner[1]
1. Purdue University

Predicting gas breakdown for micro- and nanoscale dimensions increases in importance as devices continue to shrink. A recent study derived a single universal theory to predict breakdown voltage for any gas and pressure for breakdown characterized by Townsend avalanche or field emission at microscale [1]. At microscale, the gas breakdown model more strongly depends on the electrode conditions, such as work function and field enhancement, than geometric or gas parameters [2]. Thus, more accurately predicting breakdown voltage requires further elucidating how physical electrode parameters, such as surface roughness, may alter the work function. This presentation theoretically examines the impact of sinusoidal surface roughness, specifically its amplitude and period, on work function [3] and breakdown voltage. Comparison to microscale gas breakdown experiments assessing cathode surface roughness and implications for nanoscale devices will be discussed.

Work supported by a Directed Energy Professional Society Scholarship and by the Office of Naval Research under Grant No. N00014-17-1-2702.

[1] A.M. Loveless and A.L. Garner, "A Universal Theory for Gas Breakdown from Microscale to the Classical Paschen Law," Phys. Plasmas, vol. 24, 2017, art. no. 113522.

[2] S.D. Dynako, A.M. Loveless, and A.L. Garner, "Sensitivity of Modeled Microscale Gas Breakdown Voltage due to Parametric Variation," Phys. Plasmas, vol. 25, 2018, art. no. 103505.

[3] W. Li and D. Y. Li, "On the correlation between surface roughness and work function in copper," J. Chem. Phys., vol. 122, 2005, art. no. 064708.

PHASE MIXING AND COLLISIONLESS DISSIPATION AT THE BOUNDARY SHEATH OF MAGNETIZED LOW TEMPERATURE PLASMAS

Dennis Krüger[1], Ralf Peter Brinkmann[1]
1. Ruhr University Bochum, Germany

High power impulse magnetron sputtering (HiPIMS) is an important example for the technical application of magnetized low temperature plasmas. The spontaneous emergence of self-organized structures (spokes) and the presence of anomalous transport - probably two sides of the same coin - play an important role in HiPIMS and related E×B discharges (e.g., Hall thrusters) [1]. These phenomena are not fully understood at present, although they seem to have a strong impact on the overall discharge behavior. Due to their symmetry breaking nature, in principle, a three dimensional kinetic simulation is required. Especially, for the HiPIMS regime ($n_\mathrm{e} \leq 10^{20}\,\mathrm{m}^{-3}$ and $p \approx 0.5\,\mathrm{Pa}$), conventional kinetic approaches like particle-in-cell (PIC) methods are too resource consuming to simulate relevant time scales. One possible alternative makes use of the fact, that the electron Larmor radius r_L of the thermal electrons is small compared to the typical length scale L of the system. This ansatz, however, breaks down at the plasma boundary sheath in front of the target. A hard wall model might be an effective boundary condition for the interaction of magnetized electrons with this interface [2,3]. In this work, we present numerical and analytical investigations to relate the incoming and the outgoing electron velocity distribution function (EVDF) for different inclination angles of the magnetic field. An interesting feature, which can be observed in the outgoing EVDF, are fractal type structures, which disappear due to phase mixing about a distance of a few Larmor radii away from the sheath edge.

1 Anders et al., Journal of Applied Physics 111, 053304 (2012)

2 Krüger et al., Plasma Sources Sci. Technol. 26, 115009 (2017)

3 Krüger et al., Plasma Sources Sci. Technol. 27, 025001 (2018)

This work is supported by the German Research Foundation in the

frame of the Collaborative Research Center TRR 87.

RF GAS BREAKDOWN THEORY AND EXPERIMENT AS A FUNCTION OF GAS, GAP SIZE, FREQUENCY, AND PRESSURE

Amanda Loveless[1], Zach Vander Missen[1], Abbas Semnani[1], Allen Garner[1]
1. Purdue University

Although gas breakdown for radiofrequency (RF) and microwaves has been extensively studied, a consistent and accurate model for AC breakdown voltage independent of unknown fitting parameters remains incomplete. While the RF breakdown model derived by Kihara theoretically justifies a fitting parameter based on various molecular constants, the magnitude used to match experimental results differs [1].

This study aims to elucidate the physical meaning behind the material parameter and derive a relationship dependent on frequency and pressure. We measured breakdown voltage at 0.38, 0.76, and 1.52 Torr for argon at a $\sim$1 cm gap with frequencies of 96, 140, and 191 MHz and helium at a $\sim$0.8 cm gap and frequencies of 92, 140, and 185 MHz. By using Kihara's RF equation [1] to fit the data, we demonstrate how the fitting parameter depends on the different experimental parameters, elucidating the underlying physical mechanisms involved.

1. T. Kihara, "The mathematical theory of electrical discharges in gases," Rev. Mod. Phys., vol. 24, pp. 45-61, 1952.

MODELING ELECTRODE CONFIGURATIONS FOR NANOSECOND PULSED PLASMAS

Nancy Isner[1], Tugba Piskin[1], Jonathan Poggie[1], Tatyana Sizyuk[1], Carlo Scalo[1], Allen Garner[1]
1. Purdue University

Nanosecond pulsed plasmas (NPPs) can efficiently generate ionized and excited species. While numerous studies have examined local flow field effects [1], characterization of the induced flow field and electrode geometry and the induced flow field remains incomplete. We hypothesize that altering the electrode configuration to modify the electric field will strongly influence plasma species generation and the induced flow field, motivating the development of a more comprehensive model.

This study couples a quasi-one dimensional model for a parallel plate geometry [2] to BOLSIG+ to better characterize plasma species generation [3]. The implication of electrode configurations, such as pin-to-pin and pin-to-plate, on the induced electric field and generated species will be examined. The long-term incorporation of this model into a high fidelity computational fluid dynamics (CFD) model and comparison to spectroscopic results under quiescent and flowing conditions will be discussed.

1. A. V. Likhanskii, M. N. Shneider, S. O. Macheret, and R. B. Miles, “Modeling of dielectric barrier discharge plasma actuator in air,” J. Appl. Phys., vol. 103, 2008, Art. no. 053305.

2. I. V. Adamovich, M. Nishihara, I. Choi, M. Uddi, and W. R. Lempert, “Energy coupling to the plasma in repetitive nanosecond pulse discharges,” Phys. Plasmas, vol. 16, no. 11, 2009, Art. no. 113505.

3. G. J. M. Hagelaar and L. C. Pitchford, “Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models,” Plasma Sources Sci. Technol., vol. 14, no. 4, pp. 722–733, 2005.

----

* This material is based upon work supported by the U.S. Department of Energy, Office of Fusion Energy Sciences under award DE-SC0018156.

ATOMISTIC STUDY OF POLARIZATION RESPONSE IN FUNCTIONALIZED BARIUM TITANATE NANOPARTICLES

Jessica Dyer[1], Todd Monson[2], Tyler Stevens[2], Renee Van Ginhoven[3]
1. Sandia Lational Labs
2. Sandia National Laboratories
3. AFRL

To further the goal of optimized material design for pulsed power components, we aim to achieve a fundamental understanding of the model nonlinear dielectric material BaTiO3, through concurrent experimental and theoretical study. This effort is intended to lead to improved synthesis and design control, and a validated model to enable material predictions. The ultimate goal is to improve energy storage and discharge characteristics through design models for dielectric materials that translate results from the molecular level to macroscopic device level.

In order to achieve this goal, it is first necessary to understand the atomistic level polarization response of ferroelectric BaTiO3 to the presence of surface ligands used in the material synthesis process. This response is of sufficient magnitude to obscure the energetics of surface and defect chemistry, and is highly sensitive to simulation boundary conditions. In this work, we apply density functional theory to explore the effects of different choices of surface termination and initial starting conditions on the polarization response of the material to the presence of adsorbed molecules and point defects. The examined choices include constrained optimization techniques, preconditioned ferroelectric phases, surface mirroring, and inclusion of compensating electrode layers. The advantages and shortcomings of each option are discussed both in the current context and in relation to previous literature results. Where possible, we place results in the context of our ongoing concurrent experiments.

DENSITY RISE AWAY FROM THE ANTENNA IN A HELICON PLASMA SOURCE FOLLOWING RESONANCE CONE ABSORPTION IN A DIVERGING AXIAL MAGNETIC FIELD

Arun Pandey[1], Mainak Bandyopadhyay[2], Arun Chakraborty[3]
1. Institute for Plasma Research
2. ITER-India, Institute for Plasma Research
3. ITER-India

A Helicon wave heated hydrogen plasma is created by applying 800 W RF power to a Nagoya-III antenna at 13.56 MHz frequency, which excites m = ± 1 azimuthal mode in the plasma. A permanent ring magnet provides the axial field required for the helicon wave excitation. The plasma expands from the source chamber to the expansion chamber in a diverging magnetic field. Diagnosis of the wave field through a b-dot probe confirms the helicon wave excitation in the hydrogen plasma. The dc magnetic field is varied from 40 G to 85 G in the source region by changing the ring magnet position to study the effect of the diverging field in the expansion chamber. The field in the expansion chamber reduces down to < 10 G within a distance of 6 cm from the source boundary. The axial profile of the density attains a maximum value under the antenna and decays as we move away from the antenna into the expansion chamber. In the expansion chamber a second peak in density, weaker than the first one, is observed for a particular magnetic field configuration but is absent for other configurations. The phase and amplitude of the axial component of the wave field is measured and a wave damping is observed for the magnetic field configuration in question. This wave damping corresponds to the resonance cone absorption of the helicon wave. No such damping is observed for other cases where there is no dramatic increase in the downstream density.

INVESTIGATION OF ELECTRON EMISSION CHARACTERISTICS OF MULTI-FINGER FERROELECTRIC TRIGGER SOURCE FOR PSEUDOSPARK SWITCH

Udit Narayan Pal[1], Mohit Kumar Verma[2], B. L. Meena[3], Varun .[4], Ajeet Kumar Dhakar[5]

1. CSIR-Central Electronics Engineering Research Institute, Pilani, India
2. Electrical Engineering Department, National Institute of Technology (NIT), Calicut-673601, India
3. Microwave Devices Area, CSIR- Central Electronics Engineering Research Institute (CEERI), Pilani, Rajasthan-333031, India
4. CSIR- CEERI, Pilani, India and AcSIR, Ghaziabad, India
5. Cyber Physical System Area, CSIR- Central Electronics Engineering Research Institute (CEERI), Pilani, Rajasthan-333031, India

State of the art low pressure cold cathode pseudospark switches (PSS) for high pulsed power applications require special kinds of trigger electron source, which possess long life, reliable, durable, uniform electron emission, economical, etc. [1-4]. A high dielectric (dielectric constant $\sim$2000) ferroelectric based trigger source is one of the best suited trigger mechanism for the PSS [2-4]. In this paper electron emission and breakdown characteristics of the ferroelectric trigger source has been presented for the generation of required trigger electrons for fast, low jitter and reliable switching. Electrodes with different finger tips and PZT ferroelectric dielectric disc has been analyzed. The electrical and optical diagnostics of ferroelectric trigger source have been performed to analyse electron emission and breakdown characteristics at different operating parameters, such as, gases and pressures, voltages, resistors and inductors. Electrostatic and plasma simulation studies have also been performed to investigate the electric field lines and electron emission processes. An electric field $\sim$107 V/cm in vacuum as well as in gases has been observed between the tips of the electrode and ferroelectric disc. The emission characteristics are strongly dependent on the gases, pressures, voltages and resistances. It is showing better emission characteristics $\sim$30 A at higher pressure $\sim$60 Pa in case of helium and hydrogen gases for 1 kΩ resistance while in case of argon and nitrogen gases at comparable lower pressure $\sim$10 Pa, $\sim$20 A emission current has been observed for 20 kΩ resistance.

References:

[1] K. Frank, et al., IEEE Trans. Dielectr. Electr. Insul., vol. 14, pp. 968–975, 2007.

[2] H. K. Dwivedi, et al., IEEE Trans. Plasma Sci., vol. 30, pp. 1371-1375, 2002.

[3] V. Pathania, et al., IEEE Trans. on Dielectric Elec. Ins., vol. 22, pp.3299-3304, 2015.

[4] R. P. Lamba, et al., Plasma Sources Sci. Technol., 27, 035003, 2018.

ELECTRON EMISSION IN LIQUIDS

Sarah Lang[1], Allen Garner[1]
1. Purdue University

Discharge formation and breakdown in water have critical implications for water sterilization and biomedical applications [1]. Several studies demonstrate current scaling in liquids following field emission by the Fowler-Nordheim law (FN) and space charge-limited emission (SCLE) by the Mott-Gurney law (MG) with collisions [2]. Recent theoretical work for gases has unified the asymptotic solutions of FN and MG with the Child-Langmuir law (CL) for SCLE at vacuum, even demonstrating a triple point where all three as [2]. This presentation assesses the feasibility of applying a similar unification of MG and FN for liquids. Experimental implications will be discussed.

1. J. E. Foster, "Plasma-based water purification: Challenges and prospects for the future," Phys. Plasmas, vol. 24, no. 5, 2017, Art. no. 005501.

2. K. Dotoku et al., "Field emission into nonpolar organic liquids," J. Chem. Phys., vol. 69, no. 3, pp. 1121-1125, 1978.

3. A. M. Darr, A. M. Loveless, and A. L. Garner, "Unification of field emission and space charge limited emission with collisions," Appl. Phys. Lett., vol. 114, no. 1, 2019, Art. no. 014103.

UNIFICATION OF THERMIONIC, FIELD AND SPACE CHARGE LIMITED EMISSION

Sarah Lang[1], Allen Garner[1], Adam Darr[1]
1. Purdue University

A recent theoretical study unified field emission modeled by Fowler-Nordheim (FN) and space charge limited emissions (SCLE) with and without collisions modeled by Mott-Gurney (MG) and Child-Langmuir (CL), respectively [1]. This study showed the existence of a triple point, where the three asymptotic solutions matched, and the ubiquitous nature of CL at high voltages, even at high pressure [1]. Theoretical work has also connected FN to thermionic emission modeled by the Richardson-Laue-Dushman (RLD) equation using a general thermal-field emission (GTFE) equation [2]. This presentation explores the potential connection of the GTFE with SCLE, particularly the existence of the triple point as GTFE approaches FN. Experimental implications will be discussed.

Work supported by a Purdue Doctoral Fellowship and the Air Force Office of Scientific Research under award number FA9550-18-1-0218.

1. A. M. Darr, A. M. Loveless, and A. L. Garner, "Unification of field emission and space charge limited emission with collisions," Appl. Phys. Lett., vol. 114, no. 1, 2019, Art. no. 014103.

2. K. L. Jensen, "A tutorial on electron sources," IEEE Trans. Plasma Sci., vol. 46, no. 6, pp. 1881-1899, 2018.

INVESTIGATING TRANSPORT PROPERTIES OF COLLISIONLESS MAGNETIZED PLASMAS IN PULSED POWER SYSTEMS VIA HIGH-ORDER KINETIC SIMULATIONS

Genia Vogman[1], James Hammer[1], William Farmer[1]
1. Lawrence Livermore National Laboratory

Pulsed power experiments rely on magnetically insulated transmission lines to deliver mega-amps of current to a load to produce and study high energy density matter. Experimental results show that the formation of low-density plasmas in the power feeds gives rise to parasitic currents, which affect load dynamics and prevent scaling of load parameters. To understand the inimical transport properties of these low-density, magnetized, collisionless plasmas and how they affect experimental outcomes, the cross-field environment within the power feeds is studied using high-order time-dependent continuum kinetic simulations, which offer enhanced solution accuracy and can robustly capture equilibria. The effects of drifts, anisotropies, finite Larmor motion, charge separation, and sheared flow instabilities are examined. The computational study is facilitated in part through the development of machinery for constructing self-consistent kinetic equilibria and through the generalization of existing fluid theory analysis. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under Project No. 18-ERD-048. LLNL-ABS-767941

QUANTIFYING STREAMER DYNAMICS FOR AZIMUTHALLY SWEPT 3D WEDGES IN PIN-TO-PLANE PIC-DSMC SIMULATIONS

Ashish Jindal[1], Chris Moore[2], Andrew Fierro[1], Matthew Hopkins[1]
1. Sandia National Laboratories
2. Sandia National Labs

The dynamics of streamers in PIC-DSMC simulations of 3D pin-to-plane wedge geometries are formally quantified for several azimuthally swept wedges in terms of electron velocity and density as temporal functions of spatial direction and coordinates r,ϕ,z. Particles are tracked with picosecond temporal resolution out to 1.4 nanoseconds, spatially binned, and averaged over six independent simulations each sourced with a random plasma seed. An air model[1] comprised of Townsend breakdown and streamer mechanisms via tracking excited state neutrals that can either undergo quenching or spontaneous photon emission collisions[2] is employed. A 100 μm radius 1 eV plasma with a 10^{18} m^{-3} particle density placed at the tip of a 100 μm hemispherical pin electrode (at 6 kV) in a 600 Torr air filled gap, 1.5 mm above a planar grounded cathode, seeds the domain. Prior 2D studies have shown that the reduced electric field, E/n, can significantly impact streamer evolution[3]. We extend the analysis to 3D wedge geometries (to limit computational costs) with wedge angle azimuthally swept in 15^o increments from 15^o to 45^o to examine the wedge angle's effect on streamer branching, propagation, and velocity. Initial results suggest that solution convergence in terms of the parameters described above may be achievable.

1. C. Moore et al., Development of PIC-DSMC Air Breakdown Model in the Presence of a Dielectric, ICOPS, 2016.

2. A. Fierro et al., Discrete Photon Implementation for Plasma Simulations, Physics of Plasma, 23, 2016.

3. A. Jindal et al., Streamer Formation Near a Dielectric Surface with Variable Quantum Efficiency, ICOPS, 2017.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

DIELECTRIC-DIRECTED SURFACE FLASHOVER UNDER ATMOSPHERIC CONDITIONS

Paul Clem[1], Chris Moore[2], Laura Biedermann[1]
1. Sandia National Laboratories
2. Sandia National Labs

High-voltage arc formation near a dielectric material is a complex process by which surface charging, secondary electron emission, and photoelectron emission modify the local electric field to determine the arc path and breakdown threshold. Strong electric field enhancement at the triple-point junction of dielectric, metal, and atmosphere may act to generate initiating electrons to seed prompt formation of streamers. This study investigates the fundamental role of dielectric particle characteristics in influencing voltage breakdown threshold, statistical time lag, and reproducibility under high voltage conditions with and without external ultraviolet stimulation. We are investigating whether field emission at triple points can minimize variance in atmospheric breakdown.

Experiments were performed in dry air at 600-Torr using a low-inductance test-stand. Dielectric granules of varying permittivity were placed on planar electrodes, offset from a rounded rod electrode which defines 0.25mm, 0.5mm or 1-mm gaps. 200 μm dielectric granules minimally affect electric field in the majority of the gap, but set up high field cathode triple points on the ground plane. We will discuss how dielectric material properties impact surface charging, electron emission, and material conversion, thereby directing the flashover path. These flashover experiments are used in validation efforts of our PIC-DSMC code (c.f. "Development and Validation of PIC-DSMC Air Breakdown Model in the Presence of Dielectric Particles").

1. C. Moore et al., "Development and Validation of PIC-DSMC Air Breakdown Model in the Presence of Dielectric Particles," 20th International Pulsed Power Conference, May 31 - June 4, 2015.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

EFFECTS OF POLARIZATION FORCE ON NONLINEAR STRUCTURES IN A CHARGE VARYING DUSTY PLASMA

YASHIKA GHAI[1], N.S. saini[2]
1. Guru Nanak Dev University
2. GNDU, ASR

The effects of polarization force are of significant interest to the researchers. In the abundant literature on the study of different wave-modes in dusty plasmas, significant importance has been paid to the effects of polarization force on the propagation characteristics of dust acoustic waves in different plasma environments. Specifically, the study of polarization force in a non-Maxwellian plasma has received a great deal of attention from the plasma physicists. The effects of charge variation of dust particulates were not being considered while deriving an expression for polarization force on the dust particulates. Our aim is to remove this lacuna and investigate the effects of dust charge fluctuation on the polarization force in a dusty plasma containing kappa-distributed electrons and ions. In the arbitrary amplitude limit, Sagdeev pseudopotential technique shall be employed to derive an energy integral equation to investigate the effects of polarization force on nonlinear structures in charge varying dusty plasma. Nonlinear solitary structures shall be studied in the considered plasma environment and the effects of polarization force on solitary structures are investigated in a charge fluctuating dusty plasma.

DETERMINATION OF FIRST TOWNSEND IONIZATION COEFFICIENT BY SIMULATION

Nathan Crossette[1], Thomas Jenkins[1], John Cary[1], Jarrod Leddy[1], David Smithe[1]
1. Tech-X Corporation

In 1963, L.M. Chanin and G.D. Rork[1] measured the first Townsend ionization coefficient for various gasses and a range of pressures experimentally in a vacuum tube. A Townsend discharge is an ionization avalanche that occurs between two electrodes when secondary electron emission caused by ion impact on the cathode is negligible. The first Townsend coefficient, α, is essentially a measure of how many ionization events a single electron will cause when subject to a uniform electric field. In this study, we reproduce the experimental setup of Chanin and Rork's device in VSim[2], a highly parallelized particle-in-cell/finite-difference time-domain code. Various particle interactions are included, and the first Townsend coefficient is calculated and compared to the reported value. This Work supported by U.S. Department of Energy, SBIR Phase II award DE-SC0015762.

[1] L.M. Chanin and G.D. Rork, Phys. Rev. 133, A1005 (1964)

[2] C. Nieter and J. R. Cary, "VORPAL: a versatile plasma simulation code", J. Comp. Phys. 196, 2004, pp. 448-473.

INVESTIGATION OF ELECTRON EMISSION USING MOLECULAR DYNAMICS SIMULATIONS

Amanda Loveless[1], Kristinn Torfason[2], Ágúst Valfells[2], Allen Garner[1]
1. Purdue University
2. Reykjavik University

Continued miniaturization of electronic devices requires a comprehensive understanding of electron emission behavior at micro- and nanoscales for applications involving micro- and nanoelectromechanical systems (MEMS and NEMS, respectively) and microplasmas. While Paschen's law (PL) traditionally governs gas breakdown, field emission (FE) causes experimental deviation from PL at microscale [1]. Further reducing gap distance makes electron emission space-charge limited as defined by Mott-Gurney with collisions and Child-Langmuir (CL) at vacuum [2]. While previous work has unified PL with FE [1] and FE, MG and CL [2], more detailed simulations showing ion interactions are necessary to develop a comprehensive theory. This presentation applies molecular dynamics (MD) simulations to assess FE [3,4] with ionization and collisions and determine its impact on microscale breakdown. Understanding and quantifying the interplay and transitions amongst these emission regimes is vital for optimizing device design and ensuring reliable results.

SPONTANEOUS DENSITY VARIATIONS OBSERVED IN STEADY-STATE PLASMAS SUSTAINED USING FOCUSED MICROWAVES.

Remington Reid[1], Adrian Lopez[1]
1. US AFRL

The US Air Force is investigating the dynamics of plasmas sustained for long times using focused microwaves laboratory in conditions which approximate free-space. When the plasma density is sufficiently below the cut-off density the plasma develops regular desnity variations with a wavelength equal to one half the wavelength of the drive beam. We hypothesize that these density variations are the result of standing waves generated by multiple reflections of the drive beam within the plasma. Preliminary simulations taking into account beam diffraction, ionization and diffusion support this interpretation.

TO CONTROL THE ANGULAR MOMENTUM OF TRAPPED ELECTRONS IN TAPERED FOAM TARGET

Sheetal Punia[1], Manish Dwivedi[2], Hitendra kumar Malik[3]
1. Indian Institute of Technology Delhi
2. Indian Institute of technology, delhi
3. Indian Institute of technology,delhi

We have developed an analytical model to control the angular momentum of electrons trapped in ultra-relativistic laser-plasma interaction. The energy coupling from laser to plasma can be enhanced by using the foam target which regulates the near-critical density more efficiently in the medium. When laser is incident on the target, the ponderomotive force and self-generated electromagnetic fields associated with the laser affect the electrons. Owing to the tapered geometry of medium, the laser wavefront confronts hollow cone which results in an open-mouth bubble. Inside the bubble, electrons are assumed to be accelerated in laser-piston regime [1] where the relativistic electrons form a density peak sheath at the head of laser pulse. When the electrostatic field overcomes the ponderomotive force the electrons start reflecting from the peak sheath. The reflected electrons follow the path of inner lining of the bubble and induce transverse self-injection. Non-linear scattering of laser field results the radiation reaction force which causes the self-injection of electrons in the laser pulse. The incident laser pulse carries large spin and orbital angular momentum which can be transferred to the particles via direct laser acceleration regime. The angular momentum associated with the energetic particle beams gives an additional degree of freedom which has potential applications in different fields such as condensed-matter spectroscopy and new electron microscopes [2].

STIMULATED RAMAN SCATTERING OF THE MULTI-GAUSSIAN BEAM IN A RELATIVISTIC PLASMA

Manish Dwivedi[1], RAJAT DHAWAN[2], Hitendra Kumar Malik[1]
1. Indian Institute of Technology Delhi, India
2. Indian Institute of Technology Delhi

In the present work, the non-linear propagation of multi-Gaussian beam, consisting of coherent Gaussian beams with similar distribution, has been studied in collisionless plasma in the relativistic regime. We investigated the stimulated Raman scattering (parametric instability) of electromagnetic wave pulse and the evolution of its spot size. A theory of stimulated Raman scattering is developed by the composition of the hydrodynamic model and Maxwell's equations. We drive mode structure equation governing the amplitude mode, from which the fundamental mode and the Eigenvalue are found. The equations are coupled with low-frequency electron and ion plasma oscillations. It is observed that in the transition from weak to strong relativistic plasma, the growth rate for stimulated Raman scattering (SRS) instability is reduced. Numerically, we obtained the frequency shift and the growth rate of scattered off EM wave. The effect of eccentric displacement on the evolution of spot size has been uncovered by using WKB approximation and non-paraxial theory. It has been observed that the relativistic non-linearity strongly depends on the eccentric displacement as the beam possesses different radial intensity distributions for its different value. Oscillating focusing as well as defocusing has been observed in different cases.

ANALYSIS OF SHEATH FORMATION AND CHARGED SPECIES DENSITY IN COLLISIONAL ELECTRONEGATIVE WARM PLASMA

Rajat Dhawan[1], Sheetal Punia[1], Hitendra Kumar Malik[1]
1. Indian Institute of Technology Delhi, India

Plasma is a multi-component gas, composed of ions, electrons and neutrals. Therefore, collisions between different plasma species must be entertained. Moreover, energy and momentum are redistributed by their presence in the plasma. The presence of negative ions in the system has a huge impact on the characteristics of various quantities like sheath thickness, density and potential profile. Also, their presence plays a crucial role in semiconductor industries, microelectronics industries, plasma cleaning, plasma etching, plasma propulsion and plasma nitriding. In this paper, we accomplished a mathematical model to examine the behaviour of charged species present in electronegative plasma under the effect of their finite temperature and collisions with neutral atoms. It is found that collisional parameter as well as temperature have an intense effect on the plasma species profile. These result in the modification of sheath structure and hence, the sheath thickness. In this proposed mathematical model, both the ions, i.e. positive ions and negative ions, are described by fluid equations considering their drift term with collisional and pressure gradient terms. Here, we considered the CF4 electronegative plasma, primarily composed of CF3+ and F- ions where former ions are produced by the ionization and later ions by the attachment of electrons with neutral CF4. Rate of detachment of electrons from F- ions, which results in reduction of negative ions, is also taken into consideration. Therefore, ionization, attachment and detachment frequencies are also included in proposed model to execute real behaviour of charge species. CF4 plasma is adopted because of its increasing applications in etching and film deposition processes.

SUBMICROSCALE GAS BREAKDOWN AS A FUNCTION OF CATHODE PROTRUSIONS

Russell Brayfield[1], Andrew Fairbanks[1], Amanda Loveless[1], Weihang Li[1], Catherine Darr[1], Allen Garner[1]
1. Purdue University

Nano- and microscale surface features can have drastic impact on field enhancement and work function, altering field emission from the material. This can significantly change gas breakdown voltage for microscale gaps at atmospheric pressure [1], where field emission drives breakdown rather than Paschen's law. This presentation reports the nanofabrication of surface feature protrusions [2] and assessment of their impact on field enhancement and breakdown. Nanoscale devices with gaps ranging from 10s to 100s of nanometers were constructed to simulate individual surface protrusions. The devices were made of gold layered onto silicon wafer material to yield nanoscale and microscale gaps with protrusions of various aspects ratio to assess the impact of protrusion shape on field enhancement, as previously reported theoretically [2]. We report DC breakdown of these nanogaps at atmospheric pressure and discuss extensions to other pressure conditions.

[1] S. Dyanko, A. M. Loveless, and A. L. Garner, "Sensitivity of modeled microscale gas breakdown voltage due to parametric variation," Phys. Plasmas, vol. 25, 2018, Art. no. 103505.

[2] J. Lin, P. Y. Wong, P. Yang, Y. Y. Lau, W. Tang, and P. Zhang, "Electric field distribution and current emission in a miniaturized geometrical diode," J. Appl. Phys., vol. 121, no. 24, 2017, Art. no. 244301.

This material is based upon work supported by the Office of Naval Research under Grant No. N00014-17-1-2702. A. M. L. gratefully acknowledges funding from a graduate scholarship from the Directed Energy Professional Society and a fellowship from the Purdue Research Foundation.

IMPULSIVE FLASHOVER ACROSS SOLID/GAS INTERFACES: BREAKDOWN CHARACTERISTICS AND THE PATH OF SPARK CHANNELS

Martin Given, Mark Wilson, Scott MacGregor, Zhe Wang , Igor Timoshkin

Comprehensive understanding of the surface flashover behaviour in different gases requires clarification of the role of the relative permittivity of dielectric spacers. In this paper, the breakdown behaviour across solid/gas interfaces in 3 different gases, CO2, N2 and dry bottled air all at atmospheric pressure reported. Five dielectric materials with relative permittivities ranging from 2.1 to 6.3 were used to manufacture solid spacers. The breakdown voltage across these spacers was measured under standard lighting impulse conditions and the path of the thermalized breakdown channel was captured using open shutter photography. These tests were aimed at investigating the effects of the gas type and the relative permittivity on the surface flashover behaviour.

Statistical analysis of the obtained images of the thermalized breakdown channels under negative energisation shows under negative energisation the probability of a breakdown channel propagating across the surface of the insulation rather than through the gas is higher for CO2 as compared with N2 and air. Under positive energisation, the breakdown path demonstrated a tendency of initial development through the gas with consequent attachment to the solid surface.

The breakdown strength of the bulk gasses, Vbulk ¸ was obtained and compared with the breakdown strength of solid/gas interfaces, Vflash. It was found that: (1) Under negative energisation, the flashover voltage in solid/ N2 was up to 18% higher than Vbulk in the bulk gas; (2) Time to breakdown across solid/ N2 and solid/air interfaces under negative energisation was up to 2-fold longer as compared with the time to breakdown in the bulk N2 and air; (3) A reduction in the breakdown voltages and times to breakdown was registered for all tested gases and spacers for positive energisation and Large variations in time were obtained depending on the type of gas and solid dielectric material.

REMOTE PLASMA ASSISTED GRAPHENE GROWTH FOR DESIGNING GRAPHENE/SI HETERO-INTERFACES

Rohit Medwal[1], Charmine Tay[2], Joseph Vimal Vas[3], Mayank Mishra [4], Rajdeep Rawat

1. Nanyang Technological University

2. Temasek Junior College, Singapore 469278

3. Natural Sciences and Science Education, National Institute of Education, Nanyang Technological University

4. National Institute of Education, Nanyang Technological University, Singapore 637616

Graphene has gained a lot of attention due to its exception properties of high electron mobility (104-5 cm2/Vs), electric current carrying capacity (∼108 A/cm2), optically transparent (> 95 %) and considered as an excellent candidate for next-generation optical, electrical and spintronic devices. Graphene properties can be modified by altering the graphene/substrate interfaces by changing the chemical potential gradient, thereby, induced effective field at interfaces. Here, in the present research, we demonstrated the graphene/silicon interfaces to design the Schottky barrier with a large potential gradient. Graphene was synthesized using the plasma assisted chemical vapor deposition method and was transferred on the silicon substrates. The quality of graphene was confirmed using the Raman spectroscopy technique. The presence of equally intense G and 2D peaks shows the growth of high-quality graphene. Thereafter, the graphene/silicon interface was exposed to the hydrogen plasma at 30 Watt and distance between the plasma electrode and graphene/silicon was kept 15 cm to avoid any direct damage on the graphene/silicon interfaces. Plasma was monitored using optical emission spectroscopy during the graphene synthesis and plasma assisted hydrogen functionalization of graphene/silicon interface. The hydrogen desorption was performed by the thermal annealing of graphene/silicon interface at 150 °C. The adsorption and desorption hydrogen on graphene/silicon was also estimated with the help of a probe station by measuring the resistance of graphene keeping distance between the two electrodes fixed. Electrical measurements show the improved diode type behavior at graphene/silicon interface after hydrogen functionalization. Results will be useful to design graphene interfaces for spintronics device to improve the effective field at the graphene hetero-interfaces.

DESIGN,BUILD, AND TEST OF A LOW COST 3D PRINTED SPECTROMETER FOR EXPLOSIVE COPPER AND CONDUCTIVE POLYMER WIRE EXPERIMENTS

Antonio Breno de Alleluia[1], Mark D Johnston[2], Edl Schamilogly[1]
1. The University of New Mexico
2. Sandia National Lab

The field of study of the explosion of metallic conductors has great scientific interest for researchers [1] because of its adjustable input power, low-temperature plasma generation, and production of nanoparticles for materials science applications. X- and Z-pinch configurations of wires are studied across a broad range of pulsed power drivers. The diagnostics for such experiments typically demand very expensive instrumentation due to the specific requirements for operation and control of the system.

Plasma spectroscopy [2] is a noninvasive method capable of characterizing the spectral emission off copper and conductive polymers neutrals and ions during the experiment. A Marx bank generates voltages up to 100 kV in a microsecond time frame and supplies the energy to the wire explosion. Two different materials, copper and polylactic acid (PLA) conductive were evaluated in an air atmospheric pressure during wire explosion. A low-cost lab made spectrometer was manufactured applying the fused deposition modeling (FDM) process[3]. The 3D printed parts for the prototype were designed under constraints of basic optics and plasma spectroscopy diagnostics. The intensity of the light from the explosion was recorded by a fast video camera attached to the spectrometer.

The incorporation of 3D printers for the design of pieces of equipment reduces the cost of manufacturing and acquisition as well as the time for delivery. Furthermore, this tool gives the developer the ability to customize solutions for each experiment more effectively. Experimental data collected with 3D printed spectrometer will be compared with a manufactured commercial version in order to evaluate its performance.

1. J. Jadidian et al., “Visualization of a Copper Wire Explosion in Atmospheric Pressure Air,” IEEE Trans. Plasma Sci., vol. 39,2842,2011.

2. H.J. Kunze Introduction to Plasma Spectroscopy (Springer 2009).

3. D.G. Schniederjans, “Adoption of 3D-Printing Technologies in Manufacturing: A Survey Analysis,” IJPE, vol. 183, Part A, 287, 2017.

DIELECTRIC ELASTOMERS: AN INVESTIGATION IN STRAIN DEPENDENT ELECTROSTATIC PRESSURE OF SOFT COMPLIANT DIELECTRICS

Barnard Onyenucheya[1], James Allen[2], Jennifer Zirnheld[3], Kevin Burke[3]
1. Primary Contributor
2. Secondary Contributor
3. Faculty Advisor

Dielectric Elastomers have the potential of exhibiting large strains when the material is in the presence of an electric field. The dielectric in this case is a soft acrylic (VHB 4910) film that is sandwiched between two compliant electrodes that are subjected to a high voltage potential. When high voltage is applied, attracting charges lead to a contractive force known as electrostatic pressure. The electrostatic pressure deforms the elastomer membrane and the contraction occurs in the thickness (z plane) direction, which leads to actuation and expansion of the film. The pressure in the z direction is usually governed by electrostatic pressure from Pelrine, $\rho = \epsilon_0 \epsilon_r E^2$. In the Pelrine model the relative permittivity is held constant when calculating for pressure. Recent research has found that relative permittivity in this case is not at all constant. New literature has shown that permittivity decreases as stretch rates increase. From a microscopic level, polarization within the DEA determines the material's permittivity, which makes it deformation dependent. This work looks to investigate, theoretically and experimentally, a polarization dependent electrostatic pressure model. Using the Tettex 2822 measuring system we can back-solve for the permittivity of the DEA as a function of stretch. This data was collected and used to find a best fit curve to determine various permittivity ranges of the DEA from its relax state to its max deformation.

CATALYTIC AND ACOUSTIC NANO/MICROMOTORS

Aysegul Uygun Oksuz[1], Gamze Celik Cogal[2], Gozde Yurdabak Karaca[3], Emre Uygun[4], Lutfi Oksuz[5]

1. Suleyman Demirel University, Chemistry & Bioengineering Department
2. Suleyman Demirel University, Chemistry Department
3. Suleyman Demirel University, Bioengineering Department
4. Suleyman Demirel University, Civil Engineering Department
5. Suleyman Demirel Unviersity, Physics Department

Nano/micromotors that can convert local chemical fuels or external physical inputs into autonomous motion and perform a variety of advanced functions ranging from active drug delivery to environmental remediation and nanofabrication [1]. Synthetic micro/nanomotors can be self-propelled or externally powered in the liquid phase by different types of energy source such as catalytic, electro/magnetic or acoustic [2]. Several methods including electrochemical/electroless deposition, physical vapor deposition, strain engineering and three-dimensional direct laser writing have been fabrication to create the micro/ nanomotors. Compared with other methods, the plasma-based process is fast and environmentally friendly. By using plasma method the materials can be rapidly prepared onto different substrates at room temperature without using any solvent. Besides, in nanomotors fabrication experiments, plasma methods provide homogeneous coating.

In this study, multiple approaches to powering nanomachines, utilizing individual chemical or physical stimuli, were investigated. In accordance with this purpose, Gold (Au) nanowire prepared by template electrodeposition method for acoustic propulsion and Platinum (Pt) coating for catalytic propulsion RF magnetron sputtering method was used. Fabricated nanomotors were analyzed by Scanning Electron microscopy (SEM) and Mapping analysis. Catalytic and ultrasound propulsion effects were examined on nanomotors speed and direction. For this purpose, speed and direction of nanomotors were investigated by using Optic Microscope (Nikon Ti Eclipse) according to different fuel concentration and acoustic wave power.

[1]. Chuanrui Chen, Fernando Soto, Emil Karshalev, Jinxing Li, Joseph Wang, 2019, Hybrid Nanovehicles: One Machine, Two Engines, Advanced Functional Materials, 29, 1806290.

[2]. Dekai Zhou, Yuan Gao, Junjie Yang, Yuguang C. Li, Guangbin Shao, Guangyu Zhang, Tianlong Li, Longqiu Li, 2018, Light-Ultrasound Driven Collective “Firework” Behavior of Nanomotors, Advanced Science, 5, 1800122.

CALCULATION OF ELECTRON-IMPACT IONIZATION CROSS SECTIONS OF DICHLORODIFLUOROMETHANE (R12) AND TETRAFLUOROETHANE (R134) MOLECULES USING DEUTSCH-MÄRK (DM) AND BINARY-ENCOUNTER-BETHE (BEB) METHODS

Feng Tang[1], Xiong Jiayu[2], Zhang Boya[2], Lv Qishen[1], Li Xingwen[2]
1. Shenzhen Power Supply Bureau Co., Ltd.
2. State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University

SF6 has been employed as insulation and arc-quenching medium in high voltage apparatus since the 1960s. However, due to the high global warming potential (GWP) of SF6 gas, the alternative to SF6 is required. R12 and R134 gases offer good dielectric properties to be good replacements of SF6 as insulation medium considering the environmental concerns. In order to further study the ionization processes in those gases, the electron-impact ionization cross sections are calculated by Deutsch-Märk (DM) and Binary-Encounter-Bethe (BEB) methods. The molecular structures, binding energies of valence electrons, ionization potentials and the molecular orbital compositions of R12 and R134 were determined by ab initio calculation. The comparison of DM and BEB results both give important reference for the two SF6 substitute gases.

TWO-DIMENSIONAL NUMERICAL SIMULATION OF NANOSECOND PULSED DISCHARGE IN SULFUR HEXAFLUORIDE GAS AT HIGH PRESSURE

wang haiyang[1]
1. Northwest institute of nuclear technology

Pulsed discharges have attracted much attention in recent years due to their widely applications in the fields such as the generation of electron beams, x-rays, pulsed gaseous lasers and plasma-assisted combustion. Compared with the general discharges driven by AC and DC power source, high breakdown voltage and high energy electrons are the unique phenomena in pulsed discharge. These phenomena could no longer be interpreted by the traditional Townsend and Streamer mechanisms. Based on the breakdown of high-energy electrons, different hypotheses are proposed to describe nanosecond pulse discharge. However, all these hypotheses admit that the electrons with high energy play an important role in the avalanche development in nanosecond pulse discharge.

Based on the plasma hybrid module of numerical software, which solves the charge continuity equations and the simplified Boltzmann equation, an analytical physical model is established to simulate the inception breakdown process in nanosecond pulse discharge in SF6 gas at high pressure. Furthermore, the effect of amplitude of applied voltage, gap distance and gas pressure on the generation of temporal and spatial distribution of electrons and ions are studied.

NUMERICAL SIMULATION OF CORONA DISCHARGE IN NEEDLE ELECTRODE CONFIGURATION IN A LARGE-SCALE SPACE

Liu Zhi[1], Li Chuan[1], Wang Pengyu[1], Zhang Ming[1]
1. HUST

Abstract:Needle electrode is often used as an electrode of charged particle generating devices to study discharge characteristics due to its high efficiency. However, for the charged particle distribution of needle electrode corona discharge in a large-scale space, there is still a lack of effective numerical simulation method. To solve this problem, a novel method based on the combination of fluid dynamics model and ion flow transport equation (based on Kaptzov hypothesis) was put forward in this paper, and the method is theoretically demonstrated in a one-dimensional axisymmetric wire-cylinder structure. Based on this method, the influence of applied voltage level on the distribution of charged particles under a needle electrode was further discussed. Finally, the verification experiment of charged particle distribution was carried out using a charged particle counter, and the experimental results shows a good consistency with the numerical simulation results. This research can provide a reference for the further study of corona discharge in needle electrode configuration in a large-scale space.

Key words: numerical simulation, corona discharge, large scale space, needle electrode

PROGRESS PORTING VPIC TO SEVERAL MODERN ARCHITECTURES

William Nystrom[1], Robert Bird[1], Luis Chacon[1], Guangye Chen[1], William Daughton[1], Patrick Kilian[1], Ari Le[1], Scott Luedtke[1], Adam Stanier[1], David Stark[1], Lin Yin[1], Brian Albright[1]

1. Los Alamos National Laboratory

VPIC is being ported and optimized on several modern architectures. These include KNL processors available on Trinity, Cori and Stampede2, Skylake processors available on Mare Nostrum and Stampede2, IBM Power 9 processors and Volta GPUs available on Summit and Sierra and ARM ThunderX2 processors, available on Astra at Sandia and ARM clusters at Los Alamos National Laboratory. VPIC is in production on several of these systems. These architectures vary in many ways including available memory bandwidth, vector length, threads per core, clock frequency and overall node architecture. This work is focused on single node performance. Current efforts to optimize single node performance are exploring changes to data layout of key data structures, use of performance portability frameworks such as Kokkos and performance profiling with a variety of performance analysis tools. Results will be presented which compare the performance of VPIC on these different architectures.

This work was supported by the US Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001).

SPEED-LIMITED PARTICLE-IN-CELL MODELING OF LOW-TEMPERATURE PLASMA DISCHARGES

Tom Jenkins[1], Andrew Chap[1], Greg Werner[2], John Cary[3]
1. Tech-X Corporation
2. University of Colorado
3. Tech-X Corporation and University of Colorado

Speed-limited particle-in-cell (SLPIC) modeling is a new simulation technique [Werner *et al.*, PoP **25**, 123512 (2018)], potentially much faster than conventional PIC, for modeling plasmas characterized by low-velocity kinetic processes. Numerical constraints (e.g. timestep limitations associated with particle cell-crossing times or stability limits) often place challenging restrictions on PIC models of these plasmas; even though the kinetic physics of interest predominantly involves slow particle evolution, the fastest particles dictate the maximum allowable timestep. For high-Z plasmas, large ion/electron mass ratios separate the species timescales to the point that kinetic simulation may be prohibitive, and computational costs can be high even in hydrogenic plasmas. SLPIC provides a possible solution. SLPIC (like PIC) retains a fully kinetic description of the plasma, but imposes an artificial speed limit on fast particles whose kinetics do not play a meaningful role in the system dynamics. Larger simulation timesteps, which enable faster simulations of such discharges, are thus permitted. The speed-limiting is done in a mathematically rigorous sense to maintain accuracy over longer timescales; we may, for instance, speed-limit the bulk of the electron distribution to evolve only on characteristic ion timescales (and use larger simulation timesteps, which need only resolve these scales, to simulate the discharge).

In this poster we'll demonstrate the use of SLPIC methods using the VSim code [Nieter & Cary, JCP **196**, 448 (2004)], moving from simple models of collisionless sheath formation (for which SLPIC has achieved $>$150x overall speedup relative to PIC with comparable accuracy) to more general low-temperature plasma discharges that include collisional effects and complex geometries. We'll also demonstrate how SLPIC can rapidly model plasma discharge evolution through transient or fluid-like phases, and then continuously transition to a smaller-timestep conventional PIC model as kinetic processes in the discharge become important.

Funded by US DoE, SBIR Phase II Award DE-SC0015762.

SIMPLIFIED RADIATION MODEL FOR ATMOSPHERIC PLASMAS

Michael Mallon[1], Marina Kühn-Kauffeldt[2], Jose-Luis Marques-Lopez, Jochen Schein
1. University of the Bundeswehr Munich
2. Universität der Bundeswehr München

The use of stark broadening in plasma diagnostics is a common tool to derive information about electron density and temperature distributions. In contrast, only limited theoretical work is available, which can be used to interpret experimentally acquired spectra. Current ab initio models do not give a sufficient explanation on the driving effect of radiation interaction with the plasma particles especially in gas mixtures, which are of great importance for technical applications. This work seizes the concept of a radiation model, which calculates the net energy emission intensity within a given spectral window for a specific gas mixture. The line profile in this case derives from a quantum physical description of the dominant effect on spectral lines for thermal plasma – Stark Broadening.

The model is built on a simplified geometry. Here a plasma cylinder is situated between two electrodes. However, it incorporates radiative emission and absorption phenomena of spectral lines depending on the underlying electron density distribution and influencing the same vice versa. The model generates information on the spectrally resolved net emission intensity and calculates the resulting electron density and temperature profile for a given input current and a given distance to a cooling wall.

The method proposed has been calculated for pure Argon and Argon-Helium gas mixtures and compared to experimental spectra as well as plasma parameters acquired from Thomson scattering measurements. As a next step calculation of gas mixtures including metal vapor such as Argon Aluminum are planned.

ADVANCED OPTIMIZATION AND MACHINE LEARNING FOR MAGNETRON DESIGN

Anton Spirkin[1], Peter H. Stoltz[1], John W. Luginsland[2]
1. Tech-X Corporation
2. Confluent Sciences

High-power microwave source design has evolved from analytic scaling laws to advanced computational methods that can virtually prototype devices before metal is cut in the laboratory. However, with this success has come the requirement that the DOD have the capability to quickly design novel HPM sources for applications with different power and frequency requirements. This need for rapid design capability has pushed both optimization and machine learning techniques into the field of high power RF sources.

We perform 2D simulations of the Rising Sun magnetron using kinetic modeling framework VSim and optimization engine Dakota. We simulate operation of the magnetron in a series of conditions as a part of the optimization study with the goal to identify the optimum device geometry that operates in a specified frequency bandwidth and at the same time produces adequate output power. We investigate a broad spectrum of control parameters, multiple optimization formulations and a combination of linear and non-linear constraints to fully describe magnetron's physical state of operation. Furthermore, we apply machine learning techniques to investigate modes of operation of the magnetron with optimized geometry, to efficiently navigate through the physical parameters space, predict and mitigate its performance.

A DEY-MITTRA-CONFORMING POISSON SOLVER FOR NANOSCALE VACUUM CHANNEL TRANSISTOR APPLICATIONS

Gregory Werner[1], John Cary[1]
1. University of Colorado

We implement a parallel finite-difference Poisson solver with embedded/conformal/curved conducting boundaries [e.g., Shortley & Weller, J. Appl. Phys. 9, 334 (1938); Adelmann et al, J. Comput. Phys. 229, 4554 (2010)] within the VSim framework, using Trilinos packages [Heroux et al, ACM Trans. Math. Softw. 31, 397 (2005)]. The resulting electric field is precisely static under the Dey-Mittra electromagnetic update in the presence of embedded boundaries [cf. Dey & Mittra, IEEE Microwav. Guided Wave Lett. 7, 273 (1997)]. Using VSim's particle-in-cell simulation capability with surface-aware field interpolation, this implementation can accurately calculate floating potentials of conductors in plasma, as well as surface charging of dielectrics. We report on solver performance, for variable Cartesian mesh, and apply it to model field emission and the resulting circuit characteristics of nanoscale vacuum channel transistors.

MODELING POWER-FLOW USING THE PERSEUS/FLEXO AND HYDRA MHD SIMULATION CODES

Nathaniel Hamlin[1], Mark Hess[1], Charles Seyler[2]
1. Sandia National Laboratories
2. Cornell University

In current and future pulsed-power devices, it has become increasingly important to have predictive capability for determining the amount of energy coupled through the magnetically-insulated transmission line (MITL) to the load. Because of the high magnetization and low densities of electrode plasmas in the MITL gap, extended-MHD effects may play a critical role in power-flow physics. In this presentation, we show simulations from PERSEUS [1]/FLEXO and HYDRA [2], which are both capable of modeling MHD and extended-MHD effects in inner MITL power-flow. Specifically, we focus our attention on relevant power-flow plasma quantities, such as plasma density and current density, as predicted by both codes. This problem has recently been simulated with PERSEUS in Hamlin and Seyler [3], and serves as a relevant test problem for understanding the role that extended-MHD plays in power-flow systems.

----

* The work of N. D. Hamlin and M. Hess is funded in large part by Sandia National Laboratories. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under Contract No. DE-NA0003525. The work of N.D. Hamlin and C.E. Seyler is supported by the National Nuclear Security

Administration stewardship sciences academic program under Department of Energy

cooperative agreements DE-FOA-0003764, DE-FOA-0001153 and DE-NA0001836.

[1] C. E. Seyler and M. R. Martin, vol. 18, 012703, 2011

[2] M. Marinak et al, Physics of Plasmas, vol. 8, 2275, 2001

[3] N. D. Hamlin and C. E. Seyler, Physics of Plasmas, vol. 25, 102705, 2018

FRACTAL FEATURES OF AG-DLC FILMS BASED ON TWO MORPHOLOGICAL IMAGES

Azizollah Shafikhani[1], Arezou Zarei[2]
1. 1- Physics department, Alzahra University; 2-School of Physics, Institute for research in fundamental sciences (IPM)
2. Physics department, Alzahra University

In the present study, Ag nanoparticles were synthesized in amorphous hydrogenated carbon films (Ag-DLC) on glass substrates by RF-PECVD and RF-sputtering co-deposition method. Afterwards, Methyl orange (MO_1.43 M) was used as an analyte on the Ag-DLC and then, the layer was washed by distilled water. It was done three times in 30 min. Two AFM images were taken before and after dropping MO.

Fractal dimension (D) is a parameter that represents the chaos and fragmental property of a self-affine surface. D evaluating was possible by the scaling performance of surface roughness measurement. Autocorrelation function (ACF) and structure function (SF) methods were utilized to calculate D based on two morphological AFM images with limited resolution. D obtained by ACF method was also close to the results in the SF method. Chaotic features of these layers were proven by the phase-space figure and Levy distributions of Data sets. Mono-fractality and long-term correlation were investigated based on a Hurst exponent. MO corrosion was ignored due to the roughness of the surface.

Keywords: fractal dimension; Ag-DLC; AFM images; autocorrelation function; structure function; chaos

DIODE DESIGN FOR INCREASED RADIATION DOSE IN HERMES III FAR-FIELD

Troy Powell[1], Andy Biller[1], Keith Cartwright[1], Timothy Renk[1], Timothy Pointon[1]
1. Sandia National Labs

DIODE DESIGN FOR INCREASED RADIATION DOSE IN HERMES III FAR-FIELD

Troy C. Powell, Andrew Biller, Keith L. Cartwright, Timothy J. Renk, and Timothy D. Pointon

Sandia National Labs, 1515 Eubank SE

Albuquerque, NM 87123 USA

Increasing radiated dose in the HERMES III far-field region is both a matter of mitigating current loss in the MITL and electron incident angle on the Bremsstrahlung converter. The self-magnetic field of the high currents in the diode causes the electrons to pinch at steep angles once the radial electric field drops to zero near the converter. Since a lower incident angle (closer to norm) increases the dose nonlinearly, diode design should minimize this pinch angle. Designs include extended and indented anode configurations. Indented anode designs are compared with results shared by T. Renk and P. F. Ottinger (using LSP) as well as older results from Sanford (using MAGIC). All designs are reported along with their associated simulation results.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

THERMODYNAMIC PROPERTIES AND TRANSPORT COEFFICIENTS OF C4F7N/CO2 THERMAL PLASMA AS AN ALTERNATIVE TO SF6

Lisong Zhang, Mingtian Ye, Lei Pang, Qiaogen Zhang

The paper is devoted to the calculation of equilibrium compositions, thermodynamic properties (mass density, enthalpy and specific heat at constant pressure) and transport coefficients (electrical conductivity, viscosity and thermal conductivity) of C4F7N/CO2 thermal plasma. Assuming local thermodynamic equilibrium, the species composition is determined using the principle of minimization of the Gibbs free energy. The transport properties are calculated by the Chapman-Enskog method. Some recently updated cross-sections or interaction potentials in the literature is adopted to obtain collision integrals. These data are computed in the temperature range between 300 K and 30 kK, for a pressure between 0.1 MP and 1 MPa and for several CO2 proportions. Transport coefficients of pure CO2 plasma are also compared with previously published values. The results clarify some basic chemical process in C4F7N/CO2 mixtures and provide reliable reference data for the arc simulations.

A HIGH ORDER CONVECTED SCHEME SOLUTION OF THE WIGNER-POISSON SYSTEM

Matthew Link[1], Michael S. Murillo[1], Andrew Christlieb[1], Frank Graziani[2], Mark Sherlock[2]
1. Michigan State University
2. Lawrence Livermore National Lab

We present a new code for solving the Wigner-Poisson system. Drawing from techniques for solving Vlasov-Poisson, we employ Strang splitting to divide Wigner-Poisson into an advection equation and an integral equation describing velocity space. A forward, Semi-Lagrangian scheme based on the Convected Scheme handles the advection piece while a Fourier transform handles the velocity integral operator. High order is achieved by using WENO to calculate small corrections to the displacement of the Convected Scheme and through Spectral Deferred Correction. Since Wigner-Poisson is the quantum analog of Vlasov-Poisson, we study traditional problems such as Landau damping and the two stream instability in 1D-1V and compare the two models. Eventually, we seek to incorporate our Wigner-Poisson code in a study of stopping power in DT fusion.

DATA STORAGE OF PARTICLE-IN-CELL SIMULATIONS FOR BIG DATA ANALYSIS OF CAPACITIVELY COUPLED PLASMA REACTORS

Yeun Jung Kim[1], Jin Seok Kim[1], Hae June Lee[1]
1. Pusan National University

Capacitively coupled plasmas (CCPs) are widely utilized in etching and deposition processes in semiconductor manufacturing. Nowadays, the nonuniformity of plasma density and temperature distributions is a critical issue near the wafer edge which results in non-uniform etching or deposition profiles. Computer simulation is a good tool to understand the background physics of the nonuniformity and to find a better condition to keep uniformity at the edge. Notably, a particle-in-cell (PIC) simulation is an excellent method to investigate the electron energy probability function (EEPF) which is essential for the control of electron heating mechanism and chemical reactions. In this presentation, we report the spatial changes of EEPF in a two-dimensional PIC simulation for CCP reactors. In order to find out the tendency of the plasma properties over wide parameter variations, a big data analysis is designed to utilize the data storage of PIC simulation results. HBase that runs on top of Hadoop eco system is used to store a large amount of PIC simulation data, which organizes the essential data into two kinds of tables for effective data management.

A FLUID SOLVER APPROACH VIA DISCONTINUOUS GALERKIN METHODS TO VISCOELASTIC MODELS FOR DENSE PLASMAS

PIERSON GUTHREY[1], MICHAEL MURILLO[1], Andrew CHRISTLIEB[1]
1. MICHIGAN STATE UNIVERSITY

We seek a nonequillibrium, heterogenous, large-scale model for strongly coupled plasmas. We generate a generalized hydrodynamic model for strongly coupled plasmas using density functional theory closures of BBGKY hierarchies via hypernetted chain theory. We formulate these equations in the form of a balance law, thereby providing a ”memory” effect, facilitating correlation. This isothermal “single fluid” form of the electrostatic limit is modelled in a fluid context with an exact form of the functional term that is a non-local integral term rising out of hypernetted chain theory. These models, dubbed the Visco-Elastic Density functional (VEDF) equations, provide the first continuum models that match the dispersion of waves in electrostatic ultra-cold correlated plasmas. The resulting equations admit no quasilinear homogenous form and thus we recast the equations as a balance law system treated regionally-implicitly with DG-FEM. We use the DG cell sizes to represent a spatial scale over which model parameters are constant. The generalized pressure and dissipative stress are handled explicitly via a multi-cell reconstruction, as we assume the relevant length scales are different than the length scales of the cells. Here we present work towards a 3D VEDF Solver software package, highlighting our approach to computing the correlation contribution to the generalized pressure.

MOMENTUM COUPLING IN MAGNETIZED PLASMAS

David COOKE[1], Remington REID[1], James Patton[1], Ashley Stiles[2]
1. Air Force Res Lab
2. Assurance Tech Corp

Many interesting and important problems in plasma science involve the differential motion of regions of plasma, threaded by the same magnetic field lines. In all reference frames, there is a difference in the motional electric field between regions, a difference in potential parallel to the magnetic field, and currents that couple the different regions, thus transferring momentum by J x B forces. Examples of this dynamic interaction include the coupling between the ionosphere magnetosphere and solar wind; plasma generation in space, charged or large extended spacecraft including tethers, the penetration of plasma jets into plasma-sphere, and the interaction of Jupiter with its moon Io. The standard model for interaction is a MHD-like picture where oblique Alfvén waves mediate the coupling current. If the currents are large and spread over the largest possible volume the coupling is strong. If sheaths and charge layers form, the coupling is diminished. In the years leading up to the flight of the Tethered Satellite System, TSS-1R, in 1996, this standard model was applied but it never lead to definite predictions of the tether current, and the mission results showed no dependence on the Alfvénic parameters. The results did indicate a plasma probe-type interaction, but unlike anything known at that time and still not fully explained today. We are exploring the lessons learn from TSS, to see if the standard model of momentum coupling needs repair, and to better understanding of the problem of a positively charged probe in a flowing plasma. Our approach includes a unique ExB drift plasma chamber, numerical simulation, and theoretical review. Results from all fronts will be discussed.

EXPERIMENTAL INVESTIGATION OF COLLIDING PLASMA FLOWS

Andrew Hamilton[1], Vladimir Sotnikov
1. Air Force Research Laboratory

This experimental investigation of colliding plasma flows which are frozen-in opposing magnetic fields was conducted to better understand and describe microscopic instabilities and macroscopic-flow patterns. The Plasma Physics and Sensors Laboratory (PPSL), located at Wright-Patterson AFB, developed an experimental setup where a pulsed power system is used to create colliding flows through an Ohmic explosion process from a parallel arrangement of fine-metallic wires creating conditions similar to that of colliding winds in binary star systems. These laboratory experiments create collisionless and collisional shocks in succession. The collisionless shock forms through interpenetration and mixing of the initial portion of flows emitted from fine metallic wires. The latter collisional shock is formed by the colder and denser partially-ionized metallic gases from the wire. This collisional period is conducive to observations of radiative shocks. To characterize these experiments, several optical diagnostics were utilized. This effort shows light emission imaging results collected during experiments of colliding flows agree with theoretical developments in (M. A. Malkov, V. I. Sotnikov 2018), progress on numerical interferometric analysis to extract atomic and electron volumetric densities when symmetry is not available, and progress on a non-equilibrium spectroscopic model under developed to analyze spectral data and provide electron density measurements to complement the other diagnostics.

CHARACTERISTICS OF NONLINEAR STRUCTURES IN A MULTICOMPONENT SUPERTHERMAL PLASMA WITH ELECTRON BEAM

SUNIDHI SINGLA[1], YASHIKA GHAI[1], N.S. SAINI[1]
1. GURU NANAK DEV UNIVERSITY, AMRITSAR

The observations of inertial, drifting charged particles penetrating in various space and astrophysical plasma environments have led the researchers to investigate the influence of charged particle beams on nonlinear waves and structures formed in such environments. It has been indicated that the injection of drifting electrons in the upper layers of Earth's magnetosphere is caused by the solar wind. These electrons are considered to perturb the magnetospheric plasma and give rise to nonlinear waves and modify conditions for the existence of solitary structures. Moreover, the observations of GEOTAIL spacecraft in the Earth's auroral region signify that the broadband electrostatic noise in this region is associated with the nonlinear electrostatic solitary waves that might be related to the dynamics of electron beam instability. It has been reported by various satellite observations that certain high temperature plasmas present in space obey non-Maxwellian distributions instead of Maxwellian. One such non-Maxwellian distribution is the famous kappa distribution that is used by plasma physicists to fit the velocity distribution of superthermal charged particles. The motivation of this investigation is to study the ion acoustic solitary waves in a plasma comprising warm inertial ions, superthermal kappa-distributed hot electrons penetrated by an inertial electron beam. Using the reductive perturbation method, KdV, mKdV and Garner equations are derived to study the ion acoustic nonlinear structures in a superthermal plasma invaded by an electron beam. The combined effects of an electron beam and variation in different physical parameters on the properties of ion acoustic nonlinear structures such as Gardner solitons and double layer have been analyzed. The findings of this investigation might be useful to understand the propagation of ion acoustic structures in different space and astrophysical plasma environments penetrated by an electron beam.

LABORATORY SIMULATIONS OF SOLAR WIND INTERACTIONS WITH AIRLESS BODIES: MAGNETIC ANOMALIES AND WAKES

Tobin Munsat[1], LiHsia Yeo[1], Xu Wang[1]
1. University of Colorado

The Colorado Solar Wind Experiment (CSWE) simulates solar wind plasma with ion energy up to 1 keV. We present two sets of experimental results related to the interaction of the solar wind with airless bodies: 1) solar wind interactions with lunar magnetic anomalies (LMAs); and 2) wake formation with various Debye lengths relative to the object size. In the first experiment, a permanent magnet was used to create a vertical dipole field behind an insulating surface that faces a plasma flow. Potential profiles on the upstream side were measured using an emissive probe. It was found that surfaces in the dipole lobes are charged to a large positive potential by unmagnetized beam ions and the surface in the cusp is charged negatively by magnetically focused electrons. At lower ion beam energies ($<$ 200 eV), the surface potential in the dipole lobes follows the ion beam energy. However, at higher ion beam energies (200-800 eV), the surface potential becomes significantly lower than the ion beam energy. The exact mechanism is not well understood though various tests have been performed. In the second experiment, an obstacle was inserted in the plasma flow and the wake formed behind it was characterized, including both potential and electron density profiles. The wake is filled by electrons because supersonic beam ions stream by. The ratio of the Debye length to the size of the obstacle was varied from larger than to smaller than 1 to simulate wakes behind bodies with various sizes in space, from small asteroids/rocks to the Moon. Potential and electron density features are shown in preliminary results.

NUMERICAL SIMULATION OF A SPARK CHANNEL EXPANSION IN WATER AND ITS COMPARISON WITH AN EXPERIMENTAL RESULT

Vitaliy Stelmashuk[1], Petr Hoffer[1], Karel Kolacek[1], Jaroslav Štraus[1]
1. Institute of Plasma Physics of Czech Academy of Sciences

The main difficulties in verification of numerous mathematical models of an electrical discharge in water is a lack of experimental studies observing a spark channel expansion and its comparison with an experimental result. As a rule, the authors compare an acoustical signature produced by an underwater discharge and also how a bubble cavitation matches the simulation. The presented investigation numerically studies an incompressible approach for a spark expansion and compare it to experimental results obtained by a high speed camera and optical hydrophone. An electrical energy delivered to a plasma channel through Joule heating is divided between an internal energy of the plasma–vapor mixture inside the channel and a mechanical work done by an expanding channel. The total energy deposition is described by an energy balance equation [1]. The pressure in liquid on a spark wall p(t) is described using two mathematical expressions for the pressure p(t) proposed by Naugolnych / Roy [1] and Braginskki [2]. The temporal variations of a spark channel radius, its velocity and pressure wave generated by an expanding spark have been obtained and compared with the experiment. The spark expansion process is perfectly predicted by incompressible approach when the input energy is less than 16 J and can be used for practical applications under this limit.

Acknowledgement

This work was performed under auspices and with the support of the Grant Agency of the Czech Republic (contract 18-12386S) and of the Ministry of Education, Youth, and Sports of the Czech Republic (INTER-EXCELLENCE/Inter-transfer contract LTT17015).

References

[1] Naugolnych K A and Roy N A 1971 “Spark Discharges in Water” (Moscow: Nauka) translation: Foreign Technology Division, Wright-Patterson AFB, OH, 1974).

[2] Braginskii S.I., “Theory of a spark channel”, Soviet Physics JETP, vol. 34(7), December

ELECTRON HEATING MODE TRANSITIONS IN A CAPACITIVELY COUPLED OXYGEN DISCHARGE

Jon Tomas Gudmundsson[1], Andrea Proto[1]
1. University of Iceland

Using particle-in-cell Monte Carlo collision simulations we have demonstrated an electron heating mode transition from drift-ambipolar (DA) mode to α-mode in the capacitively coupled oxygen discharge as the operating pressure [1,2], electrode separation, and driving frequency [3] are increased. Here we explore further the transition as pressure and electrode separation are varied. When operating at low pressure (10 mTorr) the electron heating is a combination of DA- and $\alpha-$mode heating while at higher pressures ($>$ 30 mTorr) electron heating in the sheath regions dominates. At fixed discharge pressure varying the electrode spacing the electron heating is a combination of DA- and $\alpha-$mode heating for small electrode spacing and it transitions to pure $\alpha-$mode heating as the electrode spacing is increased. We relate the transition to increased electronegativity and generation of drift and ambipolar electric field within the electronegative core when the discharge pressure is low or electrode spacing is small. It is important to note that the addition of the single metastable molecules and secondary electron emission to the oxygen discharge model has a significant influence on the discharge properties and in particular to lower the effective electron temperature [3,4].

[1] J. T. Gudmundsson and B. Ventéjou, The pressure dependence of the discharge properties in a capacitively coupled oxygen discharge, Journal of Applied Physics, 118(15) (2015) 153302

[2] H. Hannesdottir and J. T. Gudmundsson, Plasma Sources Science and Technology 25(5) (2016) 055002

[3] J. T. Gudmundsson, D. I. Snorrason and H. Hannesdottir, The frequency dependence of the discharge properties in a capacitively coupled oxygen discharge, Plasma Sources Science and Technology, 27(2) (2018) 025009

[4] A. Proto and J. T. Gudmundsson, The influence of secondary electron emission and electron reflection on a capacitively coupled oxygen discharge, Atoms, 6(4) (2018) 65

ION COLLECTION CHARACTERISTICS FROM A PULSED LASER-INDUCED BARIUM PLASMA WITH AN INJECTION OF THERMAL ELECTRONS

Jian Chen[1], Jing Li[1], HEPING LI[1]
1. Tsinghua University

Recently, pulsed lasers have been widely used as a power source to generate various kinds of plasmas, such as laser-plasma accelerators [1], laser-driven magnetic reconnection [2], etc. In this paper, we established a one-dimensional (1-D) PIC model for investigating the ion collection characteristics from a pulsed laser-induced barium plasma. The plasma is first created by a laser pulse in a short time period ($\sim$10 ns) and confined between two parallel collectors with biased voltages, and then, decays until most ions deposit on the collectors. We assume that the laser is merely an energy source for generating plasmas with no considerations of the laser-plasma interactions. The particle collisions in the plasma region are included, and the particle reflection, particle-induced electron emission from the collector walls, as well as the ion sputtering on the collector surfaces, are modelled by fitting the experiment data. The 1-D PIC modeling results show that the injection of the thermal electrons from the negative collector can excite a standing wave. This will heat the plasma electrons, and lead to a significant shortening in the total ion collection time. It indicates that this novel method with the injection of the thermal electrons can significantly change the structure and dynamics of the plasma sheath; and thus, results in a great improvement of the ion collection efficiency.

Acknowledgement: This work has been supported by the National Natural Science Foundation of China (No. 11775128). We also thank Dr. Alexander V. Khrabrov of PPPL for fruitful discussions.

References:

[1] S. Steinke, et al., Nature, 530 (2016) 190.

[2] X Yuan, et al., Plasma Phys. Control. Fusion, 60 (2018) 065009.

NANOSECOND DISCHARGE IN AIR IN "NEEDLE – ELECTROLYTE" SYSTEM

Vasyl Chyhin[1]
1. Vasyl

Synthesis of nanostructures of metals is modern and promising application of pulsed discharges with liquid electrodes. Using of a spark with electrolyte cathode for the synthesis of nanostructures of copper and nickel in processing of CuSo4, NiSO4 salt solutions by the plasma is known. Using of "needle electrolyte surface" gaps of the size of 2-4 mm with switching pulse condenser of low capacitance is the most widespread. In order to accelerate the synthesis of nanostructures and increase their release to the macroscopic quantities it is necessary to increase the plasma volume and the pulse energy input in the plasma.

STUDY OF ION-TEMPERATURE EFFECTS ON A COLLISIONAL MAGNETIZED DUSTY PLASMA SHEATH USING FLUID SIMULATION METHOD

Shesaraj Bhandari[1]
1. Central Department Of Physics

The effect of ion temperature and ion-neutral collision on a magnetized dusty plasma sheath has been investigated numerically using fluid equations. The plasma is considered to have nano-sized cold fluid dust grains, hot electrons helium ions and neutral particles. The compiled equations are solved numerically under initial conditions. The results show that there is a significant effect of ion temperature on the dust velocity profile and the effect is more prominent for collisional case. When the ion temperature increases, the ion density decreases slowly down, while electron density falls exponentially, the wall potential decreases leading to the increase of the thickness of the sheath. In addition, the result revels that the effect of ion temperature is more obvious on the dust dynamics in collisional case.

ANALOGUE OF CHEMICAL POTENTIAL OF COULOMB DUST BALLS IN NEON CRYOGENIC PLASMA

Dmitry Polyakov[1], Valeria Shumova[1], Leonid Vasilyak[1]
1. Joint Institute for High Temperatures of the Russian Academy of Sciences

The Coulomb dust balls have been observed in neon dc glow discharge at pressures of 0.15-1.2 Torr at 77K. The spherical dust structures can be mono or multicomponent, i.e. they can represent mixtures of dust particles and clusters formed by dust particles [1]. The correlation has been revealed between the discharge parameters at which dust spheres form, and their sizes, composition, phase and dynamic state of their components. The various composition and dynamics of dust sphere components lead to non-monotonic dependencies of their sizes versus discharge parameters. Plasma with dust balls was simulated using the diffusion-drift model [2]. The radial distributions of potential energy of dust particles within dust spheres and an analogue of chemical potential (CPA) of dust balls have been calculated. A change in CPA has been found to indicate a change in the mixture of dust ball components. The maximum CPA of dust ball corresponded to the minimum of its size and was located to the left of the phase line at pressures corresponding to minimum values of discharge current and potential energy of dust particle at which the dust ball was formed. The transition from maximum value of CPA has been found to complete melting of complex clusters accompanied by transition from multicomponent multiphase mixture of complex and simple clusters to homogeneous composition of clusters in liquid state.

Work supported by the Russian Foundation for Basic Research, Grant No. 19-02-00454.

1. D. N. Polyakov, V. V. Shumova, L. M. Vasilyak, Plasma Sources Sci. Technol. 2017, 26, 08LT01.

2. V. V. Shumova, D. N. Polyakov, L. M. Vasilyak, Plasma Sources Sci. Technol. 2014, 23, 065008.

PHASE TRANSITIONS IN CRYOGENIC DUSTY PLASMA IN NEON

Valeria Shumova[1], Dmitry Polyakov[2], Leonid Vasilyak[1]
1. Joint Institute for High Temperatures of the Russian Academy of Sciences
2. Joint Institute for High Temperatures of Russian Academy of Sciences

In neon dc discharge at 295K, dust structures consist of individual dust particles [1, 2]. With decreasing temperature, individual dust particles form clusters [1-3]. Dust structures at 77K can be multicomponent, i.e. represent a mixture of dust particles and clusters formed by dust particles. Variation in discharge current I can lead to phase transitions in dust structures in different directions. Phase transitions in dust structures at a pressure of 0.15 Torr and 77K have been found in our study. At I=0.631 mA dust structure was quasi-crystalline. 3D dust quasi-crystal was formed by cluster chains consisting of 2D complex clusters. An increase in current to 0.633 mA was accompanied by a change and disappearance of the dust structure symmetry, quasi-crystal was destroyed. Thus, was observed the evidence of continuous second-order phase transition. At I=0.633 mA and higher, the mixture of cluster chains (mini-crystals) and of 1D threadlike clusters was observed. At I=0.691 mA, there was an abrupt jump in dust structure volume, i.e. the density of dust cloud decreased sharply, which indicated first-order phase transition. Here, the melting of complex dust clusters and partial melting of simple dust clusters were observed. With following current increase to 3.5 mA, there was no significant change in the dust mixture composition.

Work supported by the Russian Foundation for Basic Research, Grant No. 19-02-00454.

1. D. N. Polyakov, V. V. Shumova, L. M. Vasilyak, J. Phys.: Conf. Ser. 2016, **774**, 012181.

2. D. N. Polyakov, V. V. Shumova, L. M. Vasilyak, Plasma Sources Sci. Technol. 2017, **26**, 08LT01.

3. D. N. Polyakov, V. V. Shumova, L. M. Vasilyak, J. Phys.: Conf. Ser. 2018, **1058**, 012029.

COLLISION OF SHOCK WAVES IN A NON-MAXWELLIAN STRONGLY COUPLED DUSTY PLASMA

Papihra Sethi[1], N. S. Saini[2]
1. Guru Nanak Dev University, Amritsar
2. Guru Nanak Dev University,Amritsar

Dust is ubiquitous in nature and is characterized by the presence of charged massive dust particles in addition to the ions, neutral and electrons. Dusty plasma plays an important role in laboratory and astrophysical environments. The charged particles interact with each other via the long range Coulomb interactions and the large amount of charge enables dust grains to strongly couple with the neighboring charged particles, which makes dusty plasma a complex media for fundamental research. Dust grains are subject to additional force such as polarization force due to deformation of Debye sheath around the dust grains in the background of nonuniform plasmas. The interaction of two or more solitary waves is a nonlinear phenomenon and occurs due to propagation towards each other, exchanging their energies and separating off after the collision. The phase shift physically means the energy utilization by solitary waves to preserve their shape and size after collision. The observations of various satellite missions have confirmed the omnipresence of non-Maxwellian particles with suprathermal tails at higher energies in most of the astrophysical and space plasma environments. Such kinds of non-thermal particles are naturally found in solar wind, Jupiter and Saturn environments. Owing to the importance of polarization force, kappa distribution and omnipresence of charged dust fluid, we have investigated dust acoustic shock waves in a strongly coupled plasma with negatively charged dust, Maxwellian electrons and superthermal ions. The effect of various parameters such as polarization force, ratio of effective dust to ion temperature, kinematic viscosity on the structures and collisions of dust acoustic shock waves is examined. The study may find relevance in space and astrophysical environments.

STUDY OF DUST KINETIC ALFVÉN PERIODIC WAVES IN NONEXTENSIVE PLASMAS

RUPINDER KAUR[1], N.S. saini[2], kuldeep singh singh[3]
1. GURU NANAK DEV UNIVERSITY, AMRITSAR
2. GNDU, ASR
3. gndu, amritsar

Alfvén waves are the electromagnetic waves. The restoring force in kinetic Alfvén waves is provided by magnetic tension and inertia is provided by ion mass.Dust is an ubiquitous component in astrophysical and space environments such as planetary rings, cometary tails, interstellar clouds, and earth's mesosphere and ionosphere [1]. The presence of charged dust particles generates new types of eigen modes such as dust acoustic (DA), dust ion-acoustic (DIA), and dust lattice (DL) modes . In the presence of an external magnetic field, dust grains can respond to the perturbations on long time and space scales, and this response to perturbations can generate the dust kinetic Alfvén waves via polarization drifts of dust fluid [2]. The present work focuses on the study of dust kinetic Alfvén cnoidal waves (DKACWs), which has their major applications in transporting and dissipating energy in various space and astrophysical plasma environments [3]. A theoretical investigation is carried out to study dust kinetic Alfvén periodic waves containing two temperature superthermal electrons in nonextensive plasma. The nonlinear Korteweg-de Vries (KdV) equation is derived by using the reductive perturbation (RPT) technique. Further, the solution of KdV equation is numerically analyzed to study cnoidal waves. The variation of different plasma parameters has been analyzed on the characteristics of DKACWs. The findings of this research work may have important applications in Saturn's magnetosphere where two temperature superthermal electrons are present.

References:

[1] P. K. Shukla and A. A. Mamun, Introduction to Dusty Plasma Physics (Institute of Physics, Bristol, 2002).

[2] A.S. Bains, B. Li, and L.-D. Xia, Phys. Plasmas 21, 032123 (2014).

[3] N. S. Saini, Barjinder Kaur, Manpreet Singh, and A. S. Bains, Physics of Plasmas 24, 073701 (2017).

PULSED POWER-INDUCED CO2 DISSOCIATION FOR CO PRODUCTION

Wilfred Hoeben[1], Tom Huiskamp, Guus Pemen[1]
1. Eindhoven University of Technology

Carbon dioxide CO_2, as thermodynamically stable end product of fossil fuel based combustion, is an interesting source for carbon monoxide CO, if a sustainable energy source is used. CO is a major precursor in chemical synthesis, e.g. Fischer-Tropsch based CO hydrogenation to synthetic hydrocarbons and future fuels.

In this study, pulsed power technology has been applied for generating a non-thermal plasma for CO_2 dissociation; the CO_2 average bond dissociation energy is 8.3 eV. A capacitor-spark gap pulsed power source has been utilized, typically delivering 200 mJ pulse energy (at repetition rates up to 100 Hz) to a concentric wire-cylinder electrode geometry in an atmospheric pressure and ambient temperature operated reactor. Power-to-gas coupling has been studied by varying gas flow and pulse repetition rates. CO_2 conversion and CO production efficiencies have been determined as a function of the energy density, for plasma batch operation of CO_2 mixtures with nitrogen, argon or helium.

CO_2 conversion has appeared to be most favorable using Ar as buffer gas. This is explainable by the average metastables energy which decreases according to the order $He > Ar > N_2$, combined with the assumption that He metastables production under the applied plasma conditions is less favorable. Although CO_2 conversion levels increase with energy density, also the probability of CO_2 back oxidation increases, when oxygen is not removed from the system. Additionally, it has appeared that the plasma provides enough energy to even split CO with a bond dissociation energy of about 11.2 eV; in other words, carbon deposition has been observed.

MODELING OF THE PLASMA CHEMISTRY IN AN ELECTRON BEAM INDUCED DISCHARGE*

Tzvetelina Petrova[1], John Giuliani[1], Stephen Swanekamp[1], Steve Richardson[1], Stuart Jackson[1], Paul Adamson[1], Joseph Schumer[1]
1. Naval Research Laboratory

A simulation code is under development for the solution of the time-dependent Boltzmann equation, self-consistently coupled with time-evolving nitrogen plasma chemistry of an electron beam driven discharge. The application is to a N2 filled chamber of pressure 0.1 to 10 Torr driven by the NRL 90 kV Febetron generator with a e-beam current pulse of 100 ns, peak current of 4 kA, and beam current density ranging from 25 to 300 A/cm^2. The code follows the time–dependent response of the electron energy distribution function (EEDF) to the changing electromagnetic field induced by the e-beam. During the e-beam pulse, the gas undergoes ionization and excitation due to collisions with the beam electrons with subsequent plasma chemistry. Processes included in the kinetics part of the model are electron-neutral and Coulomb collisions, vibrational excitation, electron collisional excitation, and ionization by plasma and beam electrons. The plasma chemistry module includes collisions with electrons, dissociation and dissociative ionization of N2 molecules. Conditions are such that the creation of secondary as well as later generations of plasma electrons by the e-beam are important. A circuit model of the 2D axisymmetric gas target solves for the electromagnetic fields and the return current density is computed from a generalized Ohm's law. Plasma conductivity and the return current are studied in a wide range of gas pressure and e-beam current densities. The importance of individual plasma chemical processes and species production is evaluated.

*Work supported by NRL 6.1 Base Program.

GENERATION OF CARBON MONOXIDE FROM CARBON DIOXIDE USING NANOSECOND PULSED DISCHARGE

Tatsuya Ichiki[1], Asuki Iwasaki[1], Douyan Wang[2], Takao Namihira[2]
1. Graduate School of Science and Technology, Kumamoto University
2. Institute of Pulsed Power Science, Kumamoto University

Carbon monoxide is a gas generated by incomplete combustion and carbon compounds, and generally recognized as a toxic gas. Also, it is known as greenhouse gas. The emission amount of carbon dioxide is increasing year by year, which is recognized as a severe environmental problem. On the other hand, it is considered to be an industrially useful material used for the synthesis of methanol. Carbon dioxide was converted to carbon monoxide using nanosecond pulsed discharge which created by a very short, high voltage with pulse width is 5 ns. The nanosecond pulsed discharge was generated in a coaxial cylinder type rector with a large discharge volume. The applied voltage from the nanosecond pulse generator to the reactor was adjusted to 30, 40, 50 kV and the pulse repetition rate was adjusted 50 - 400 pps. The initial carbon dioxide concentration of simulated gas was regulated at 100 %; and gas flow rate was controlled to 2, 5, and 10 L/min. The results showed that carbon monoxide was successfully generated and by products was not detected. Detailed results will be presented at the conference.

IMPACT OF GAS-CHEMISTRY MODEL ACCURACY ON MODELING INTENSE ELECTRON BEAM DRIVEN PLASMA

Paul Adamson[1], Steve Richardson[1], Tzvetelina Petrova[1], Stephen Swanekamp[1], John Giuliani[1], Stuart Jackson[1], David Hinshelwood[1], Joseph Schumer[1]
1. Naval Research Laboratory

A thorough and accurate plasma–chemistry model that includes all of the important species and reactions is vital for correctly capturing the rapid breakdown of air by intense electron beams. A rigid beam model that uses a standardized approximation to Maxwell's equations and the beam dynamics equations is being developed to test various simplified models of intense electron beam driven plasmas. Here we describe a sensitivity study in which the species, reactions, and underlying methods for determining associated rate equations are varied within the rigid-beam model coupled to a Boltzmann solver. In varying the underlying methods for determining excitation cross sections and reaction rates, we employ first-principal quantum mechanical B-spline R-matrix methods, approximate methods such as the binary-encounter Bethe model, and experimental results where available.

CHARACTERISTICS AND PARAMETERS OF PLASMA OF MERCURY FREE UV-VUF RADIATORS ON RADICALS OF HYDROXYL (OH) WITH PUMPING BY NANOSECOND CAPACITIVE AND BARRIER DISCHARGES

Vasyl Chyhin

An aplication of gas-discharge UV-UV lamps in photochemistry, biophysics, medicine, and micro-nanoelectronics stimulated the study of physical processes in plasma of the relevant radiation sources. It also gave a boost to experimental and theoretical studies of the optimal composition of working gas mixtures of environmentally safe, free of mercury lamps for the spectral range of 140-360 nm. UV and VUF lamps with hydroxyl radicals (OH) of water are of increasing interest, because they use an environmentally friendly and cheap working environment based on gas mixtures of inert gases with a pair of water. To obtain the plasma in pair water, promising is the use of pulsed capacitive and barrier discharges. These types of discharges allow to prevent the contact of electrodes with aggressive plasma.

DETAILED GAS ANALYSIS IN NANO SECOND PULSED NON-EQUILIBRIUM PLASMA PROCESSING OF HYDROCARBONS FOR MASS BALANCE

Shariful Islam Bhuiyan[1], Kungpeng Wang[1], Christopher Campbell[1], Abdullah Hil Baky[1], David A. Staack[1]
1. Texas A&M university

Low temperature atmospheric pressure non-equilibrium plasma was generated in liquid hydrocarbon with gas bubbles to characterize the reformed gases formed by hydrocarbon processing. A 10g sample of hexadecane was used as liquid hydrocarbon while 90% CH4, 10% H2 gas bubbles of 50 sccm was flown throw it. A RC circuit was used to generate nano-second pulsed plasma with 20pF capacitor and 1.5M ohm resistor. Energy deposited was 500KJ/kg over a duration of 3 hours. The electrodes were on a pin-plate configuration with the top being a quarter inch rod and the bottom electrode being the capillary. The bottom electrode was set to high voltage while the top electrode acted as ground. A closed system loop was developed that recirculated the gases through the plasma reactor and into a gas chromatography in real time to characterize and analyze them. Preliminary results show that 3.9% of the gases captured were reformed gases formed from methane, hydrogen and hexadecane cracking by plasma reaction. The rest of the gas sample was Methane and hydrogen whose percentage concentration will be quantified in future. Of the 3.9% reformed gases, Ethane is 10%, Ethylene 15%, Propane 1%, Propylene 2%, Acetylene 40%, C4 – 3%. C5 – 15%, and C6+ 14%. To quantify the above results, an independent fast refinery gas analysis method was created to detect hydrocarbons in vapor phase using Shimadzu gas chromatography 2014. A complete mass balance is required to understand the thermodynamics and reaction kinetics of non-equilibrium plasma processing and reforming of hydrocarbons.

EFFECTS OF NON-MAXWELLIAN ELECTRON ENERGY DISTRIBUTION FUNCTION ON PLASMA CHEMISTRY IN CL_2 AND CF_4

Xifeng Wang[1], Alexander Khrabrov[2], Igor Kaganovich[2]
1. University of Michigan
2. Princeton Plasma Physics Laboratory

Control of low-temperature plasmas for materials processing is critical to the quality of the product. Therefore, it is required to further refine and customize reactive fluxes. In this regard, a global model was used to study the electron kinetic effects in Cl_2 and CF_4 plasmas. The model was benchmarked against another global model by using the same set of gas phase and wall surface chemical reactions assuming a Maxwellian electron energy distribution function (EEDF). In this model the reaction rate coefficients are calculated by integrating EEDFs with cross sections; the wall recombination coefficients are approximated using available experimental data. The model was validated by comparison with experimental data for chemical composition and plasma density. We used a bi-Maxwellian EEDF (with the hot and cold electron temperatures) to investigate electron kinetic effects on the chemical composition. As the temperature of hot electrons increases at the given constant power, densities of Cl^+, Cl^- as well as Cl increase gradually in Cl_2 plasmas. By contrast, the chemical component in CF_4 plasmas is affected less by variation of hot electron temperature at given power absorbed in plasma. This is due to the relatively high dissociation energy thresholds. However, chemical composition can be significantly modulated by increasing power. Therefore, discharge power and temperature of hot electrons should be used simultaneously to control the densities of chemical species.

SYNTHESIS AND MATERIAL CHARACTERIZATION OF SILVER NANOFLUIDS PRODUCED THROUGH LASER ABLATION IN LIQUIDS

Rizbi Hasan[1], Magesh Rajan[1]
1. South Dakota School of Mines and Technology

Silver nanofluids hold enhanced physical, chemical, thermal and transport characteristics compared to the base fluids, which signify a great potential for a variety of applications including biomedical applications and drug delivery etc. Nanofluids are a new class of fluids engineered by dispersing nanoparticles of size less than 100 nm in base fluids.

In this work, we will present the results of producing scalable enhanced nanoparticles in water using laser induced plasmas at liquid-metal phase boundaries. The formation and dynamics of laser plasmas and shock waves at liquid-metal phase boundary was affected by the conditions of strong liquid confinement. The plasma and shock spatio-temporal dynamics and velocities varied for different laser transfer matrix and experimental conditions. The plasma electron density of the laser induced plasma at liquid-Ag phase boundaries was measured using a two-wavelength laser interferometry. In order to better understand the relationship and synthesis of effective nanofluids the results of correlating the plasma characteristics with the nanoparticles size and size distribution will be presented.

The characteristics of nanoparticles produced at the liquid-Ag phase boundaries using laser induced plasma has a strong relation with the laser transfer matrix. We present the effects of nanoparticle size distribution for different experimental conditions. We will also present data on nanoparticle characterization using static light scattering, dynamic light scattering, SEM, TEM, SEAD, EDS and XRD.

SPECTROSCOPIC INVESTIGATION OF AIR EXCITED AND IONIZED BY AN ELECTRON BEAM*

S. L. Jackson[1], D. D. Hinshelwood[1], S. B. Swanekamp[1], Tz. B. Petrova[1], J. L. Giuliani[2], A. S. Richardson[2], P. E. Adamson[1], J. W. Schumer[1]
1. Naval Research Laboratory
2. Plasma Physics Division, Naval Research Laboratory

Plasma chemistry induced in air by an electron beam is being studied at the Naval Research Laboratory. An electron beam is produced in vacuum using a Febetron pulsed-power generator modified to produce a peak voltage of 80 kV, a peak current of 4 kA, and a pulse width of 100 ns. The beam then passes through a thin anode followed by a thin pressure barrier into a cavity filled with low-pressure dry air. Visible and near-ultraviolet spectral lines are used to diagnose the presence of excited and ionized states induced as the beam transits the air. The time dependence of these excited states at different pressures is compared with the electron density and current within the cavity, as well as framing camera images of the visible emission.

*Supported by the Naval Research Laboratory Base Program.

RELATIVISTIC HERMITE-COSINE-GAUSSIAN LASER BEAM SELF-FOCUSING IN THE COLLISIONAL PLASMAS

Masoud Alimohamadi[1], Arezou Zarei[2]
1. Department of Physics, Frahangian University,Tehran,Iran
2. Department of Physics,Sahrood University of Technology, shahrood ,Iran

The operation of the relativistic self-focusing with a Hermite-cosine-Gaussian (HcosG) laser beam in collisional plasma has been considered. The equation of beam width parameter and self-trapped mode has been derived by using a paraxial approximation. The resulted has shown decentered parameter play a key role on the self-focusing nature of the beam. Also, the beam width parameter during laser propagation in the collisional plasma is investigated.

DEVELOPMENT OF A PLASMA SOURCE TO ACCOMMODATE AN LIF DIP MEASUREMENT SYSTEM

John Foster[1], Christopher Durot[1], Jenny Smith[1]
1. University of Michigan

Understanding air plasma chemistry requires accounting for the myriad of gas phase reactions initiated and mediated by electrons and excited species in the presence of an applied field. In the case of a time-varying electric field, this task of tracking reactions is even more complex. Models developed to track these physical processes require physics verification, model benchmarking and ultimately experimental validation. This effort aims to produce experimental measurements of the time-varying electric field associated with a pulsed air plasma. The effort is two-pronged, including diagnostic development and a plasma source to validate the diagnostic with a controlled and well-defined electric field. Here we describe a glow discharge hollow cathode source that provides a source of excited species which flow into a well-controlled, plasma- free electric field. These species will be probed by an LIF dip diagnostic for calibration and validation. Preliminary optical emission spectra of the source plasma as a function of pressure and power with argon and air as well as absorption spectroscopy of argon excited species using a white light source are presented along with specific features of the plasma source. Argon metastable density as a function of discharge power and pressure is also presented.

WHAT DIFFERENT EFFECTS CAN BE TAKEN BY DIFFERENT LIQUID-DISSOLVED GASES ON THE CONCENTRATION OF AQUEOUS RONS?

YING YANG[1], LanLan Nie[1], XinPei Lu[1]
1. Huazhong University of Science and Technology

The chemical process that occurs in plasma-liquid interaction is a key issue in plasma biomedical applications and clinical treatment processes. The researchers have discussed the effects of different plasma sources and liquid components on the generation of aqueous RONS [1-3] while almost no one cares about the different liquid-dissolved gases have what different influence on the concentration of aqueous RONS. Since the aqueous oxygen is involved in the formation and transformation of the aqueous RONS according to the researches, and the proportion of the gas component in the living body is different from the proportion of the gas component in water body in the atmospheric environment. Therefore, we designed an experiment, in which we dissolved different kinds of gases in double distilled water (DDW), including CO2, O2, N2 and air, to separate the effects of different gas components in the liquid on the formation of liquid active particles.

The experimental results show that the presence of aqueous oxygen plays an important role in the formation of ROS and RNS, which can promote the generation of various aqueous RONS, and nitrogen has a certain influence on the formation of RNS. CO2 also has a positive impact on the formation of RNS while it is slightly detrimental to the formation of OH. Taking H2O2 and NO2—as examples, the rule of H2O2 concentration in various DDWs shows: unprocessed (μM) $>$ N2 (μM) (or O2 (μM)), and CO2 (μM) $>$ O2 (or N2) $>$ air-free(μM), and the rule of NO2— is: unprocessed (μM) $>$ O2 (μM) (or N2 (μM)) and CO2 (μM) $>$ O2 (or N2) $>$ air free (μM).

DESIGN OF HIGH-VOLTAGE PULSE GENERATOR CONTROL SYSTEM FOR CSNS LINAC RF SYSTEM

Maliang Wan[1], Wenzhong Zhou[1], Zhencheng Mu[1], Jian Li[2], Xinan Xu[2], Meifei Liu[1], Bo Wang[1], Linyan Rong[1], Zhexin Xie[1], Zonghua Zhang[2], Jimin Qiao[2]

1. Dongguan Branch,Institute of High Energy Physics,Chinese Academy of Sciences

2. Institute of High Energy Physics,Chinese Academy of Sciences

China Spallation Neutron Source (CSNS) is the first neutron source facility in developing countries. it includes a powerful linear proton accelerator, a rapid circling synchrotron, a target station and three neutron instruments. As one of the largest science and technology infrastructure projects in China, CSNS is expected to have positive effects in promoting the sciences, high-tech development and national security. Klystron power supply of CSNS is an important part of linac. high-voltage pulse generator provides for Klystron.

High-voltage pulse generator is composed of 400Hz series-resonant DC high-voltage power supply and solid state modulator. it includes variable frequency power supply (50Hz converted to 400Hz), boost transformer (0.5kV-6kV), 400Hz series-resonant LC, energy storage capacitor and pulse high-voltage modulator.

AC power transfer to the 500V of 400 Hz square wave,and then LC series-resonant circuit inspires high-voltage ,AC High-Voltage transfer to DC High-Voltage by Silicon Stack and capacitance, at last realize the output of DC high-voltage. The core component of high-voltage pulse modulator is composed of 150 MOSFET power switches, which are synchronously triggered by the optical pulse,the pulse width and repetition rate of optical signal is variable, so the DC supply is modulated pulse High-Voltage supply.

This paper introduces the structure of the pulse high-voltage generator system and the principle of the system, Focusing on the introduction of high-voltage pulse generator control system, the operation of high-voltage pulse generator.

COMPACT RAPID CAPACITOR CHARGER FOR MOBILE MARX GENERATOR APPLICATIONS

Argenis Bilbao[1], Stephen Bayne[1]
1. U.S. Army Research Laboratory

Abstract - The purpose of this paper is to show the work being performed to develop a compact rapid capacitor charger suitable to charge Marx banks to voltages ranging between 5 kV to 10 kV. The capacitor charger is being constructed with mobility in mind; for this reason it is powered using a series of high current LiPo batteries. A detailed description of the different system components is presented to familiarize the reader with rapid capacitor chargers. Additionally, a sketch of the proposed system packaging is shown along with volumetric and specific power densities. These figures are of paramount importance in mobile applications. Results of the preliminary tests are discussed outlining the performance achieved while charging test capacitor banks. Future improvements to the system are shown and their implementation paths discussed.

A COMPACT 100 KW HIGH-VOLTAGE POWER SUPPLY WITH BALANCED BIPOLAR OUTPUT

Jordan Chaparro[1], Kevin Lawson[2], Matthew McQuage[3]
1. Naval Surface Warfare Center
2. Booz Allen Hamiton
3. NSWCDD

A passively balanced, bipolar high voltage power supply was created to drive a compact pulsed power system. The supply was designed to average 100 kW when charging a capacitive load to ±50 kV with a total volume of less than 15 L. The supply is sourced from a low-ESR ultra-capacitor bank charged to 285 V and operates with runtime durations less than a few seconds. The converter employs a novel high turn ratio, low leakage inductance transformer to achieve a resonant impedance less than 200 mΩ at a switching frequency of 20 kHz. The step-up transformer output is converted to a balanced bipolar output by a dual polarity diode multiplier circuit with a common ground reference. The resonant converter is based on an LCL-T configuration and operates in constant current mode. Design details and experimental measurements of the converter will be presented.

AN ENERGY ADDER CIRCUIT FOR HYBRID ENERGY HARVESTING SYSTEM

Andréa Villarim[1], Cleonilson Protasio
1. Federal University of Paraíba - Brazil

In recent years, the development of ultra-low power consumption electronic devices has made possible to use low-capacity batteries or to even avoid the use of them by harvesting energy (such as solar, thermal, RF, among others) available in the environment to power the devices. Nowadays, in order to optimize the performance of energy harvesting systems, hybrid energy harvesting systems are being studied and developed in order to use different energy sources, thus increasing the quantity and availability of energy supplied. A fundamental circuit in hybrid energy harvesting systems is the one that receives energy from different sources and performs the right combination to a single power output. In general, the power combination circuits are time-shared, *i.e.*, only one source is connected to the load while the others are in the standby state or accumulating energy. To harvest available energy sources simultaneously, it is introduced an actual energy adder circuit applied for hybrid energy harvesting systems capable of harvesting, conditioning and adding energy from different energy sources. In this way, a particular parallel combination of DC-DC converters was developed where an internal circuit to control the converters switching time has been used to guarantee the operation and efficiency of the hybrid harvesting system. As a result, a greater amount of energy from different sources can be used. The experimental results show the performance obtained of the proposed energy adder circuit.

ABLATION AND BREAKDOWN CHARACTERISTICS OF HIGH CURRENT GAS SPARK SWITCH WITH DIFFERENT PROFILES

Yu Wang, Yongmin Zhang, Aici Qiu, Yong Lu, Qiaojue Liu

In the field of high voltage discharge device and pulse gas laser, electrode profiles, in the determination of the polar electric field, have a direct impact on the quality of the product. From the demand of practical engineering, for the high-current two-electrode self-breakdown repetitive spark switch, in this paper, we selected the ball electrode, flat bulb electrode, Chang and Bruce, four different types of electrodes which were made of 90WNiFe in the same geometry except its profile. Under ∼20kV average self-breakdown voltage, ∼40kA average peak current and dry air environment, these four pairs of electrodes are tested for 5000 shots short circuit discharge in standard atmospheric pressure, respectively. During the experiment, the distance between two electrodes were set to be 2,3,4,5,6 mm respectively and obtain the self-breakdown voltage curve to provide guidance for engineering practice. Self-breakdown voltage statistics and discharge stability are investigated. Furthermore, after the experiment, the high voltage electrodes were scanned by electron microscopy to observe the distribution of erosion area and ablation morphological characteristics of different electrodes.

MEASUREMENT OF DIODE REVERSE RECOVERY LOSSES AS A FUNCTION OF SWITCHING FREQUENCY*

David Wetz[1], Christopher Martinez[1], Jacob Sanchez[1], Joshua Ruddy[1]
1. University of Texas at Arlington

In compact pulsed power applications, high voltage is often sourced by a DC to DC resonant converter that draws power from a manageable, lower voltage source. As the converter's switching frequency is increased, the size of the magnetics decreases increasing overall power density. Despite its many advantages, increasing the frequency can increase the switching losses within the rectifying diodes and solid-state switches. The research presented is focused on the studying the reverse recovery losses associated with Silicon Carbide Schottky diodes used in a high voltage full-bridge rectifier at switching frequencies ranging from 10 kHz to 65 kHz. The testbed assembled to study the diodes will be presented along with the results collected to date.

----

* Work is sponsored by Air Force Research Laboratory (AFRL)/RDHP, Kirtland Air Force Base, under FA9451-17-D-0070

HIGH RATE CHARGE AND DISCHARGE OF HIGH VOLTAGE CAPACITORS*

Christopher Martinez[1], David Wetz[1], Jacob Sanchez[1], Joshua Ruddy[1]
1. University of Texas at Arlington

In the work presented here, a well controlled study has been performed to characterize the performance of a high voltage, pulsed power capacitor when it is recharged to 100 kV in 100 μs. A CLC testbed has been assembled to supply the high rate pulsed recharge current to the capacitor being studied. Experiments are being performed in a controlled temperature environment ranging from 20oC to 60oC. The capacitors are of interest for use in compact, repetitive rate, Marx generator sources used to supply pulsed power to a few different loads. The testbed will be discussed along with the performance results collected to date.

----

* Work supported by the US Office of Naval Research (ONR) under grant N00014-17-1-2847

SKIN EFFECT IN COAXIAL CONDUCTORS OF PULSE FACILITIES

Boris Fridman[1], Maxim Medvedev[1]
1. Efremov Institute of Electrophysical Apparatus

The results of study of the skin effect in coaxial conductors of pulse facilities are presented. The analytical expressions for skin parameters [1] of the coaxial conductors are deduced, and the methods for measurement of these parameters are described by the example of the coaxial cables. Transients in electrical circuits with the coaxial conductors are studied, and the method based on Inverse Fast Fourier Transform for computation of these transients is described. The measurements of pulse voltages in the circuits with the coaxial conductors confirm correctness of the proposed mathematical models and the computation methods.

[1] B. Fridman. Skin Parameter of Massive Conductors and Transients in Electrical Circuits of Pulsed Power Facilities. IEEE Trans. Plasma Science, vol. 46, No. 10, 2018, pp. 3273 – 3278.

MULTI-PULSE PERFORMANCE OF AMORPHOUS METAL MAGNETIC CORES AT HIGH MAGNETIZATION RATES

Daisy Acosta-Lech[1], Timothy Lee Houck[1], Michael K. Misch[2], Koby Sugihara[2]
1. Lawrence Livermore National Laboratory
2. Mission Support and Test Services

Amorphous metal magnetic cores are essential in developing multi-pulse solid state systems due to their high magnetic saturation value. In order to operate in multi-pulse mode, the magnetic core must provide enough volt-seconds before reaching saturation. They must prove to be reliable and maintain little to no load loss during the high rate pulses. This paper presents the efforts to characterize the performance of various MetGlas cores at high magnetization rates and use this data to develop models for simulation. Results of the test are used to match the magnetic cores and to assemble cells with identical volt-second ratings.

COMPATIBILITY OF SLA AND FDM PRINTED COMPONENTS WITH COMMON INSULATING OILS

Casey Ottesen[1], Haylie Orozco[1], Elisha Converse[2], Brad Hoff[3], Steven Hayden[2], Sabrina Maestas[3], Craig Kief[1]
1. COSMIAC at University of New Mexico
2. Aramco Research Center - Boston, Aramco Services Company
3. Air Force Research Laboratory

To enable the use of additively manufactured polymer materials as structural and insulating components within high voltage pulsed power systems, better understanding of material compatibility with common pulser material environments is required. The present work examines the effect of long-duration contact of printed polymeric components with three high voltage insulating oils: Diala, Luminol, and Royco 66. Test pieces printed using stereolithography (SLA) were evaluated for changes in mechanical properties and dielectric strength after submersion in insulating oil for a nine-month duration. Test pieces printed using fused deposition modeling (FDM), also submerged in oil for a nine-month duration, were evaluated for changes in mechanical properties only, due to known problems with highly anisotropic dielectric strength. GC-MS was used for oil composition analysis on neat and plastic-exposed oils to identify any chemical leeching that occurred during the exposure period and to correlate changes in chemical composition with bulk mechanical and dielectric properties that result from oil immersion. Data and analysis of experimental results will be presented.

OPTIMIZATION OF L-BAND WAVEGUIDE CIRCULATORS FOR A BROAD BANDWIDTH AND HIGH TRANSMISSION OPERATION

Kaviya Aranganadin [1], Ming-Chieh Lin[1], Hua-Yi Hsu[2]
1. Hanyang University
2. National Taipei University of Technology

Circulators are used in many industrial microwave heating applications. Three waveguide ports and a ferrite are combined to selectively direct energy from one port to another along the direction of wave propagation. A circulator is often employed directly after the RF power source in order to protect the source such as a magnetron from excessive levels of reflected power. Thus, an overheating issue which may cause a reduced efficiency and a shorter tube lifetime can be avoided. The industrial L-band WR975 circulators operating at a frequency range from 900 to 930 MHz have been designed and simulated. Commercially, an L-band circulator operated at 896 $\pm$ 10 MHz is available. However, for a wider bandwidth ($\sim$ 30 MHz) application, we would need two units operated in dual frequencies between 896 MHz and 915 MHz to cover the frequency range required. In this work, via a finite element method based simulation study, it was found that by reducing the height of the waveguide circulator in half a broader bandwidth can be achieved and this also leads to a reduction of overall fabrication cost. This paper discusses a detailed design and modeling of the L-broadband circulator operating at 915 MHz with a bandwidth of 43.5 MHz, from 892 to 935.5 MHz, an insertion loss of 0.25 dB for the entire bandwidth, and 0.22 dB at frequency of 915 MHz. For the entire bandwidth, the transmission efficiency is over 94.3% and it is more than 95% from 900 to 930 MHz of operating region which reduces power reflections for improving the performance and reliability of magnetrons. In addition, this L-band waveguide circulator was studied and optimized for different ferrite materials.

----

* This work was upported by the research fund of Hanyang University, National Research Foundation of South Korea, and MASTEK, Inc. in Taiwan

STUDY ON PULSE CHARACTERISTICS OF GAN HEMTS

Dong Wei Gang[1]
1. Fudan University

Abstract—GaN HEMT is a novel power transistor which has a broad application in pulsed power system due to its superior electrical and thermal performance. However, there are few studies on the pulse characteristics of GaN HEMTs. This paper studies by experimentation and physics-based simulation the electrical characteristics of GaN HEMTs under heavy current and ultrashort pulse. A test platform has been set up. The pulse characteristics of GaN HEMTs under different working conditions are measured, including rising edge, on-resistance, on-loss and over-current capacity. The corresponding safe working area is obtained. Combined with theoretical calculation, the transient behavior and dynamic performance of the device under ultrashort pulse are analyzed. It is hoped that through our research, GaN HEMTs can be better applied in pulsed power system.

Index Terms—GaN HEMT, pulsed power system, pulse characteristic, over-current, ultrashort pulse.

AN EIGENVALUE APPROACH TO STUDY SPIDER RF OSCILLATOR OPERATING SPACE

Ferdinando Gasparini[1], Mauro Recchia[1], Marco Bigi[1], Alberto Maistrello[2], Andrea Zamengo[1], Elena Gaio[1]

1. Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete Spa), Corso Stati Uniti, 4, Padova, Italy

2. Consorzio RFXConsorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete Spa), Corso Stati Uniti, 4, Padova, Italy

The SPIDER experiment features four radiofrequency (RF) circuits to heat the plasma generated in its inductively coupled ion source. Each circuit includes a tetrode-based Colpitts push-pull oscillator (200kW rated power) operating at 1 MHz frequency, a coaxial transmission line to feed the load composed of a couple of RF antennas and a resonant matching network. The SPIDER operation has shown two phenomena that affect the performance of the RF circuit: the so-called “frequency flip” that prevents the operation at the best load impedance matching condition and a limitation on the maximum RF power delivered by the RF generators.

Theoretical models of the SPIDER RF circuits have been developed able to predict the frequency flip occurrence, that has been also experimentally observed. By using the validated models, an operational setup to avoid the frequency flip occurrence has also been synthesized and successfully implemented. However, limitation in the maximum delivered RF power are still present, thus the RF circuit modelling approach has been further developed exploiting the state space analysis to achieve a deeper comprehension of its operation.

The results of the eigenvalue analysis of the circuit gives as outputs both the operating frequency of the system and equivalent load seen by the oscillator at that frequency. The equivalent load is used as input for an steady state electrical model of the push pull connection of the tetrodes, which exploits the algebraic model of the tetrode and permits the identification of the RF power delivered by the oscillator as a function of the tetrodes polarization voltages.

A validation of the models developed is presented on the base of the SPIDER experiments.

OUTPUT CHARACTERISTICS OF HORN ANTENNAS IN TRANSIENT REGIME

Jing-Shyang Yen[1], Xuan-De Huang[2], Chia-Wei Lin[2], Kaviya Aranganadin[3], Chii-Ruey Lin[4], Jwo-Shiun Sun[5], Hua-Yi Hsu[6], Ming-Chieh Lin[3]

1. Department of Electronic Engineering, National Taipei University of Technology,
2. Department of Mechanical Engineering, National Taipei University
3. Department of Electrical and Biomedical Engineering, Hanyang University
4. Department of Mechanical Engineering, Minghsin University of Science and Technology
5. Department of Electronic Engineering, National Taipei University of Technology
6. Department of Mechanical Engineering National Taipei University of Technology

The transient output properties of horn antennas for high power microwave (HPM) applications have been studied using a 3-D conformal finite-difference time-domain (CFDTD) simulation. For benchmark purpose, fundamental modes in standard rectangular and circular horn antennas are studied and compared with those simulated in frequency domain using HFSS. For steady state operation, the output characteristics shows similar behaviors in both frequency and time domains while in transient regime the time dependent characteristics demonstrates very interesting phenomena. The transient effects on far-field propagation should be considered in a short pulse HPM operation. The output characteristics of higher order modes for a specific application have been further investigated. Preliminary results obtained including near field and far field patterns and corresponding antenna parameters will be presented

1. C. S. Lee, S. W. Lee, and S. L. Chuang, “Plot of modal field distribution in rectangular and circular waveguides”, IEEE Trans. Microwave Theory Tech. 33, 271-274, (1985)

2. D. K. Cheng, Field and Wave Electromagnetics, 2nd Edition. (Assison-Wesley Publishing Company, 1989).

----

* Work supported by the National Taipei University of Technology, Minghsin University of Science and Technology in Taiwan, and Hanyang University in Korea.

E-BAND POWER COMBINING EXPERIMENT FOR HIGH POWER MILLIMETER WAVES*

Ahmed Elfrgani[1], Firas Ayoub[1], Marios Patriotis[1], Edl Schamiloglu[1]
1. University of New Mexico

Millimeter wave summation is the only way to achieve high power generation due to the limited power handling capability of a single high power microwave source. In this work, a 12-way power combiner was experimentally studied. The amplitude and phase of each input are adjustable using 12 attenuators and 12 phase shifters. The output of the power combiner was received by an open-ended waveguide probe. The experiment was performed in E-band where the designed frequency was at 78 GHz.

The power combiner converts the fundamental mode of the rectangular waveguide to the TE01 mode in overmoded circular waveguide. The TE01 output mode is a reasonable option due to the fact that conductive losses decreases for this mode as frequency increases.

----

* Work supported by DARPA Grant #N66001-16-1-4042

HIGH POWER ĆUK CONVERTER FOR FUSION SCIENCE APPLICATIONS

Alex Henson[1], Tim Ziemba, James Prager[1], Kenneth E. Miller[2], Satbeer Singh[1]
1. Eagle Harbor Technologies, Inc.
2. Eagle Harbor Technologies, Inc

Eagle Harbor Technologies (EHT), Inc. is developing a Ćuk converter for local helicity injection and magnet driving and control for the Pegasus Toroidal Experiment at the University of Wisconsin – Madison. A Ćuk converter has low output ripple; high efficiency; voltage gain greater than one, allowing for deeper energy storage utilization; continuous power flow that lowers output EMI, reducing noise generation; continuous input and output current – energy flow from the series capacitor allows for greater control of the injector currents; and series arrangements can be utilized that isolate individual switch modules so a failure does not potentially damage all solid-state switches. EHT will utilize previously developed precision gate drive technology that allows for high frequency switching, which reduces the capacitor and inductor values significantly, making the design more compact and lower cost. EHT has designed and built a first-generation Ćuk converter that was tested at Pegasus. We will present the Phase I project plan and the results of the project.

INVESTIGATION OF LASER-EXCITED NONLINEAR MODES IN AN UNDER DENSE PLASMA USING 2D SIMULATION CODE

Ameneh Kargarian

In this work, the excited nonlinear modes in the interaction of a high power laser with an under dense plasma have been investigated using a two-dimension electromagnetic simulation code. The results show that by increment of the plasma density the electrons obtain more energy from the laser before the instabilities start to grow in the environment. After the occurrence of the instabilities, the significant amount of the laser energy exists from the finite-size plasma and so cannot absorb any more by the plasma particles. The obtained simulation results are in relevance to the experiments on the plasma-based accelerators as well as the plasma heating.

PLASMA WATER TREATMENT AND OXIDATION OF ORGANIC MATTER IN WATER

Kamau Wright[1]
1. University of Hartford

Low temperature plasma microdischarges in contact with aqueous solutions which include organic dyes are studied. Plasma treatment of samples over a duration of time encompassing one hour are observed. The Ultraviolet–visible (UV-Vis) spectrum of select samples is analyzed to assess and measure the change in organic dye content. Results are presented which indicate the efficacy of small scale plasma systems to oxidize organic matter in water. The color change in the water is observed and the associated changes in absorbance and reflectance are characterized. With the present system, dye-containing samples were made visibly clear during testing. Further tests with water treatment parameters such as total organic carbon are also being pursued. The efficacy of using plasmas for cleaning water, specifically related to the presence of oil in water is discussed.

THE WENDELSTEIN 7-X STELLARATOR: PLASMA GENERATION, HEATING AND CURRENT-DRIVE WITH THE WORLDWIDE LARGEST ELECTRON CYCLOTRON HEATING FACILITY

Manfred Thumm[1], on behalf of the W7-X Team[2]
1. Karlsruhe Institute of Technology, IHM
2. Max-Planck-Institute for Plasma Physics

The stellarator Wendelstein 7-X (W7-X) is equipped with a steady-state capable 10 MW ECH system, operating at 140 GHz, which corresponds to the 2nd cyclotron harmonic of electrons in the magnetic field of 2.5 T. Ten megawatt-class gyrotrons, two 5 MW quasi-optical transmission lines (94 % transmission efficiency) as well as 4 directly steerable and 2 novel remotely steerable launchers inside the plasma vessel are operational and already delivered more than 7 MW X2-mode heating to W7-X plasmas. Besides the reliable plasma start-up and routine ECH wall conditioning, stationary discharges up to 100 s have been achieved, which were only limited by the maximum test divertor energy load. Combined with pellet injection, the highest triple product $(0.68 \times 10^{20} keV m^{-3} s)$, observed up to now in stellarators, was achieved, exclusively by electron heating heating [T Sunn Pedersen et al 2019, Plasma Phys. Control. Fusion 61, 014035]. The corresponding plasma parameters were $T_{i0} = T_{e0} = 3.8$ keV, $n_{e0} = 0.9 \times 10^{20} m^{-3}$ and $\tau_E = 0.22$ s. For the first time, dense W7-X plasmas were sustained by 2nd harmonic O-mode (O2) heating, approaching the collisionality regime for which W7-X was optimized [T Stange, submitted to PRL]. O-mode heating needs high T_e and multi-pass absorption that was obtained by tungsten covered Mo mirror tiles with holographic gratings at the inner wall. After boronization of the plasma vessel, stationary O2-heated plasmas above the X2 cut-off with hydrogen gas fueling only; hydrogen plasmas with 6 MW ECRH for 30 s at only 1 MW divertor heat load (detached plasma), thermalization $(T_i = T_e = 1.5 keV)$, density $1.6 \times 10^{20} m^{-3}$ and radiation control with $W_{dia} = 800$ kJ were achieved, which is a reference scenario for later long-pulse high density discharges. Power deposition scans did not show any indication of electron temperature profile resilience. In low-density, low-power plasmas compensation of the bootstrap current with electron-cyclotron current drive (ECCD) was demonstrated [RC Wolf et al 2019 Plasma Phys. Control. Fusion 61, 014037]. The long discharges were used to demonstrate current control and bootstrap current compensation by ECCD. Until 2018, the plasma vessel was equipped with an uncooled divertor, which allowed to extend the integrated heating energy from 4 MJ to 80 MJ. The full steady-state capability will be reached in 2021, after an actively cooled high heat-flux divertor has been installed which can tolerate steady-state heat fluxes of up to 10 MW/m^2. Plans for later upgrades include a further increase of the ECH power to 18 MW and the introduction of tungsten as a first-wall material.

Acknowledgment

This work was carried out within the framework of the EUROfusion Consortium and has received funding from the EURATOM research and training programme 2014-2018 and 2019-2020 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

----

* W7-X Team: see author list of T Klinger et al., Nucl. Fusion 2019 doi.org/10.1088/1741-4326/ab03a7

PARAMETRIC INTERACTION OF VLF AND ELF WAVES AND IMPACT ON ENERGETIC ELECTRONS IN A RADIATION BELT

Vladimir Sotnikov[1]
1. Air Force Research Laboratory

Different sources for Very Low Frequency (VLF) whistler wave generation including parametric mechanisms of excitation with involvement of Extremely Low Frequency (ELF) waves, Ion Acoustic (IA) waves as well as conventional loop antennas will be analyzed. Whistler waves interact with Radiation Belt (RB) electrons via cyclotron resonance. This interaction leads to enhanced pitch angle diffusion and shifting energetic electrons towards the loss cone. In order for this interaction to be efficient it is necessary to create certain level of finite amplitude VLF electromagnetic whistler waves in the interaction region. In the case of conventional sources a great deal of the source power is radiated not as a whistler wave but as a quasi-electrostatic Low Oblique Resonance (LOR) mode which does not propagate on great distances from the source region. Only a small percentage of the power $\sim (3 – 5)\%$ is radiated as an electromagnetic whistler wave. We present new results on parametric interaction of LOR waves with IA waves and ELF waves to demonstrate the possibility to overcome this difficulty. It will be shown that interaction of LOR waves with low frequency waves gives rise to electromagnetic whistler waves on combination frequencies. It is shown in this work that the amplitude of these waves can considerably exceed the amplitude of whistler waves directly excited by a loop source. Additionally, particle-in-cell (PIC) simulations, which demonstrate the excitation and spatial structure of VLF waves excited by conventional and parametric sources will be presented.

MODULATIONAL INSTABILITY AND STUDY OF FREAK WAVES IN AN ION BEAM PLASMA WITH TWO TEMPERATURE SUPERTHERMAL ELECTRONS

Nimardeep Kaur[1], Kuldeep Singh[1], N.S. Saini[1]
1. Guru Nanak Dev University

From past few decades, there has been a great deal of interest in understanding different types of nonlinear solitary structures in various kind of plasmas. The study of ion-acoustic solitary waves in multi-component plasmas holds an mportant place in both theoretical and experimental point of views. The satellite observations in space plasma confirm that these waves generally occur in association with ion beams. It was also shown that the ion acoustic solitary waves are associated with up flowing ion beams. The propagation of an ion beam into a plasma can strongly affect the conditions for the occurrence of solitary waves and may modify their properties. Most of the space and astrophysical environments show the existence of superthermal particles. These particles are well modelled by the kappa type distribution. We have derived the nonlinear Schrodinger equation (NLSE) using multiple scale perturbation technique. From the nonlinear and dispersion coefficients, we have studied the instability conditions. Both dark and bright envelope solitons are observed. It is observed that physical parameters (e.g., beam concentration, superthermality of electrons and beam velocity) play a significant role to modify the envelope solitary structures associated with these low frequency waves. The characteristics of first- and second-order freak waves has been studied in detail in the presence of ion beam. The findings of the present study may be useful in understanding the amplitude modulation of low frequency solitary waves in various space/astrophysical plasma environments such as Saturn's magnetosphere, polar cap region of Earth's magnetosphere where ions, two temperature superthermal electrons and ion beams are present.

SOLAR WIND DRIVEN WHISTLER INSTABILITY IN EARTH'S CUSP REGION

M N S Qureshi[1]
1. GC University, Lahore

One of the fundamental questions in space plasmas still not fully understood is how the energy is transported from solar wind to the Earth's magnetosphere. In the present study, we observe electron velocity distribution (EVD) functions in the Earth's magnetosphere using the CLUSTER data. The EVD functions are observed at different times when the CLUSTER traversing the southern cusp region, such as when the electron density is very low typical of cusp values and when it suddenly increases due to some solar wind disturbances at the magnetopause. We found that the observed EVD functions are flat top distributions and have two populations; a cold bulk magnetospheric population and a hot solar wind tenuous population. Observed EVD functions are then fitted by generalized (r,q) distribution which is the generalized form of kappa and Maxwellian distribution functions and can be reduced to kappa and Maxwellian distributions in the limit r =0, q = k+1 and r =0, q goes to infinity, respectively. We derive the expressions of real frequency and damping/growth rates by employing generalized (r,q) distribution function and plot them using the observed plasma parameters and fitting values of spectral indices r and q. When solar wind electrons with flat top distribution enter into the Earth's magnetosphere, we obtain enhnced growth causing the Whistler waves to grow and hence responsible for the transport of energy from solar wind to the magnetosphere.

LOW ENERGY ELECTRON IRRADIATION INDUCED CHARGING OF DIELECTRIC MATERIALS: MEASUREMENTS AND ANALYSES.

Mohamed Belhaj[1], Sarah Dadouch[1]
1. ONERA

Charging of dielectric materials under electron irradiation is a commonly encountered problem in many space applications. Spacecraft charging due to solar and cosmic radiations may lead to critical discharge phenomenon. Indeed, under irradiation (especially electron irradiation), insulators as well as floating conductors may charge negatively or positively depending on the incident electron properties (energy, incidence angle , flux) and on the specific material properties (composition, surface roughness, contamination, temperature, etc.) The knowledge of the electrical properties electron emission yield, conductivity and radiation induced conductivity) under electron irradiation for each material of the spacecraft is needed for spacecraft plasma interaction software. The aim of our contribution is to present the results of charging proprieties (magnitude and kinetic) under low incident electrons energy (from few eV to keV) for Teflon and alumina. The energy distribution of the emitted secondary and backscattered electrons was measured dynamically with the help of high speed hemispherical electron energy analyzer. The evolution of the surface potential of the irradiated sample was derived from the energy shift of the secondary electron pic.

MODELING DSX PLASMA INTERACTIONS USING NASCAP-2K

Myron Mandell[1], david cooke[2], James McCollough[3], William Johnston[3], Adrian Wheelock[3], Dale Ferguson[4], Victoria Davis[1]

1. Leidos

2. US Air Force Res Lab

3. US Air Force Research Lab

4. US Air Force Res. Lab

Wave Particle Interaction Experiment (WPIx) will be conducted on the DSX (Demonstration and Science eXperiments) mission to be launched in 2019. WPIx broadcasts VLF (Very Low Frequency) into the MEO (Medium Earth Orbit) environment using an 80 meter tip-to-tip dipole antenna biased to kilovolt potentials. The spacecraft-plasma interactions code Nascap-2k is used to model the dynamic plasma sheath during VLF transmission. Simulations have been performed for several cases of plasma density, plasma temperature, VLF frequency, and applied voltage. Because a positive antenna element easily collects electrons from the environment, most of the time one antenna element is near zero potential and the other is negative near the full applied bias. The sheath around the negative element is very large at MEO densities. While a small ion current is collected by the antenna, most of the ions accelerated into the sheath orbit the antenna and leave at high energy when the potential is relaxed. The current flow in the antenna is computed from the surface electric field using a pseudopotential method. This current is used to obtain the antenna impedance (capacitance and phase shift) and its dependence on plasma and operational parameters. A similar pseudopotential approach gives the electron current in the near-field plasma, along with the energy imparted to plasma electrons and their flow along magnetic field lines. Finally, the spectrum of ions to the LEESA (Low Energy ElectroStatic Analyzer) particle detector during VLF transmission is obtained from ion macroparticles striking the surface containing LEESA. These analyses will aid in planning operations and understanding results for WPIx.

TRANSIENTS ON ARC AND CONVERTOR CURRENTS IN THE MULTICUSP CESIATED SURFACE CONVERSION H - SOURCE AT LANSCE

David Kleinjan[1]
1. Los Alamos National Laboratory

The Multicsup Cesiated Surface Conversion H- Ion Source at the Los Alamos Neutron Science Center (LANSCE) has provided beam at ∼14 mA, 120 Hz, and 10% D.F. for many years of neutron science research. Recently, random high current transients were discovered in the arc current used to ionize hydrogen in the LANSCE H- ion source, and in the convertor current used to convert protons to H- ions. Most have no effect, but more severe transients can cripple beam output. Hypothesized causes are related to cesiation effects, plasma potential changes, tungsten filament evaporation/sputtering, or from the arc modulator circuitry. A dedicated study was recently done on the LANSCE H- Ion source test stand to determine the cause of these transients. Current understanding indicates that the more severe transients come from a combination of cesiation effects and plasma potential changes. The status of these current transient studies on the LANSCE H- ion source will be discussed.

ATMOSPHERIC PRESSURE BREAKDOWN AND EVIDENCE FOR FIELD EMISSION IN GHZ SPLIT-RING RESONATORS

Zane Cohick[1], Michael Lanagan[1], Douglas Wolfe[1], Benjamin Hall[2]
1. The Pennsylvania State University
2. Lasers for Innovative Solutions

Microplasmas generated using microwaves have generated interest in recent years since they have promising qualities such as high-electron densities, breakdown occurring at voltages lower than predicted by Paschen's law, and the potential for remote excitability. One prominent method for generating microwave microplasmas is to employ a microwave split-ring resonator (SRR). However, while some comparative materials studies have been performed at low to moderate pressure, studies of the effect of different materials and fabrication methods at atmospheric pressure has remained absent. In addition, as field emission is expected to play a larger role as gap size is decreased, it is believed that the study of breakdown voltage vs. gap size for sub-100um may help clarify breakdown mechanisms.

Here we study plasma generation in silver and gold SRRs with gap sizes ranging from 100um to less than 10um fabricated using screen-printing, fs- and ns- laser ablation, and focused ion beam milling. Minor forays are also made with regard to SRRs with copper oxide nanowires and e-beam evaporated Cu. Breakdown is studied both in dark conditions and when SRRs are illuminated with deep ultraviolet irradiation. In order to characterize breakdown voltage distributions, we utilize Weibull statistics. Significant differences are found in the performance of SRRs fabricated using different techniques – differences occur due to Q-factor as we found in previous studies, but also independent of Q-factor. In addition, we find that there is a relationship between Weibull modulus and breakdown voltage. Differences in Weibull modulus and breakdown voltage are investigated by analyzing SEM micrographs of the SRR structure near the region of plasma generation. The large differences in SRR breakdown performance under dark conditions is attributed to the lack or presence of seed electrons which could result from field emission.

EXPERIMENTAL, ANALYTICAL AND COMPUTATIONAL STUDIES OF ELECTRON GUN GRID HEATING

Andrew Cross[1], Kristopher Frutschy[1], Allen Garner[2], Vasile Neculaes[3]
1. GE Global Research
2. Purdue University
3. GE

Electron guns are at the heart of various vacuum tubes used for applications that include communications, RF accelerators, industrial nondestructive inspection and medical imaging. An electron gun is typically comprised of the electron emitter and electrodes/electron gun elements used for beam extraction, control and focusing. A critical component of an electron gun for linear vacuum tubes is the mesh grid, which is typically placed at a certain distance from the emitting surface for beam extraction and control. For microwave tubes, the grid electrode serves the important function of beam pre-bunching. A linear microwave tube benefits from having a pre-bunched beam before entering the microwave circuit by having increased interaction efficiency, considerable reduction in vacuum tube length, and enhanced output power. Modulating the voltage on the grid electrode with a hundred microns of the emitting surface pre-bunches the electron beam and intercepts a fraction of the incident electron beam. Grid deformation, grid heating, secondary emission from the grid, and precise control of grid position and placement during electron gun assembly when designing a mesh grid-based electron gun.

Understanding and avoiding mesh grid overheating in electron guns is critical since it may critically impact electron beam optics. This work uses experiments, analytic calculations from first principles and 3D finite element (FE) simulations to assess electron gun mesh grid heating. Analytic and FE studies recover the experimental trends; in experiments, we have determined electron beam mesh grid intercepted power that causes grid destruction using a dispenser cathode as the electron emitter and a Mo grid placed 250 microns away. 3D FE simulations accounting for temperature-dependent material properties and the analytic theory predict mesh grid heating in reasonable agreement with experimental results.

GENERATION OF DEUTERIUM IONS IN A VACUUM ARC AND IN A GLOW DISCHARGE WITH A HOLLOW CATHODE

Valeria Frolova[1], Alexey Nikolaev[2], Efim Oks[1], Alexey Vizir[3], Georgy Yushkov[4]
1. Tomsk State University of Control Systems and Radioelectronics
2. High Current Electronics Institute, Tomsk, Russia
3. High Current Electronics Institite, Tomsk, Russia
4. High Current Electronics Institute

Plasma containing deuterium ions is used mainly for generating neutron fluxes as a result of the bombardment of a solid target with accelerated deuterium ions. Deuterium ions can be obtained, both in a glow discharge with operating gas of deuterium, and in a vacuum arc with metal cathode filled by deuterium. The report presents the results of investigations of the process of generation of deuterium ions in both discharge systems. The results of the study of the influence of the parameters of discharge systems of arc and glow discharges on plasma parameters, mainly on its mass-charge composition, are also presented. It is shown that in a glow discharge under certain conditions effective generation of three-atom deuterium ions is possible. In the arc discharge with a deuterium filled zirconium cathode introduction of a magnetic field leaded to essential increase of the ratio of deuterium ions to zirconium ions in arc plasma. The presented experimental results are discussed.

The work is supported by Russian Science Foundation under grant # 18-19-00069.

POWER CONSUMPTION IN A MINIATURE MICROWAVE INDUCTIVELY COUPLED PLASMA SOURCE

Ilija Stefanović[1], Michael Klute[2], Ralf-Peter Brinkmann[3], Nikita Bibinov[4], Wolfgang Heinrich[5], Horia-Eugen Porteanu[6], Peter Awakowicz[7]

1. Ruhr-University Bochum
2. Ruhr University Bochum
3. Ruhr-Universität Bochum, Faculty of Electrical Engineering and Information Technology, Institute for Theoretical Electrical Engineering, Germany
4. Ruhr University
5. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany
6. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenzte
7. Ruhr-Universität Bochum, Faculty of Electrical Engineering and Information Technology, Institute for Electrical Engineering and Plasma Technology, Germany

Miniature Microwave Inductively Coupled Plasma (MMWICP) source is a novel and versatile non-thermal plasma source, which profit of high electron density and high power efficiency. In its compact version a single MMWICP source comprises a quartz tube of 5 mm inner diameter enclosed by a copper resonator of 8 mm thickness. This basic unit can be combined in an array of two (double), four (Quadriga) or more sources. Here, the single source is characterized by Optical Emission Spectroscopy (OES). A continuous stream of nitrogen gas is running through the glass cylinder at a pressure of 2000 Pa. This specific pressure is chosen to satisfy the Local Field Approximation (LFA), which is used in the latter data analysis. For the OES measurements nitrogen as a test gas is selected for its well-known population kinetics. In particularly, the second positive system of neutral nitrogen (380 nm line) and first positive system of nitrogen molecular ion (391 nm) are monitored, for which the population kinetics can be described by a simple collision radiative model. The OES measuring unit consists of a macro objective, CCD camera and two narrow band-pass filters, which isolate the corresponding emission lines. With previously absolutely calibrated OES unit, the radially resolved absolute line intensities are collected with a 28 micrometer resolution. Simultaneously, an absolutely calibrated high resolution Echelle spectrometer monitors the rotational lines distribution form respective emissions. Using the rate equations of collision-radiative model and BOLSIG+ for solving a Boltzmann equation under the assumption of LFA, it is possible to measure the spatially resolved electron density and electric field. Moreover, the spatially resolved deposited power density is calculated. In the presentation we will discussed the power dissipation in CCP, ICP and hybrid mode of operation. In respect to power efficiency MMWICP will be compared to other microwave plasma sources.

TEST BEDS FOR ELECTRON EMISSION STUDIES

Michel CARON[1], Martial Toury[1], Laurent Hourdin[1], Remi Nicolas[1], Bertrand Etchessahar[1], Rodolphe Rosol[1], Jerome Magnan[1], Remi Maisony[1]
1. CEA

For electrodes coated with thin insulating layers, material properties like emissivity, stability, radiation endurance are key parameters for successful application in plasma physics, space industry or accelerator technology. In this paper, we report on test beds used at CEA for basic physics experiments dealing with material properties. Two studies are presented:

- The first one is dedicated to the characterisation of material under controlled field emission conditions. The experimental set up is presented as well as the results of the characterisation of pure metallic material or insulating coated metallic electrode.

- The second study deals with Electron Induced Electron Emission (EIEE) from a thin insulating layer deposited on top of a metallic electrode. The main experimental results are reported. They confirm that emission properties depend on the layer thickness, on the bias voltage and on the primary current intensity. All these dependencies can be qualitatively explained by surface charging effects which occur when the metallic back electrode cannot supply a sufficient amount of current to balance out the charge in excess. The experimental set up and results are presented and discussed via two mechanisms: Radiation Induced Conductivity (RIC) and electron injection from the back barrier into the conduction band of the insulator governed by the internal electric field strength.

DEVELOPMENT OF A 1MW PULSED AIR CORE ELECTROMAGNETIC TOROIDAL COUPLER FOR WIRELESS POWER TRANSMISSION WITH REDUCED STRAY EMISSION

Fatima Zahra Boudara[1], Marc Rivaletto[2], Laurent Pecastaing[3], Antoine Silvestre De Ferron [3], Jean-pierre Brasile[4], Sylvain Paquet[4]
1. Laboratory SIAME
2. Pau University
3. SIAME laboratory
4. Effitech

Wireless power transmission (WPT) has seen rapid growth during the last decades. It is a promising technology which has gained worldwide attentions in several applications (smart grid, defense systems…). WPT has proved its capability to be convenient, safe and autonomous. Nevertheless, this technology requires a high power and large area coupler which increases the human exposure to the electromagnetic field. In this context, an air core electromagnetic coupler with reduced stray emission was developed. It is a part of a system which ensures a proper DC / DC conversion between a low-voltage bus (three-phase rectified, fuel cell, battery) and a bus regulated to another voltage value while ensuring the galvanic insulation between both. The transfer of very high power and the galvanic insulation can only be achieved in sinusoidal mode via an air core electromagnetic coupler. So, the innovative proposed architecture confines the magnetic radiation in a torus in order to have an efficient coupling factor (k=0.72) without any use of shielding plate. Our toroidal coupler works mainly in pulsed regimes (1MW) and it is a light solution for several needs. The operating frequency of the compact coupler is 200kHz, the expected average power is 200kW resulting in a satisfactory efficiency of 98%. The effectiveness of the proposed novel system was first investigated by CST 3D numerical modeling then tested with an experimental step-up at low and high level of power. The simulation and the experimental results will also be discussed.

ASSESSING EFFECTIVE MEDIUM THEORIES FOR DESIGNING COMPOSITES FOR NONLINEAR TRANSMISSION LINES

Xiaojun Zhu[1], Andrew J. Fairbanks [1], Allen L. Garner[1]
1. Purdue University

Nonlinear transmission lines (NLTLs) are interest because they can sharpen pulses to produce oscillations from 100 MHz to low GHz once their permittivity and permeability have saturated and the electromagnetic shockwave has formed [1]. NLTLs typical use nonlinear dielectrics such as barium strontium titanate (BST), nonlinear magnetic materials such as nickel zinc ferrites (NZF), or both nonlinear dielectric and magnetic materials to provide these shock waves. An alternative approach involves designing composites comprised of BST and/or NZF inclusions in a host material, analogous to electromagnetic interference designs incorporating inclusions of various shapes in a plastic to tune the composite's electromagnetic properties [2]. Appropriately designing NLTL composites requires predicting these effective properties and, eventually, the high power microwave systems comprised of them. This study benchmarks various effective medium theories (EMTs) [3] to predict the permittivity and permeability of various composites of BST and/or NZF inclusions in the linear regime (for a fixed voltage and current). We first apply EMTs to predict DC permittivity of BST composites and then to AC measurements of permeability and permittivity for BST, NZF, and BST/NZF composites. We describe preliminary applications of CST Microwave Studios to predict the effective permittivity and permeability and compare to experiment and EMTs.

This material is based upon work supported by the Office of Naval Research under Grant No. N00014-18-1-2341.

[1] J.-W. B. Bragg, J. C. Dickens, and A. A. Neuber, "Ferrimagnetic nonlinear transmission lines as high-power microwave sources," IEEE Trans. Plasma Sci., vol. 41, pp. 232–237, 2013.

[2] A. L. Garner, G. J. Parker, and D. L. Simone, "A semi-empirical approach for predicting the performance of multiphase composites at microwave frequencies," IEEE Trans. Dielectr. Electr. Insul., vol. 23, pp. 1126-1134, 2016.

[3] A. Sihvola, Electromagnetic Mixing Formulas and Applications (IEE Electromagnetic Waves Series, Vol. 47), IEE, London, 1999.

DEVELOPMENT AND DIAGNOSTICS ON COMPOSITES FOR NONLINEAR TRANSMISSION LINES

Andrew Fairbanks[1], Xiaojun Zhu[1], Julio Hernandez[1], Shengjie Gao[1], Wenzhou Wu[1], Tyler Tallman[1], Allen Garner[1]
1. Purdue University

Nonlinear transmission lines (NLTLs) utilize nonlinear dielectrics to sharpen the input pulse to generate an electromagnetic shockwave for compact, high repetition rate, high power microwave sources. This shock wave generates microwave oscillations that can be propagated as a directed beam toward the intended target. Materials such as barium titanate (BT), barium strontium titanate (BST), and nickel zinc ferrites (NZF) have been used in NLTLs for their nonlinear dielectric or magnetic properties. Alternatively, one may adjust a composite's effective bulk parameters by adding inclusions of different permittivity, conductivity, or permeability. For instance, adding 2-3% of stainless steel fibers to a plastic makes the composite resemble stainless steel electrically for electromagnetic shielding [1]. Others have evaluated the dielectric properties of composites using nickel zinc ferrites coated in BT in a ceramic base medium for high energy density capacitors. The BT coated ferrite composite has a higher permittivity and lower magnetic loss than a bare ferrite composite [2].

This study evaluates the permittivity of composites comprised of various volume loadings of BST, the permeability of composites comprised of various volume loadings of NZF, and the permittivity and permeability of materials comprised of inclusions of both materials. Measurement system development for measuring nonlinear permittivity and permeability at microwave frequencies will also be discussed.

This material is based upon work supported by the Office of Naval Research under Grant No. N000014-18-1-2341.

References

[1] A. L. Garner, W. Lafayette, G. J. Parker, and D. L. Simone, "A Semi-Empirical Approach for Predicting the Performance of Multiphase Composites at Microwave Frequencies," IEEE Trans. Dielectr. Electr. Insul., vol. 23, pp. 1126–1134, 2016.

[2] R. Curry, A. Pearson, K. Noel, and S. Mounter, "Development of Metamaterial Composites for Compact High Power Microwave Systems and Antennas," Columbia, MO, 2016.

DESIGN AND TESTING OF A COMPACT 40 KV CAPACITOR BASED ON NANODIELECTRIC COMPOSITES*

Kevin O'Connor[1], Robert Kutz[2], Milton Miranda[3], Mark Prelas[4], Randy Curry[5]
1. NanoElectromagnetics LLC
2. NanoElectromagnetics, LLC
3. NanoElectromagetics, LLC
4. University of Missouri Center for Physical and Power Electronics
5. University of Missouri

Compact pulsed power systems are often limited by the size and shape of the capacitors required for high voltage energy storage. Marx banks, pulse forming networks, and other devices requiring multiple capacitors are larger than necessary due to the size and shape of the capacitors as well as the geometry of the connection terminals. The size and weight of the capacitor are determined by the energy density of the capacitor dielectric and the dielectric strength of the surrounding insulation. While doorknob-style capacitors are commonly implemented in these devices, the cylindrical shape does not permit efficient packing of multiple capacitors to fill the available volume. Alternative capacitors, such as those based on mica films, have an improved form factor but have end terminations that add inductance in many assemblies. A new effort is addressing these design issues by building the capacitor upon nanodielectric composites. The nanodielectric composites combine high dielectric constant ceramic particles with low dielectric constant, high dielectric strength polymers to produce materials with both high dielectric constant and high dielectric strength. The combination of these two properties enables higher energy densities than possible with conventional ceramics. The composite materials can also be formed or machined into complex shapes to improve capacitor packing density while maintaining low inductance connection points. This effort is focused on development of 40 kV, 2.5 nF capacitors for compact capacitor banks in a vehicle stopping system. In this contribution, the tradeoffs are discussed with the design and simulated performance. The test requirements are described, and preliminary test data is analyzed.

* This effort was sponsored by the U.S. Government under the DoD Ordnance Technology Consortium (DOTC) Other Transaction Agreement (OTA) (W15QKN-18-9-1008) with the National Armaments Consortium (NAC). The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

APPLICATION OF PROPYLENE CARBONATE-BASED NANO-FLUID IN PULSE FORMING LINE

Zicheng Zhang[1], Yanpan Hou[2], Shifei Liu[2], Hanwu Yang[2], Jiande Zhang[2], Baoling Qian[2]

1. National University of Defense Technology, China

2. National University of Defense Technology

Propylene carbonate, due to its great permittivity, high insulation strength, good self-healing, and easy shaping, has a good potential in compact pulsed power source as the energy storage medium of pulse forming line. In this paper, nano-particle modification technology is introduced in the pulse power source to improve the insulation characteristics of propylene carbonate. Investigations are focused on the application of propylene carbonate-based nano-fluid. Firstly, the nano-fluid is prepared by ultrasonic dispersion method and tested by dielectric breakdown in the microsecond regime. Secondly, by using the optical diagnosis method of ultrafast high-speed camera, physical images of streams during pulsed breakdown are captured. And a physical model of breakdown for nano-fluid is proposed, revealing the physical mechanism of nano-modification to improve the pulsed insulation of the base fluid. Finally, the nano-fluid is applied in a liquid forming line of pulsed power source through the purification system. The operation voltage of nano-fluid-based pulse forming line is 40% higher than that of the Propylene carbonate-based pulse forming line. And the pulsed power source can operate with 20 GW output power and 65 ns duration at 5 Hz rep-rate. These efforts promote the interdisciplinary development of nano-science and pulsed power technology and show a promising application of nano-fluid in the pulsed power source for the future.

HIGH CURRENT DENSITY PULSE TRANSMISSION EXPERIMENTS WITH DIFFERENT CONDUCTOR MATERIALS ON THE PRIMARY TEST STAND

Wenkang Zou[1], Guilin Wang[1], Bin Wei[1]
1. Institute of Fluid Physics, China Academy of Engineering Physics

High current density pulse transmission is critical important in large scale pulsed power facilities, in which a maximum current of 50∼60 MA is needed to transmit to Z-Pinch load in centimeter dimension. With MA/cm current density, the transmission line surface will suffer from pulsed megagauss (MG) magnetic field and will experience evident evolution. Thermal plasma will form due to magnetic field diffusion, which may influence the transmission property of the transmission line. The plasma formation characteristics highly depend on material. In the past years, on the 10 MA Primary Test Stand (PTS), high current density pulsed transmission experiments with different materials were conducted, for example the stainless steel experiment [Wenkang Zou, Physics of Plasmas 25, 022120(2018)] and the recent molybdenum experiment. In this presentation, these experimental results will be presented.

ON THE VUV OPTICAL EMISSION OF N-APPJS

XinPei Lu[1], FengWu Liu[1], Nie LanLan[1]
1. Huazhong University of Science and Technology

In the past several decades, to understand the fast propagation behavior of nonequilibrium atmospheric pressure plasma jets (N-APPJs), many simulations have been reported. It is believed that photoionization plays key role for such behavior. In all the simulation model, it is either assumed that high energy photons are emitted by N2 in the wavelength range 98–102.5 nm, which induce the ionization of oxygen molecule, or simply replaces the photoionization by a given background electron density. However, no N2 emission from N-APPJs in the wavelength range 98–102.5 nm has been reported by experiment. In this paper, It is found that, for all the working gas, i.e. He, He+0.1%, 0.5% of O2 or N2, Ar, Ar+0.1%, 0.5% O2 or N2, and for the plasma jet driven by either pulsed DC power supply or kHz AC power supply, no N2 emission between 98 – 102.5 nm can be measured. On the other hand, the O II 83.3 nm emission is detectable, which is able to ionize O2, O, and N. Therefore, the widely used photoionization model for N-APPJs need to be revised.

A BIPOLAR HIGH VOLTAGE PULSE GENERATOR USED FOR IRREVERSIBLE ELECTROPORATION ABLATION

Lanxi Li[1], Weidong Ding[1], Jiaqi Yan[1], Saikang Shen[1], Yanan Wang[1], Jiayin Yan[1], Yinan Zhu, Zheng Zhongbo[1], Chongjian Ge[1]
1. Xi'an Jiaotong University

Irreversible electroporation ablation is an irreversible perforation of cell membrane under the pulsed high voltage electric field with certain energy, which leads to cell death and apoptosis, finally achieves the ablation of tumors. The developing technology used by microsecond pulse generator raises a series of new requirements for generator: output voltage pulses with adjustable voltage levels, pulse width and frequency, bipolar pulse, high voltage, fast rising time, high repetition frequency, miniaturization and strong adaptability to complex load. In order to meet the requirement, a bipolar high voltage microsecond pulse generator based on all solid-state Marx generator is put forward in this paper.

This pulse generator consists of four Marx circuit stages and full-bridge solid-state modulator. Two MOSFETs, a capacitor and a diode are concluded in each Marx unit. In addition,the full bridge solid-state modulator is used to realize the polarity alteration of output pulses. A control system based on field programmable gate array (FPGA) with phase-locked loop (PLL) function is used to generate control signals. The FPGA control system produces synchronous trigger pulse which is the control signals of MOSFETs to control the pulse width and frequency. The experimental results prove that this generator can produce bipolar pulse. The output voltage amplitude ranges from -3 to 3 kV, pulse width can be regulated from 1 to 1000μs continually with a step size of 1μs, repetition frequency ranges from 1 to 10 Hz and rising time is about 96 ns. The generator has strong load adaptability, adjustable function with output voltage amplitude, pulse width and repetition frequency, and miniaturization of the pulse device. Also, the effect of ablation with the generator is considerable, so it is competent for further exploration on medical experiments under high-voltage pulsed electric field.

A BIPOLAR NANOSECOND PULSE GENERATOR WITH HIGH REPETITION FREQUENCY USED FOR IRREVERSIBLE ELECTROPORATION

Saikang Shen, Jiaqi Yan[1], Lanxi Li[1], Weidong Ding[1]
1. Xi'an Jiaotong University

Cancer is one of the main killers of human health. With the development of pulse power technology, the application of pulse bioelectricity in the field of cancer therapy is gradually getting attention. Irreversible electroporation, whose principle is applying a high voltage pulsed electric field to tumor cells, is a new type of tumor treatment with the superiority of little psychological trauma and side effect, no complications and sequelae. At present, microsecond pulsed electric field is widely used in clinic and research. However, there are problems of incomplete tumor ablation and muscle contraction during treatment. The clinical demands give rise to a new generation of nanosecond pulse generator with high repetition frequency and bipolar. High-frequency pulse can make the electric field distribution more uniform inside the tissue and bipolar pulses can relieve muscle contraction.

This paper reports on the novel development of a fully solid state Marx-type circuit to achieve output voltage pulses with high repetition frequency, nanosecond pulse width and high voltage. It adopts compact structure and adds some small capacitors to the discharge loop in order to reduce the rise time as short as possible. Two circuits with different polarity are connected in series to realize bipolar output by controlling the on-off of MOSFETs. A control system based on field programmable gate array (FPGA) is used to generate synchronous control signals for each MOSFET in order to adjust the pulse width and frequency flexibility. Finally, a 20-stage laboratory prototype of this circuit has been assembled using 1200 V MOSFETs and diodes, operating with 1000 V dc input voltage and 1 kHz frequency, giving 6 kV bipolar pulses, with 100-1000 ns pulse width and 30 ns rise time into resistive, capacitive, and inductive loads.

DOWNSTREAMING OF VALUABLE COMPOUNDS FROM MICROALGAE WITH SPARK DISCHARGES, INSTIGATED BY 100-NS HIGH VOLTAGE PULSES

Katja Zocher[1], Raphael Rataj, Anna Steuer[1], Juergen Kolb[1]
1. Leibniz Institute for Plasma Science and Technology

Microalgae have become an important resource for blue-green biotechnologies. In addition to their potential for biofuel production, microalgae comprise also valuable metabolites for pharmaceutical and nutritional purposes, such as fatty acids, proteins, carbohydrates, and pigments. However, microalgae are distinguished by a sturdy cell wall, which affords a remarkable mechanical and chemical strength that often translates into inadequate extraction yields. Therefore, conventional extraction methods have shown to be often energy and/or time consuming and consequently are associated with unreasonable economic costs [1]. Accordingly, improvements and alternatives to current extraction methods are needed for successful commercialisation.

In our previous works [2], [3], we could show that spark discharges, instigated in microalgae suspensions with 100-ns high-voltage pulses, offer a gentle and yet effective extraction method, especially for heat sensitive compounds. When comparing with extraction by burst microwave heating, proteomic analysis revealed commonalities and differences in the protein distribution pattern. Although the yields and number of extracted proteins were similar, notably valuable heat-sensitive proteins, e.g. photosystem-related proteins could be extracted abundantly in comparison to the reference method. Schlieren diagnostics and atomic force microscopy were conducted to elucidate the responsible spark properties for successful cell wall disintegration. Results show that for the generation of sparks by short high-voltage pulses, in particular the energy that is dissipated by shockwaves could easily overcome the stiffness of the microalgae.

1. Lee, A.K., et al.; Biomass and bioenergy, 2012. 46: p. 89-101.

2. Zocher, K., et al., Plasma Medicine, 2016. 6(3-4): p. 273-302.

3. Zocher, K., et al., Algal Research 39, 2019. 101416.

A MULTILAYER STRUCTURE OF COMPRESSED WATER FLOW GENERATED BY RE-STRIKE IN UNDERWATER ELECTRICAL WIRE EXPLOSION

Huantong Shi[1], Guofeng YIN[1], Yuanfei FAN[1], Jian WU[1], Xingwen LI[1]
1. Xi'an Jiaotong University

Underwater electrical wire explosion (UEWE) has attracted the attention of researchers in the field of warm dense matter physics and applied physics in the past several decades. Current pause is a common phenomenon in UEWE, however, the physical process of the re-strike in UEWE is still not very clear till now due to the difficulty of direct diagnostics, so is the formation mechanism of the re-strike shock wave. In this work, a "multilayer structure" of the compressed water flow generated by re-strike in underwater electrical explosion of Cu wire was reported, and corresponding experimental and numerical researches were carried out. It is believed that the partial heating of the re-strike arc initiate a pressure wave that propagates back and forth inside the wire, resulting in the oscillating of pressure on the wire boundary and consequently resulting in an oscillating radial density distribution of the compressed water flow generated by re-strike. This special compressed water flow leads to a "multilayer" structure in the shadow images and schlieren images. The simulation results of a one-dimensional hydrodynamic model supported the above explanations, and indicated that the radius of re-strike arc was about 0.3 times of that of the expanding wire. As the re-strike energy deposition rate increased with the charging voltage, this kind of compressed water flow with oscillated density distribution evolved into one single shock wave finally.

PULSE COMPRESSION CONSIDERATIONS FOR HIGH CURRENT RANCHERO GENERATORS

Timothy Foley[1], Thomas Gianakon[1], Christopher Rousculp[1], Robert Watt[1],
James Goforth[1]
1. Los Alamos National Lab

The Los Alamos Ranchero Flux Compression Generator (FCG) has been tested at the 76 MA level, and a 36 MA experiment was recently conducted demonstrating the functionality of an improved performance design. That test was performed with 3.5 MA initial current, which is the limit available from the capacitor bank at our high explosive pulsed power (HEPP) firing point. Computations show that the improved “Ranchero-S” FCG can generate currents of over 80 MA with 10 nH loads given sufficient initial flux. A program to develop the MK-X generator, which will be a replacement for the MK-IX FCG fielded through the 1980s and 1990s, is on-going at Los Alamos to provide initial flux for Ranchero FCGs and facilitate these very high current experiments. The function time of the improved Ranchero FCG is $\sim$25 μs, and for powering loads requiring short pulses, pulse conditioning is required. In this paper we investigate issues relating to switching the output of a Ranchero-S FCG into meaningful loads given peak currents of 80 MA while desiring load pulses in the 1 μs range for realistic inductance loads. 2D-MHD computations are used to assess design configurations, and significant issues include flux diffusion through any conductor that can hold the 80 MA and rupture rapidly, closing switches that can isolate the load from the diffused flux and then carry the desired current, and dynamic effects seen on vacuum transmission lines operating at such currents.

3D MAGNETO-HYDRODYNAMIC MODELLING OF AN OVERSTRESSED HELICAL MAGNETIC FLUX COMPRESSION GENERATOR

Anthony Johnson[1], Andrew Young[1], Adam White[1], Jalal Javedani[1], Roger Richardson[1], Jerome Solberg[1]
1. Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory (LLNL) is actively engaged in an experimental program using two-stage magnetic flux compression generators (MFCGs) as pulsed power sources for equation of state measurements. These MFCGs amplify a current pulse in two stages. The first stage uses a helical MFCG and the second stage uses a coaxial MFCG. In support of this program, LLNL recently conducted an overstress test of a megajoule class helical flux compression generator. This experiment was intended to push the generator into a regime where losses would become nonlinear. One of the goals of this experiment was to serve as a benchmark for the suite of computational tools used to predict the performance of these devices. This paper will focus on analysis of this experiment using the LLNL developed magneto-hydrodynamic (MHD) code ALE3D. Analysis of a helical MFCG with an MHD code is particularly challenging because the magnetic field is inherently three-dimensional and does not lend itself well to computational domain reductions using symmetry conditions. This means that large-scale simulations are required to analyse even the simplest helical generators. Regardless of these challenges, this paper will show that ALE3D is capable of predicting the overall behaviour of the generator as well as allowing one to see the source of the nonlinearity in gain. For this particular experiment, the analysis suggests that a significant portion of the loss in compression was due to excessive magnetic pressure on the armature and stator of the generator changing the phasing behaviour of the contact.

*This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-690731

DESIGN AND SIMULATION OF COMPACT EXPLOSIVELY-DRIVEN MAGNETIC FLUX COMPRESSION (MFC) GENERATORS FOR HIGH ENERGY APPLICATIONS.

George Vunni[1], Paul Berning[1], Peter Bartkowski[1]
1. US Army Research Laboratory

Explosive-driven magnetic-flux-compression generators are devices that convert part of the energy contained in high explosives into electromagnetic energy. These generators are one of the most efficient techniques for generating high magnetic fields and current impulses. In most generator designs, a small seed current from a capacitor bank is used to create an initial magnetic field between a pair of conducting surfaces. High explosive then drive these surfaces together, compressing the trapped magnetic flux and generating a large output current in the process. This paper presents an ALE3D magnetohydrodynamic simulation and experimental investigation of two explosively driven magnetic flux generators design by the US Army Research Laboratory. Simulation results are in good agreement with the experimental data.

A 2-D NUMERICAL MODEL FOR THE ESTIMATION OF THE TIME VARYING INDUCTANCE OF AN EXPLOSIVELY-DRIVEN HELICAL FLUX COMPRESSION GENERATOR

Ashish Sharma[1], Joy Thomas Meledath[1]
1. Indian Institute of Science

There is a considerable interest worldwide in the development of compact and single-shot expendable pulsed power sources for various applications. Explosively-driven helical magnetic flux compression generators (HFCGs) are natural contenders to provide the high power requirement for such applications. They consist of a hollow cylindrical metal tube called the armature filled with high energy explosives, placed within a helical coil that forms the stator. The explosives when detonated cause the armature to expand leading to the compression of the magnetic flux present within the space between the armature and the stator. This flux is initially set up by the seed current flowing in the circuit using a separate current source. These can be used to achieve very high magnetic fields accompanied with very high currents.

The present interest in the use of HFCGs brings about the need for a fast computer code for use in the preliminary design stage which can provide results with good accuracy. Using these codes, the performance of the generator can be analyzed before conducting actual experiments, which are difficult to conduct. The electrical equivalent circuit of HFCG can be represented by a first-order series R-L circuit with time-varying elements. During armature expansion, equivalent resistance and inductance of the generator tend to vary with time and geometry. A 2-D numerical model described in this paper presents an approach to evaluate the time-varying inductance of the generator by simulating the chemical explosion occurring within the armature using a commercially available package (AUTODYN) and using these results, a numerical code has been developed to model the time-varying inductance of the generator. The results obtained using the numerical model are compared with the ones available in the literature to validate the code developed. The results will be presented and discussed in detail in the final manuscript.

IGNITION MECHANISMS OF POLYMER BONDED EXPLOSIVES DURING DRILLING

Raimi Clark[1], Ryan Lee[2], Austin Hewitt[3], Tyler Buntin[4], David Barnett[4], James Dickens[4], W. A. Harrison[5], E. Tucker[6], John Mankowski[4], Andreas Neuber[4]

1. Center for Pulsed Power and Power Electronics (P3E)
2. Center for Pulsed Power and Power Electronics
3. Center for Pulsed Power and Power Electronics(P3E)
4. Texas Tech University
5. CNS Pantex
6. Mission Engineering Development Group

The drilling behavior of polymer bonded high explosives (HE) is investigated by varying drilling parameters and analyzing resultant forces and thermal response. A modified drill press enables remote operation and precise control of cutting speed, feed, and depth. To acquire temperature at the cutting interface a K-Type thermocouple is inserted in the coolant holes of thru-coolant drill bits and epoxied flush with the drill's flank face. The signal is amplified and digitized with an AD8495 Thermocouple Amplifier and MSP430G2553 Microcontroller with a sensing accuracy of $\pm 1°$C and a resolution of 0.48°C. Temperate data are relayed real time via blue tooth link to the control computer. Cutting forces and torques are acquired with an ATMI MC3A Force and Torque Sensor up to a sampling speed of 2,000 Hz. The comparison of downward directed forces across cutting operations is indicative of which speed and feed rate combinations limit excessive stressing of the HE, while cutting axis torques give indication in the case of drilling obstructions such as insufficient chip clearance. Drilling conditions in excess of the existing DOE-STD-1212-2012 limitations are tested to determine safe but efficient machining limits for these materials. Drilling speed, feed rate, and peck depth are varied for drilling cycles with a 5 mm diameter drill bit, and further cycles are performed to determine the effect of increasing cut diameter. In peck drilling, clearance of chip from the drill flute is crucial and governs the drill's temperature rise.

HYPERFINE STRUCTURE AND ISOTOPIC SHIFT ANALYSIS OF URANIUM TRANSITIONS USING LIF OF LASER-PRODUCED PLASMA

S. S. Harilal[1], E. Kautz[1], B. E. Bernacki[1], M. C. Phillips[1]
1. Pacific Northwest National Laboratory

Optical spectroscopy in conjunction with laser-produced plasma (LPP) is a very promising tool for in-field and non-contact isotopic analysis of solid materials. Both emission and fluorescence spectroscopy of laser ablation plumes can be used for isotopic analysis. However, the reported isotopic shifts of U I and U II transitions in the visible spectral regime are in the range $\sim$ 1-25 pm which necessitate the requirement of an extremely high-resolution spectrograph with a resolution $\geq$60000 for using emission based diagnostic tools (eg. laser-induced breakdown spectroscopy) for isotopic analysis. In addition to this, the emission spectral analysis requires thermal excitation by electrons which happen at early times of plasma evolution when the lines are broader due to various line broadening mechanisms (Stark, Doppler etc.). Laser-absorption/ laser-induced fluorescence spectroscopy (LAS/LIFS) can be used to marginalize the effect of instrumental broadening. LAS and LIFS probe the ground state atoms existing in the plasma when it is cooler, which inherently provides narrower lineshapes. We recently reported the linewidths of U transitions using LAS/LIFS of laser-produced plasmas are $\sim$ 1 pm which is significantly lower than the average isotopic shift of U atoms/ions ($\sim$ 9 pm). In addition to isotopic splitting, the hyperfine structures (hfs) may influence the lineshape of a transition. Hyperfine splitting's are usually small; however, in certain cases, they can be larger than isotope splitting. In that scenario, isotope shifts of atoms and molecules can be entangled with hyperfine structure. Here we report the isotopic shifts between U-238 and U-235 transitions and hyperfine structures of U-235 using laser-induced fluorescence (LIF) of laser-ablation plumes. We used a collinear laser geometry for isotopic detection, where both the plasma generation beam and LIF excitation beams propagate near normal to the target, which is a prerequisite for any standoff analytical detection tool.

PROPAGATION PROCESS OF STREAMERS AND TIME HISTORY OF REDUCED ELECTRIC FIELD DURING NANOSECOND PULSED DISCHARGE IN COAXIAL ELECTRODE IN ATMOSPHERIC AIR

Terumasa Ryu[1], Hitoshi Yamaguchi, Douyan Wang[2], Takao Namihira[2]
1. kumamoto university
2. Institute of Pulsed Power Science, Kumamoto University

Pulsed discharge plasmas which are one of the non-thermal plasma have been actively studied for industrial and environmental applications. The observation of discharge plasma formation is beneficial for better understanding of the plasma physics of this growing field. Generally, a pulsed discharge with time duration of 100s ns is divided into two phases, primary streamer and secondary streamer discharges. The primary streamer discharge has streamer head with the largest electric field among entire discharge phases and thereby produces a variety of radical species with high efficiency. Meanwhile, secondary streamer discharge is capable to produce many radicals by high density electron, however, causes much larger heating loss. Therefore, pulse duration of the applied high-voltage pulse has a strong influence on the energy efficiency of the plasma processes. In the recent study, a nanosecond (ns) pulsed power generator which can generate a pulsed voltage with 5 ns of duration was developed and achieved the higher efficiency on several applications (e.g. ozone generation, NO removal, and water cleaning). However, the fundamental mechanisms of these high efficiencies are not very well studied and understood. Therefore, the present study focused on obtaining the propagation process of streamers and time history of reduced electric field by measuring the intensity ratio of spectral bands of molecular nitrogen during ns pulsed discharge in atmospheric pressure air. In the experiment, the discharge propagation process and time history of reduced electric field in the vicinity of coaxial electrode were observed by using a high-speed gated emICCD camera and time-resolved spectroscopy, respectively. As the result, the reduced electric field of ns primary streamer near the high voltage inner electrode was estimated more than 1000 Td. This can be explained from the effect of significantly fast pulse rise rate of ns pulse voltage with exceeding 10 kV/ns.

IMPORTANCE OF RF MEASUREMENTS IN PULSED-PLASMA APPLICATIONS

Stephen Heagy[1]
1. Bird

The capability to measure RF power in plasma systems has existed for many years but key parameters, such as impedance of the plasma and delivered power, can be difficult to measure with high accuracy. This is especially true in pulsed RF systems, where it is difficult for the system to achieve a conjugate match from the rapidly changing plasma impedance to the RF source, resulting in reflected power. Actively monitoring the power and shape of the pulses is critical to develop and maintain consistent and repeatable processes. Changes in these measurements can indicate problems like equipment wear, drift, and instability and serve as a great starting point for process improvement. In this work, RF pulsing is studied in different pulsed-plasma applications and it is then demonstrated how directing attention to and gaining understanding of the RF measurements can assist in improving the processes.

INFLUENCING FACTORS AND ERROR ANALYSIS OF PULSE CURRENT MEASUREMENT WITH AIR-CORE ROGOWSKI COIL

Yao Xu[1], Xiaobing Zou[1], Xinxin Wang[1]
1. Tsinghua University

The error of an air-core Rogowski coil caused by eccentricity or tilting of the conductor flowing through the measured current and interference magnetic field outside the area is analyzed under uniform and uneven coiling conditions. The error which is a function of the density of the windings along the bobbin is given. In the aspect of extraction of distribution parameters, a method combining finite element simulation modeling and data fitting is proposed, which solves the problem of extracting the inter-turn capacitance of a Rogowski coil. Under high frequency conditions, the influence of the current of gap on shielding container on the measurement results is discussed. The function of the error caused by the current of shielding container is derived, and factors that affect the error are given.

A MULTI-MATERIAL VELOCIMETRY DETECTOR FOR PULSED POWER FLOW STUDIES

Mark Hess[1], G. Laity, Brian Hutsel[1], Chris Jennings[1], Daniel Dolan[1], Carlos Aragon[1], Kurt Tomlinson[2], Kyle Peterson[1]
1. Sandia National Laboratories
2. General Atomics

Pulsed power experiments at Sandia National Laboratories' Z Pulsed Power Facility have traditionally utilized single material velocimetry flyers for diagnosing magnetic pressure, and hence current, within the magnetically insulated transmission lines (MITLs). More recent experiments at Sandia suggest that energy absorption through various mechanisms, such as charged particle loss, can contribute to the measured motion of flyers as well. In order to further test this hypothesis, we have fielded flyers that are both single material, such as aluminum, and multi-material flyers, such as a combined substrate of gold and aluminum, to detect particle energy absorption on the MITL. Since each flyer material has a unique charged particle stopping power, as well as a unique sound speed, then the simultaneous velocimetry response of two different detectors can provide information about the types of charged particles depositing their energy, as well as their time-dependent energy deposition. Our presentation explains the physics of these detectors, and shows the experimental measurements from these detectors.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

BROADBAND POWER MEASUREMENTS OF HIGH-VOLTAGE, 10-NS PULSES FOR PLASMA IGNITION FOR COMBUSTION

Christopher Tremble[1], David Alderman[2], Jason Sanders[3], Dan Singleton[3], Chunqi Jiang[1]

1. Old Dominion University
2. Old Dominon University
3. Transient Plasma Systems, Inc.

Experiments have shown that transient plasma ignition (TPI) driven by nanosecond high-voltage pulses improves ignition and combustion efficiency [1]. To better understand the application through which nanosecond pulses affect combustion, the power and energy of transient plasma delivered to the combustion system are evaluated in order to optimize the pulse parameters. A broadband voltage-current measurement device was designed, fabricated and integrated in-line with the pulse transmission line and the plasma electrodes. Voltage and current were characterized for 10-ns (FWHM), $>$10 kV pulses with two different risetimes . A preliminary calibration of the V-I device showed that the 3-dB bandwidth of the voltage attenuator was 600MHz. In addition, a similar device can be developed for measurements of the impedance and dielectric properties for biological sample characterization [2].

* The work was supported in part by the Department of Energy (Phase I STTR, DE-SC001788), and the Air Force Office of Scientific Research (Award No. FA9550-17-1-0257).

PROGRESS OF BEAM DRIVEN PLASMA ACCELERATION AT FLASHFORWARD

Lucas Schaper[1], Alexander Aschikin[1], Simon Gerd Bohlen[2], Gregory Boyle[1], Theresa Karoline Bruemmer[1], Richard D'Arcy[1], Severin Diederichs[3], Brian Foster[4], Matthew James Garland[5], Lars Goldberg[1], Pau Gonzales Caminal[3], Sven Karstensen[6], Alexander Knetsch[1], Peng Kuang[1], Vladyslav Libov, Carl A. Lindstrøm[1], Kai Ludwig[1], Alberto Martinez de la Ossa[1], Timon Mehrling[7], Martin Meisel[1], Pardis Niknejadi[1], Jens Osterhoff[1], Kristjan Poder[1], Paul Pourmussavi[3], Martin Quast[3], Jan-Hedrik Roeckemann[1], Bernhard Schmidt[1], Sarah Schroeder[3], Jan-Patrick Schwinkendorf[8], Bridget Sheeran[3], Gabriele Tauscher[3], Stephan Wesch[1], Paul Winkler[3], Ming Zeng[1]

1. DESY
2. Hamburg University (DE)
3. Universitaet Hamburg
4. University of Oxford (GB)
5. CERN
6. DESY Hamburg
7. Lawrence Berkeley National Lab
8. Deutsches Elektronen-Synchrotron DESY

The FLASHForward experiment at DESY is a beam line build for beam-driven plasma-wakefield acceleration. The drive beams, supplied by the linac of the free-electron laser FLASH, have energies of up to 1.25GeV, a typical charge of 400 pC, emittance of a few mm mrad and a pulse duration down to 50fs. The extensive experimental programme consists of various experiments among which three are considered core experiments, focussing on internally (X-1) and externally (X-2) injected witness bunch acceleration as well as studies on high repetition rate and high average power operation (X-3). The latter is facilitated by the unique capability of extracting multiple electron bunches from the superconducting linac at a variable temporal spacing down to 333 ns. Here the present status of the facility and its capabilities as well as the status of current and future experiments will be detailed.

TIME-DEPENDENT BEHAVIOR OF CAPILLARY DISCHARGE DEVICES FOR PLASMA-WAKEFIELD ACCELERATION

Gregory Boyle[1], Erik Adli[2], James Anthony Chappell[3], Nathan Cook[4], Roberto Corsini[5], Richard D'Arcy[1], Anthony Dyson[6], Wilfrid Farabolini[7], Simon Hooker[6], Carl A. Lindstrøm[1], Martin Meisel[1], Jan-Hedrik Roeckemann[1], Lucas Schaper[1], Kyrre Ness Sjobaek[2], Matthew Wing[8], Jens Osterhoff[1]

1. DESY
2. University of Oslo (NO)
3. University of London (GB)
4. RadiaSoft LLC
5. CERN
6. University of Oxford
7. Université Paris-Saclay (FR)
8. University College London

The future (and potential limitations) of compact particle accelerator technology depends on the ability to characterize and manipulate the conditions in plasma discharge devices, such as plasma targets and active plasma lenses (APLs).

For many high energy physics applications and novel radiation sources, high repetition rates are required. For example, the FLASHForward [1] experiment at DESY aims to use beam-driven plasma-wakefield acceleration (PWFA) to produce GeV electron beams of sufficient quality to allow for free-electron laser gain, and plans to investigate the efficacy of PWFA at repetition rates up to the MHz level. The plasma-forming discharge causes an increase in temperature and pressure and an expansion of the plasma, and the time required for the plasma conditions to relax to a state that does not affect the formation of subsequent wakefields places a limit on the repetition rate [2].

APLs are gas-filled capillary discharge devices that can provide strong radially-symmetric focusing fields in an extremely compact size. Within the capillary an electron temperature profile develops via competition between the current heating and heat lost to capillary wall. A non-uniform radial temperature profile results in a non-linear radial magnetic field profile contributing to emittance growth, and the temporal development of this phenomena is critical to the operation of aberration-free APLs [3,4].

In this study, we investigate the heating and subsequent cooling phases of plasma capillaries after the initiation of a current discharge, to comment on the operation of high-repetition rate PWFA and aberration-free APLs.

[1] A. Aschikin et al., Nucl. Instr. Meth. Phys. Res. A, 806, 175 (2016)

[2] A. J. Gonsalves et al., J. Appl. Phys., 119, 033302 (2016)

[3] C. A. Lindstrøm et al., Phys. Rev. Lett., 121, 194801 (2018)

[4] J. van Tilborg et al., Phys. Rev. Accel. Beams, 20, 032803 (2017)

PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION: AWAKE AT CERN - CONCEPT, EXPERIMENT AND LATEST RESULTS

Mathias Hüther[1]
1. Max-Planck-Institut fur Physik (DE)

The Advanced Wakefiled Experiment (AWAKE) at CERN is a proof-of-principle experiment for the concept of a proton-driven plasma-wakefield accelerator. In AWAKE, electrons are externally injected in wakefields driven by the 400 GeV proton beam of the Super Proton Synchrotron (SPS) and accelerated over 10 meters of plasma up to energies in the GeV range.

We have shown that in plasma the initially long proton bunch is subject to the Seeded Self-Modulation (SSM) process. By self-modulation of the beam density, the proton bunch is transformed into a train of micro-bunches, which resonantly drives wakefields. Low energy electrons ($\sim$ 18 MeV) externally injected into the wakefields reached energies up to 2 GeV.

The physics of SSM, the experiments and a sample of experimental results obtained so far will be presented.

Furthermore, we show first results on the appearance of the Hosing Instability (HI), another transverse beam-plasma instability with a growth rate similar to that of the Self-Modulation Instability (SMI). The HI is caused by a small displacement of the proton bunch density distribution with respect to the bunch propagation axis. When the Self-Modulation process is not seeded, the hosing grows starting from noise and can overcome the SMI, leading to a break-up of the micro-bunch structure. In a plasma wakefield accelerator, this would drastically reduce the useful acceleration length. Even though, the HI is not a limitation for AWAKE as it mainly appears at lower plasma densities than the one optimum for acceleration, a better understanding of the physical processes is needed.

ACCELERATION OF HELICAL ELECTRON BEAMS USING LIGHT SPRINGS

José Tito Mendonca[1]
1. IPFN - Instituto Superior Tecnico, Univ. Lisboa, Portugal

The study of laser-matter interactions using twisted laser beams has received considerable attention in recent years. It is well known that photon states in such twisted beams carry a finite amount of orbital angular momentum (OAM). If instead of vacuum we consider propagation in a plasma, the twisted photons are modified. We can also define twisted plasmons, which are nothing but longitudinal photons with OAM.

In a recent work [1], we have started exploring a new paradigm for laser-plasmas interactions: the physics of light springs. They can be seen as a special arrangement of twisted waves, which have a twist in energy density, and not only in field amplitude.

Here we summarise the relevant aspects of light springs in laser-plasma interactions and explain the qualitative differences with respect to the usual twisted waves. Light springs allow us to explore new radiation and acceleration phenomena. In particular, we consider their possible use for acceleration of helical particle beams. Simultaneous acceleration of electron beams in different helical states, and compression of XUV radiation in Free Electron Lasers (FEL) using light springs, will be described. Work in progress will also be presented.

[1] J. Vieira, J.T. Mendonca and F. Quéré, Phys. Rev. Lett. 121, 054801 (2018).

STUDY OF THE EFFECTS OF LASER PULSE INTENSITY MODULATIONS ON THE PLASMA OSCILLATIONS AND ELECTRON ENERGY GAIN IN THE BUBBLE REGIME.

Anatoliy Shapolov[1], Balazs Fekete[1], Matyas Kiss[1], Sandor Szatmari[2], Sergei Kukhlevsky[1]

1. Institute of Physics, University of Pecs

2. Institute of Physics, University of Szeged

The study was evaluated on a hydrogen Z-pinch plasma guiding channel generated by a fast discharge in a capillary with diameter of 3 mm and length of 50 mm. By using the 1D MHD model a radial distribution of the electron density profile was computed which capable for guiding the high intensity TEM_{00} mode CO_2 laser pulse with input spot size of 150 μm and peak intensity of 10^{18} W/cm^2. Intensity modulation of the laser pulse was obtained by inverse Fourier transform after wave optics computations performed on the plasma guiding channel in the frequency space. For demonstrating the effects of intensity modulations on the plasma oscillations and electron energy gain in the bubble regime a density perturbation and a Particle-In-Cell (PIC) model was used, respectively. The former model provides exact value of plasma frequency and its wavelength at each point of domain, so that it was used to compare the discrete plasma frequency with the continuous one. In order to minimize the difference between two plasma frequencies a coupling factor was introduced. The PIC simulations showed that during the propagation time the electrons gain their energy in cascaded way and this process is in sync with the intensity modulations.

This study was supported by the Human Resource Development Operational Program (contract EFOP-3.6.2-16-2017-00005).

EXPERIMENTAL DEMONSTRATION OF A LASER PROTON ACCELERATOR WITH ACCURATE BEAM CONTROL THROUGH IMAGE-RELAYING TRANSPORT

Chen Lin [1], Jungao Zhu[1], Minjian Wu[1], Qing Liao[1], Yixing Geng [1], Kun Zhu[1], Chengcai Li [1], Xiaohan Xu[1], Dongyu Li[1], Yinren Shou[1], Tong Yang[1], Pengjie Wang[1], Jiaer Chen [1], Yanying Zhao [1], Wenjun Ma[1], Haiyang Lu[1], Xueqing Yan[1]
1. Peking University

Laser proton accelerator has been considered as one promising candidate for the future compact and low-cost radiotherapy system for malignant tumors. A Compact LAser Plasma Accelerator (CLAPA) has been built at Peking University, which can reliably generate and transport MeV energy protons with designed charge, spot and energy spread on to the irradiation platform. The transverse geometric emittance of laser accelerated proton beam entering the beam line has been measured using the quadruple triplet scan technique, showing a level of a few mm•mrad, which is comparable with the one from conventional accelerator. The energy accuracy of the laser accelerator is tested with a foil shielding method and is better than 3%. With the accurate beam control, Spread-out Bragg peak (SOBP), is demonstrated, for the first time, based on laser accelerated proton beams. Although the energy is low, it proves the ability of laser accelerator and takes the first step toward the future proton cancer therapy. As the next step, a full functional beam therapeutic bean line based on PW laser proton accelerator is proposed, aiming to effectively transport laser accelerated proton beam up to 250 MeV with 10-20% energy spread

THE EFFECT OF AN OBLIQUE MAGNETIC FIELD ON THE ELECTRON ACCELERATION IN A LASER-PRODUCED ION CHANNEL

Ameneh Kargarian[1]
1. Plasma physics research Institute

In this paper, we have obtained the analytical expressions for the acceleration of an electron by a plasma wave in the presence of an ion channel under the effect of an obliquely applied external magnetic field. A three dimensional single particle code is used for numerical calculation. In this configuration, plasma wave propagates along z-axis while the magnetic field is in x-z plane (angle θ with z-axis). The numerical results are presented for the electron energy gain and its trajectory. A comparative study of the gains shows that best results can be obtained with an external magnetic field under specific angle.

PRACTICAL TUNABLE ELECTRICALLY SMALL ANTENNA DESIGN FOR TRANSPORTABLE IONOSPHERIC HEATING

Benedikt Esser[1], James Dickens[1], John Mankowski[1], Andreas Neuber[1]
1. Texas Tech University

A tunable electrically small antenna (ESA) designed for transportable ionospheric heating (TIH) is presented as a practical implementation of a previously presented, basic design. Traditionally, Ionospheric Heating is achieved using large multi-element arrays of dipoles or similar antennas. One such array, the HAARP IRI, occupies 0.14 km2 in Gakona, Alaska with 180 crossed dipole elements. The presented research is aimed at eventually reducing the footprint of the array such that it becomes transportable enabling the study of ionospheric effects at any accessible location on the globe, including previously unstudied equatorial regions where the Earth's magnetic field is nearly parallel to the ground. Utilizing a vertically oriented capacitive gap in a capacitively loaded loop (CLL) coupled to a small loop antenna (SLA) driven element, the design covers a range of frequencies suitable for TIH – 3 to 10 MHz (30-100 MHz in 1/10th scale) – with greater than 80% efficiency across the range, whilst being a fraction of the size of an equivalent dipole. A natural match to a 50 Ω source negates the need for any lossy matching networks and allows for a more compact and efficient transmitter system. The CLL, comprised of two quarter-cylinder shells and two capacitor plates, are hinged to allow for tuning of the CLL capacitance thereby tuning the resonant frequency of the antenna. Additionally, tuning of the coupling between SLA and CLL is added to maintain the good port matching and gain with decreasing frequency throughout the tuning range. An electro-mechanical tuning system implemented on the prototype antenna with stepper motor driven components enables continuous angle tuning of 0-16° included and 90-14° with respect to the ground plane for CLL and SLA, respectively. A gain of approximately 5 dBi is observed in simulation with a similar measured result.

ROLE OF PHOTON PROCESSES IN THE RF BREAKDOWN OF AIR*

Xiaoli Qiu[1], Benedikt Esser[1], John Mankowski[1], James Dickens[1], Andreas Neuber[1], Ravi Joshi[1]
1. Texas Tech University

The behavior of the breakdown in air at RF frequencies for different gap lengths has been studied numerically at atmospheric pressure. The focus here is on gap lengths in the 1–5 mm range. A numerical analysis based on Monte Carlo calculations as discussed previously [1] is applied, with explicit inclusion of photon processes. The simulation results are compared with experimental data obtained within our group on RF breakdown in air at atmospheric pressure. The inclusion of photon-assisted charge growth through the photoemission process, is shown to serve as a delayed but continuous sources of electrons. This works to effectively lower the breakdown threshold, especially in geometries consisting of large area electrodes separated by short gaps, much smaller than the electrode areal dimensions.

The simulated predictions match the breakdown data quite well for the tested gap lengths. In addition, frequency-dependent breakdown fields are also obtained through the Monte Carlo calculations. A general U-shaped characteristic with frequency results. These trends as well as other features of the RF breakdown, with the important role of photons, will be presented and discussed.

[1]. H. Nguyen, J. Mankowski, J. C. Dickens, A. A. Neuber, and R. P. Joshi, ”Model Predictions for Atmospheric Air Breakdown by Radio-Frequency Excitation in Large Gaps,” Physics of Plasmas, vol. 24, 073505 (2017).

* This work was supported by an AFOSR Grant # FA9550-18-1-0062 on “Multipactor and Breakdown Susceptibility and Mitigation in Space-Based RF Systems“, and by Grant #A19-0103-001.

NUMERICAL EVALUATION OF MULTIPACTOR IN RECTANGULAR WAVEGUIDES PROBED BY THE EVOLUTION OF ELECTRON DISTRIBUTIONS*

Hieu Nguyen[1], Xiaoli Qui[1], John Mankowski[1], James C. Dickens[1], Andreas A. Neuber[1], Ravi P. Joshi[1]
1. Texas Tech University

Multipactor in a rectangular waveguide is probed that circumvents the cumbersome computations of the Monte Carlo method. A one-dimensional model based on the Vlasov equation is used to obtain the electron distribution f(x,t) in this collisionless regime. The time-evolution of the electron swarm, role of the driving RF field and secondary electron generation, are all comprehensively included is simulated. Details of the secondary electron generation t the boundaries is taken into account. The model thus allows for the study of potential multipactor growth inside waveguides as a function of dimension, external field strengths, operating frequency etc. This scheme is general, and can be extended to include both the spatial and energy-dependent distribution f(E,x,t).

Curves obtained for the electron population were compared to results of a Monte Carlo method [1]. A typical result in growth of electron energy distribution due to different excitation field magnitudes with secondary emission from copper surfaces shows the electron population either increasing or decreasing or staying roughly constant, depending on the applied electric field strength.

[1]. H. K. A. Nguyen, J. Mankowski, J. Dickens, A. Neuber, and R. P. Joshi, ”Calculations of Multipactor Growth in Rectangular Waveguide,” IEEE Trans. Plasma Sci. 47, 1364 (2019).

* This work was supported by an AFOSR Grant # FA9550-18-1-0062 on “Multipactor and Breakdown Susceptibility and Mitigation in Space-Based RF Systems.”

Authors: Hieu K. A. Nguyen, Xiaoli Qiu, John Mankowski, James C. Dickens, Andreas A. Neuber and Ravi P. Joshi

A 2.85 GHZ PULSED RF SOURCE FOR MULTIPACTOR RESEARCH UTILIZING GAN HEMTS CAPABLE OF 2 KW

Benedikt Esser[1], Zachary Shaw[1], James Dickens[1], Andreas Neuber[1]
1. Texas Tech University

A high average power, pulsed RF source operating at 2.85 GHz is described for use in multipactor research. Four state of the art GaN HEMTs from Cree/Wolfspeed capable of 700 W in long pulse mode ($\sim$ 100 μs) each are combined for a total maximum power output of 2.8 kW with a rated output of 2 kW total. A low phase noise, free running 55 MHz modulation capable VCO is used as the RF source, buffered and amplified by a LNA. Generation of a 100 μs drive pulse is accomplished via a TTL switch with a rise time of 25 ns and a typical switching time of 35 ns driven by a pulse/delay generator. The pulse is further amplified by a microwave amplifier providing the majority of gain in the system, 45 dB, and the 6 W required for the final stage. A CGHV31500F GaN HEMT amplifier is used to amplify the signal to the required 50.5 dBm ($\sim$112 W) with split feeding of the final output stage consisting of four additional parallel connected GaN HEMTs. Each of the four has 12.5 dB of gain, providing 500 W for a combined output of 2 kW. An in-line attenuator provides the operator output power control in the range of approximately 42 to 64 dBm (16 to 2,800 W). A custom control PCB was designed to control, bias, and sequence the various parts of the source. Custom power splitters and directional couplers capable of high power were designed for the system. The amplifier enables multi-carrier mode amplification as well as modulated output amplitudes. A ring resonator is used to study the multipactor phenomenon in a WR284 waveguide section, increasing the effective power to approximately 40 kW, with a high impedance section where the phenomenon is observed within the tapered impedance transformer.

NUMERICAL EVALUATIONS OF ENERGY-DEPENDENT SECONDARY ELECTRON EMISSION BY INCIDENT ELECTRONS AND CHARGED IONS*

Hieu Nguyen[1], Xiaoli Qiu[1], Joy Acharjee[1], John Mankowski[1], James C. Dickens[1], Andreas Neuber[1], Ravindra Joshi[1]
1. Texas Tech University

Multipactor is known to jeopardize the performance of vacuum electronic devices and high-power microwave systems. Though most treatments have focused on the secondary emission from incident primary electrons, the overall process is quite complicated. It involves not just the role of primary electrons, but also the effects of incident ions that might produce secondary electrons and/or cause heating of the surface layer due to the inelastic collisions as they enter the target electrode. Here we assess the secondary electron yield (SEY) as a function of the incident energy and angle of primary electrons. In addition, the potential for secondary electron emission by incident ions is also probed. Monte Carlo simulations are used along with the Furman-Pivi [1] formulation for electron-initiated SEY. Helium is used as a simple example ion. Finally, temperature increases produced at and near the electrode surface due to ion impact is also modeled based on Molecular Dynamic simulations. The values form the basis for temperature driven out-gassing from the surface, a process that will also be treated with discussion of results.

[1]. M. A. Furman and M. T. F. Pivi, "Probabilistic model for the simulation of secondary electron emission," Phys. Rev. Accel. Beams, vol. 5, no. 12, p. 124404, 2002.

* This work was supported by an AFOSR Grant # FA9550-18-1-0062 on "Multipactor and Breakdown Susceptibility and Mitigation in Space-Based RF Systems", and the Office of Naval Research (N00014-18-1-2382).

Authors: Hieu K. A. Nguyen, Xiaoli Qiu, Joy Acharjee, John Mankowski, James C. Dickens, Andreas A. Neuber and Ravi P. Joshi

DESIGN AND IMPLEMENTATION OF AN ULTRA-WIDEBAND MULTIPACTOR TEST CELL

Mirhamed Mirmozafari[1], Sirous Nourgostar[1], Dan Enderich[1], Nader Behdad[2], John Booske[2]

1. University of Wisconsin-Madison

2. Electrical and Computer Engineering Department University of Wisconsin-Madison

Multipactor is cascade avalanche growth of free electrons in RF components under vacuum. In two-surface multipactor, a free electron gets accelerated by electric field and impacts a facing surface with enough energy to liberate secondary electrons. Cascade evolution of these electrons under certain conditions can load and short circuit the RF power.

We will discuss the design and implementation of a test cell to study multipactor susceptibility and suppression in two-surface RF components. The cell was designed with a gradual transition from a coaxial line to a planar microstrip line. This allows for multipactor research over a wideband frequency range from DC to 1.5 GHz. A centered transmission line was designed, minimizing the disturbance of the fields and resulting in a low reflection of less than -30 dB over the entire frequency range. While the ending coaxial lines are fixed, a planar multipactor center section is replaceable and can stand above the ground plane with an adjustable gap distance. This platform facilitates the multipactor test with a wide range of gap dimensions, frequencies, surface treatments, and geometrical modifications.

The above-mentioned transmission line is situated in an ultra-high-vacuum chamber that simulates the low-pressure environment in space-based applications. A chain of vacuum pumps including scroll pump, turbo, and ion pumps bring the chamber pressure down to 10×e-8 Torr. The vacuum chamber has multiple arms which makes it possible to seed and collect electrons concurrently. Electron seeding is carried out using the photoelectric process. An ultraviolet LED creates UV light with a wavelength of 265 nm whose photon has enough energy to free electrons out of copper. The LED's light is transferred into the vacuum chamber through fiber patch cords and focused onto the multipactor section.

Work supported by Air Force Office of Scientific Research MURI grant FA9550-18-1-0062.

MAP-BASED MULTIPACTOR THEORY FOR TWO-CARRIER OPERATION

Moiz Siddiqi[1], Rami Kishek [1]
1. University of Maryland, College Park

Multipactor is a vacuum discharge based on secondary electron emission that plagues microwaves devices, accelerator structures, and space-borne systems [1]. A novel theory based on principles from nonlinear dynamics and chaos theory has been introduced, in which all possible modes are recovered with no a priori assumptions on the electron trajectories [2-3]. The new methodology systematically applies iterative maps to identify multipacting boundaries more reliably and comprehensively than existing models. It does so by globally analyzing the structure of dynamical space, resulting in bifurcation diagrams that predict susceptibility to multipactor over a wide range of parameters.

This model is generalized to multi-carrier operation, as found in modern space-communication devices [4]. These systems, where several radio-frequency (RF) carriers coexist, are especially challenging to analyze with conventional methods. As a result, little theoretical study on this area has been done [5-6]. Since the map-based theory rapidly scans vast areas of parameter space with no a priori assumptions, it is ideally suited to analyze this problem. This is illustrated for the lowest-order system, namely two RF carriers. Validation is conducted by scanning, in both the theory and the simulation, parameters such as the field strengths and geometry dimensions. The resulting multipactor growth rates are then compared, validating the accuracy of theoretical predictions. The effects of the second RF carrier on multipactor suppression are presented.

[1] J. R. M. Vaughan, IEEE Trans. Electron Devices 35, 1172 (1988).

[2] R.A. Kishek, Phys. Plasmas 20, 056702 (2013).

[3] M. Siddiqi and R.A. Kishek, Proc. MULCOPIM 2017.

[4] T.P. Graves, “Standard/Handbook for Multipactor Breakdown Prevention in Spacecraft

Components”, Aerospace Report No. TOR-2014-02198 (2014).

[5] S. Anza, M. Mattes, C. Vicente, J. Gil, D. Raboso, V.E. Boria, and B. Gimeno, Phys. Plasmas

18 032105 (2011).

[6] A. Iqbal, J. Verboncoeur, and P. Zhang, Phys. Plasmas 25, 043501 (2018).

THE CELL ACTIVATION PHENOMENA IN THE COLD ATMOSPHERIC PLASMA CANCER TREATMENT

Dayun Yan[1], Wenjun Xu[2], Li Lin[1], Jonathan Sherman[3], Michael Keidar[1]
1. The George Washington University
2. State Key Laboratory of Electric Insulation and Power Equipment,
3. Neurological Surgery

Cold atmospheric plasma (CAP) showed a promising application in cancer treatment through dozens of demonstrations. The activation phenomenon of the CAP-treated cancer cells is a new concept in plasma medicine. In plasma medicine, a basic concern is the role of CAP during the treatment. Our recent experimental evidence demonstrated that CAP plays at least two important roles during the cancer treatment in vitro. The first role is providing abundant reactive species in the extracellular environment such as in medium. The second role is the CAP-triggered activation of the cancer cells, which may be a unique feature of CAP treatment. Despite the CAP-triggered activation will not cause noticeable cytotoxicity on the cancer cells, such activation drastically decreases the threshold of these cancer cells to the cytotoxicity of reactive species particularly ROS. A quick sensitization and slow desensitization are two features of such activation. The activation started since the 2nd second in CAP treatment. In contrast, a full de-sensitization process of the activated cancer cells last 5 hours after a CAP treatment. This discovery drastically changes our previous understanding of the anti-cancer mechanism of CAP treatment. The activation phenomenon during the direct CAP treatment explains the stronger anti-cancer effect of a direct CAP treatment compared with an indirect CAP treatment based on the CAP-treated solutions. Recently, we demonstrated that the flow rate of helium, the discharge voltage and the discharge frequency can affect the activation state of the CAP jet-treated cancer cells. Among the three basic operational parameters, a medium discharge voltage (3.78 kV) can cause the strongest activation effect. In addition, we recently also demonstrated that a nanosecond-pulsed magnetic field generator (NMF) could sensitize the melanoma cell line B16-F10 to the cytotoxicity of a ROS, H_2O_2. The NMF treatment alone did not noticeably inhibit the growth of melanoma cells.

MATHEMATICAL MODELING OF TUMOR GROWTH AND RESPONSE TO ELECTROCHEMOTHERAPY

Jennifer Firehammer[1], Lakshya Mittal[1], Matthew DeWitt[2], Raji Sundararajan[1], Allen Garner[1]

1. Purdue University

2. Luna Innovations

Electrochemotherapy, the application of electric pulses (EPs) in combination with chemotherapeutic injection, drastically increases the effectiveness of cancer therapy. Such combinations enhance the ability of tumor cells to absorb chemotherapy drugs by permeabilizing cell membranes; however, optimizing this synergy for various EP parameters and drugs is poorly understood. This presentation investigates the response of immunogenic avascular tumors to chemotherapy and EPs individually and to electrochemotherapy to quantify the synergy between treatments. We modify a previously derived mathematical model [1] to specifically quantify the synergy for cisplatin and bleomycin compared for different EP conditions. Development of a 3-D artificial tumor model to extend this mathematical model and parameter assessment independent of physiological complications, such as the immune system, will be discussed.

SINGLE CELL LASER MEDIATED MOLECULE DELIVERY – INFRARED LASER BASED MICROINJECTION

Vasile Neculaes[1], Allen Garner[2], Dylov Dimitry, Loghin Evelina[3]
1. GE
2. Purdue University
3. GE Global Research

Single cell microinjection is a powerful technique used to introduce exogenous material into cells and to extract and transfer material between cells. Traditional microinjection is a purely physical mechanism that does not require other compounds, amplifies the physical effects of the injected substances, provides precise volume and timing control for intracellular delivery, requires less material, and facilitates experimental consistency by allowing the untreated cells to serve as the control. However, microinjection is extremely labor intensive and expensive.

This presentation outlines the development of a new laser-based single cell injection method that is inexpensive, user-friendly, rapid, user-friendly, independent of operator skill, and minimized consumables. While previous studies have demonstrated promising results for single cell laser injection using femtosecond lasers, mostly at 800 nm, these offerings are expensive (the laser alone costs $\sim$\$100k) and do not always achieve the users'expectations. On the other hand, 1550 nm fs lasers are almost an order of magnitude less expensive than 800 nm lasers. We previously showed that a 1550 nm wavelength laser permeabilized multiple cells because the greater water absorption induced greater membrane temperature gradients, which enhance membrane permeabilization [2]. This presentation extends this work by targeting a single cell of interest with a 1550 nm commercial femtosecond laser. We summarize the hardware, control software, their integration, innovative beam alignment methods, and preliminary results for propidium iodide and plasmid delivery.

[1] A. L. Garner, V. B. Neculaes, M. Deminsky, et. al, “Plasma membrane temperature gradients and multiple cell permeabilization induced by low peak power density femtosecond lasers,” Biochem. Biophys. Rep., vol. 5, pp. 168-174, 2016.

[2] J. Song, A. L. Garner, and R. P. Joshi, ”Molecular dynamics assessment of the role of thermal gradients created by electromagnetic fields on cell membrane electroporation,” Phys. Rev. Appl., vol. 7, 2017, Art. no. 024003.

ELECTROCHEMOTHERAPY ENHANCES THE CURCUMIN EFFECT ON TNBC CELLS IN A DOSAGE AND ENERGY DEPENDENT MANNER

Lakshya Mittal[1], Allen Garner[1], Ignacio Camarillo[1], Xinhua Chen, Ravi Joshi[2], Raji Sundararajan[1]

1. Purdue University

2. Texas Tech University

Compared to other breast cancer phenotypes, triple negative breast cancer (TNBC) has a much lower five-year survival rate (30% compared to 66%) because it is refractive to standard chemotherapy since it lacks three main receptors. Thus, TNBC requires alternative treatment modalities. This motivates our study of treating TNB with electrochemotherapy (ECT) using curcumin, the yellow pigment of turmeric, which is loaded with anticancer phytochemicals with minimal side effects and lower expense than traditional chemotherapeutics.

We treat MDA-MB-231 cells, and aggressive, human TNBC cell line, with 10μM or 25μM curcumin exposed to four, ten or twenty 100 μs electric pulses (EP) of 1200 V/cm to establish a correlation between the applied energy and cell death. The 24 h cell viability results show that combining EPs with curcumin effectively targets TNBCs in a curcumin dosage and EP energy density dependent manner. The viability for 10μM and 25μM curcumin alone samples did not differ significantly from control (100%). The viability was 32% and 43% for 20 and 10 EPs, respectively with no curcumin added; however, the viability was 17% and 85% for 10 and 4 pulses, respectively, with 25 μM curcumin. The highest cell death (5% viability) was achieved for 20 pulses with 25 μM curcumin. These results highlight the synergy of EP and curcumin against aggressive TNBC cells and the potential of using EP energy density to tune cellular responses. The low cost and natural herbal anticancer properties of curcumin could make this therapy an attractive alternative for TNBC treatment. Further potential tuning using a multi-electrode system was assessed using finite-element simulations. Such evaluations allow us to assess the field intensity and profile in the vicinity of a tumor target to help predict parameters for ultimate clinical applications. The implications of these results on guiding future in vivo work will be discussed.

THE INFLUENCE OF SURFACE HUMIDITY ON DISINFECTION USING COLD PLASMAS

Ankit Moldgy[1], Gaurav Nayak[1], Hamada Aboubakr[2], Sagar Goyal[2], Peter Bruggeman[1]

1. Department of Mechanical Engineering, University of Minnesota

2. Veterinary Diagnostic Laboratory, University of Minnesota

Increased risks due to outbreaks of foodborne viruses and bacteria give us strong motive for the development of a viable non-thermal technology for the disinfection of foods and their contact surfaces. Plasma discharges occurring in the presence of oxygen and nitrogen generate an abundance of reactive oxygen and nitrogen species (RONS) at close to ambient temperatures. With minimal requirements for addition of any chemicals, disinfection using atmospheric pressure air plasmas could be a sustainable and green non-thermal technology.

This work attempts to study the dependence of the biocidal activity of plasma sources on surface humidity of the sample used. Cold plasmas at atmospheric pressure were employed for in vitro treatment of pathogens spiked on stainless steel surfaces. The discharge effluent was used to treat the samples at both dry and wet surfaces.

Plasma treatment was ineffective against dry samples. Similar humidity effect has been found in food science where lipid oxidation rates are triggered only beyond a threshold level of water activity. While wet virus samples were much more susceptible to plasma treatment, the effect was strongly dependent on the amount of water on the surface. An analysis of the transport of long-lived reactive species into aqueous phase, eventually responsible for microbial inactivation, will be presented. The present findings suggest that the control of sample surface humidity is crucial for effective and reproducible plasma-based disinfection.

Acknowledgement: This work is partly supported by USDA, National Institute of Food and Agriculture (2017-67017-26172) and DOE, Office of Fusion Energy Sciences (DE-SC0016053).

COMPARISON OF PLASMA SPORICIDE USING DIFFERENT POWER SOURCES IN ATMOSPHERIC-AIR

Hao Wang[1], Liyang Zhang[1], Haiyun Luo[1], Xinxin Wang[1]
1. Tsinghua University

Hao Wang, Liyang Zhang, Haiyun Luo * and Xinxin Wang

Department of Electrical Engineering, Tsinghua University Beijing 100084, China

*Email: lhy@tsinghua.edu.cn

The sterilization of spores (sporicide) is a stubborn problem, since the firm exterior and dipicolinic acid (DPA) provide remarkable resistance of spores. Conventional methods, such as heat, UV, chemical sporicide, are usually hard to achieve sterilization effect. We used DBD pulsed plasma in air at atmospheric pressure to treat the Bacillus subtilis spores on biological indicator. The results suggest that the plasma treatment could achieve sterilization within 70s. To research the main factors of plasma sporicide, we compare the killing effects with plasmas produced by a pulse power source and an AC power source, and the result indicates that the pulse power source works far better. The transmission electron microscope (TEM) of two experiment groups show that the spore surfaces are more severely damaged in pulse power source. Analyzing the breakdown voltage and the spectrum, we infer that the higher electron field and higher electron energy by pulse power source are the key factors to destroy the exterior and DPA of bacteria spore and then kill protoplasm. This experiment prove that the pulse power source plasma is a better choice to sterilize the spores. This work is supported by the National Key Research and Development Program under contract 2017YFC1200404.

A NOVEL DEVICE ENHANCED THE ACTIVE ANTIMICROBIAL COMPONENTS IN THE PLASMA TREATED SOLUTION

Hangbo Xu[1], ruonan Ma
1. zhengzhou university

The plasma have shown a wide application prospect in sterilization, such as the medical device disinfection,tooth whitening and fruit preservation. Among these plasma generator devices, the surface dielectric barrier discharge plasma have been widely researched. This kinds of plasma device have a feature that the plasma generated area is bigger than plasma jet. But, as the the active species is short-lived and the transfer distance is extreme short, Neither the directly reached RONS nor the plasma-liquid reaction regenerated RONS generally accumulated in the surface layer of liquids. So in this experiment, a magnetic stirring apparatus was designed and utilized to enhance the solution streaming when the solution was treated by plasma.

By adjusting the rotational speed, we treated several group of solution. The short-lived ·OH and long-lived H2O2 were measured. Apart this the ORP and pH were detected, which can indicate the electrochemical properties. Analyzed these parameters, we can find the streaming of solution influence the amount of RONS in the solution. Besides, we choose yeast as a model cell to study the specific difference under the streaming or not. The yeast after treated were examined via colony forming unit (CFU) count, and further verified by LIVE/DEAD staining and scanning electron microscope (SEM).

HIGH POWER DIELECTRIC DIODE STUDIES AT SANDIA NATIONAL LABORATORY

MICHAEL MAZARAKIS[1], JONATHAN CUSTER[1], MARK KIEFER[2], JOSHUA LECKBEE[1], DEL ANDERSON[3], RAYMOND CIGNAC[3], TRINH TUNG[3], FRANK WILKINS[3], ROBERT OBREGON[3]

1. SANDIA NATIONAL LABORATORY

2. SANDIA NATIONSAL LABORATORY

3. nATIONAL SECURITY TECHNOLOGIES

We recently continued the pioneering work done by Chris Rose and Kalpac Dighe at Los Alamos National Laboratory. ("Multiple-Pulse High-Voltage Diode Isolation Testing for a Linear Accelerator (LIA)" B. Trent McCuistian, Dale Dalmas, Kalpak Dighe, Chris Rose, Manolito Sanchez, Robert Sedillo, J. Martin Taccetti, in Proceeding of the 2017 Pulsed Power Conference at Brighton, England, June 2017). We did not use Blumleins (240kV) but 30 Ohm cable pulsers. Hence, our setup was limited to 100kV maximum testing across the diode cartridges. Therefore, we were forced to test only diode cartridges of $\sim$ 40% the scale of that of LANL. Our research was mainly concentrated on the physics of semiconductor diodes and especially on measuring the reverse recovery times and currents. In addition, we explored the effect of the reverse bias pulses on a diode still under reverse recovery times. We utilized our Component Test Stand facility (CTS) ("Testing High Voltage (200kV) DC cable and feed-through designs in rep-rated modes" Michael G. Mazarakis, Mark L. Kiefer, Joshua J. Leckbee, Del. H. Anderson, Frank L. Wilkins, Robert J. Obregon, in Proceeding in Proceedings of the 2017 Pulsed Power Conference at Brighton, England, June 2017.) modified to power two diode cartridges connected in parallel to a common load (CTS-II). Although our set up could deliver two separate pulses per diode assembly, in this study, for simplicity's sake, we utilized only one pulse per diode. The cartridges were composed of 6 to 12 stages each and having three to five high power 10kV diodes.

* Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

FIELD-CIRCUIT COUPLING SIMULATION OF PETAWATT-CLASS Z-PINCH ACCELERATOR

QUAN ZHOU, Xiaobing Zou[1], Xinxin Wang[1]
1. Tsinghua University

Most of the previous studies of petawatt-class Z-pinch accelerator are performing the circuit simulation based on a full circuit model. This model may cause non-ignorable error because it is under the assumption of TEM modes transmission along the MRTLs. In this paper, a method for field-circuit coupling simulation of petawatt-class Z-pinch accelerator was developed, which considered the non-TEM modes in the MRTLs. A 3-D electromagnetic simulation of the MRTLs was conducted and MRTLs'equivalent circuit was created based on the scattering transfer parameters drawn from the electromagnetic simulation. By inserting the MRTLs'equivalent circuit into the pulsed generators and Z-pinch load, a field-circuit coupling model of the whole petawatt-class Z-pinch accelerator was obtained. This method was used in the simulation of Z800 accelerator, a petawatt-class Z-pinch accelerator, and the load was a wire-array for Z-pinch. Compared to the previous circuit model, the load current obtained with the field-circuit coupling model was lower and thus the load-implosion time was longer. Then we compared the load current of accelerators using exponential, hyperbolic and linear MRTLs respectively and recommended the linear one. The relation between the energy transmission efficiency and load parameters were also investigated.

COMPACT MARX GENERATOR TO DRIVE A LOW-IMPEDANCE MILO

Tyler Buntin[1], James Dickens[1], Andreas Neuber[1], Ravi Joshi[1], John Mankowski[1], Matthew Abide[1]
1. Texas Tech University

A low-impedance MILO is being developed at Texas Tech University, and a compact Marx generator was designed to drive it. The target design goals of the Marx are an output voltage greater than 500 kV and an output current greater than 40 kA. Risetime needs to be sub 150 ns and the pulsewidth must be greater than 100 ns. These performance goals were determined from PIC simulation of the MILO such that an RF efficiency (>10%) and RF peak power (> 1 GW) can be achieved.

Tests using smaller 3 and 4 stage Marx generators with the same topology as the final design were used to determine a per-stage inductance of approximately 120 nH. From this derived inductance, multiple configurations were simulated to decide upon the ideal design for the desired performance goals. From these simulations, an 18-stage Marx with 2 capacitors per stage was chosen as the most optimal design, and from simulations into a 12 Ohm load a number of the criteria can be met with this configuration.

The simulated peak voltage and current are 570 kV and 48 kA, respectively, while pulse risetime and pulsewidth are 170 ns and 540 ns, respectively. The designed Marx is being experimentally validated to confirm the findings of the simulation, firing into an approximately 12 Ohm water load to represent the low-impedance MILO that is being designed.

LARGE SCALE SYSTEM USING PULSED ELECTRIC FIELDS AS AN INVASIVE FISH BARRIER

Michael Kempkes[1], Timothy Hawkey[1], Ian Roth[2], Marcel Gaudreau[1]
1. Diversified Technologies, Inc.
2. Diversified Technologies, Inc

Invasive species, plants and animals introduced to ecosystems without natural predators or controls, are a global problem. The Asian Carp has invaded the Mississippi River Basin in the USA, and now threatens the Great Lakes. To prevent migration of this large invasive species into the Great Lakes, the US Army Corp of Engineers has built and operated two demonstration barriers in the Chicago Sanitary and Ship Canal since 2002. These barriers use pulsed electric fields to block Asian Carp from moving through the Canal, the primary connection between the Basin and Lake Michigan.

Diversified Technologies, Inc. was recently awarded a subcontract from exp Federal, under a prime contract from the US Army Corps of Engineers, to build the large pulsers required for a permanent barrier on the Canal.

This barrier uses bi-polar pulses driving an array of electrodes to create an electric field across the entire Canal. This barrier field will be sufficient to deter the Asian carp and even smaller fish from swimming upstream to Lake Michigan. This field must operate continuously, even in the presence of barges and ships. Two pulsers are planned, with the first in construction now. Each pulser includes:

• 4.5 MW, 4 kV DC power supply, with voltage regulation

• 4 MJ capacitor bank, which stores energy for the pulses

• Solid-state pulse switches, which produce currents up to 30 kA with a frequency of up to 100 Hz, and pulsewidths of 1 – 1,000 milliseconds

• Mechanical output reversing switch, allowing the pulse polarity on the electrodes to be reversed

This paper will detail the design and intended operation of this pulser, which will be the largest known PEF system in the world when completed.

This effort is funded under US Army Corps of Engineers contract W912P6-18-C-0021 with exp Federal.

ANALYSIS OF TRIGGERING BEHAVIOUR OF MARX GENERATORS BY USING SPICE SIMULATIONS

Benjamin Lassalle[1]
1. ITHPP

The basic operation of a Marx generator is well known and simple: capacitors are charged in parallel through high impedances and discharged in series, thus multiplying the output voltage compared to the charging voltage. As a basic explanation, in a Marx generator using spark gap switches, triggering the first stage is sufficient to double the voltage on the second stage's switch and so on. All the switches are then switched on in an avalanche mode. However, the behaviour is often more complex. The parasitic impedances of the geometry play an important role for the creation of overvoltages. This can make the design and the development of Marx generators quite challenging, especially when aiming for good reproducibility and precise timing.

To achieve the best performances, various triggering techniques have been developed, but unfortunately, there is no "best practice" technique that can be applied systematically. For each new design, the engineers must establish the best way to obtain the required performances. If the initial choice of the triggering scheme does not achieve the expected performances, a lot of time could be spent experimenting to optimize the triggering scheme. This study presents SPICE simulation methods that could be helpful to compare different triggering schemes and their effects on the generator erection time, jitter and reliability.

By using a spark gap model, the simulations presented give a thorough understanding of the benefits and drawbacks of the various available triggering schemes. These simulations could facilitate the optimization of the erection time and the delay by adjusting triggering methods. Secondly, by coupling LTspice and Python, a more complete approach is presented to take into account the statistical behaviour of the closing time of the switches and its effects on the jitter and the complete generator's operation efficiency.

CHARACTERIZATION OF NANO-SECOND PULSED POWER GENERATOR SYNCHRONIZING DOUBLE INDUCTIVE ENERGY STORAGE CIRCUITS WITH SEMICONDUCTOR OPENING SWITCH

Taichi Sugai[1], Kosuke Yawata[1], Yiwen Yang[1], Akira Tokuchi[2], Weihua Jiang[1]
1. Nagaoka University of Technology
2. Pulsed Power Japan Laboratory Ltd.

As a new method to enhance nanosecond pulsed power, aiming improvement of cold plasma applications, we designed a type of circuit that is amplified by synchronization of double simple inductive energy storage (IES) circuits with a semiconductor opening switch (SOS) diode. Secondary circuits of simple IES circuits which consist of capacitors, a pulse transformer, MOS-gated thyristors, and a SOS, were connected in parallel and in series, and power amplification has been succeeded at low repetition rate by synchronization of reverse currents through the SOS diodes in two circuits. However, there are some problems, e.g., synchronization deviation by variation of load and repletion rate, difficulty of circuit adjustment for synchronization, and low efficiency. Aiming to those improvement, characterization of the pulsed power generator was carried out by spice simulation and experimental circuit estimation. Our presentation details current and energy transfer path in the circuit including parasitic components, which were obtained from the circuit characterization.

MHD MODELING OF SHOCK PHYSICS EXPERIMENTS WITH THE PHELIX PORTABLE HIGH MAGNETIC FIELD DRIVER

Christopher Rousculp[1], M S Freeman , D A Fredenburg, F Fierro, J R Griego, F G Mariam, J T Bradley, L P Neukirch, D M Oro, A R Patten, R B Randolph, W A Reass, R E Reinovsky, A Saunders, Z Tang, P J Turchi, J T Dunwoody, T J Voorhees
1. Los Alamos National Laboratory

The PHELIX portable pulsed power driver has recently completed a set of experiments examining the response of granular material to convergent shock loading. Here a nearly 4 MA peak current is delivered to a Z-pinch load with a quarter wave cycle time of $\sim$3 us. This produces B $\sim$ 0.30 MG field at the surface of a $\sim$3 cm diameter, 1 mm thick, 3 cm tall Al liner. The liner is accelerated to $\sim$800 km/s before shock impacting a target cylinder filled with fine-grain CeO_2 powder. Design and analysis simulations are performed with 2D MHD Lagrangian/ALE code to predict the liner performance and material response. Computational results are compared to the PHELIX Faraday rotation measurements for load current as well as proton radiographic imaging of the evolution of the density profile in the CeO_2.

OPTICAL EMISSION BEHAVIOR OF ELECTRICAL WIRE EXPLOSIONS IN DIFFERENT MEDIA

Ruoyu Han[1], Jiawei Wu[2]
1. Beijing Institute of Technology
2. Global Energy Interconnection Development and Cooperation Organization

Characteristics of electrical explosions of Al, Ti, Fe, Cu, Mo, Ag, Ta, and W wires and fine graphite rods in air at room temperature and a pressure of 0.1 MPa were investigated. Additionally, Cu wires were exploded in 0.1 MPa He, 0.1 MPa Ar, and 0.1-0.3 MPa air to study the effects of gas type and ambient pressure on the explosion process. Experiments were undertaken with the SWE-2 equipment, which featured a sub-microsecond pulsed current source, a microsecond pulsed current source, a wire-loading receptor, a chamber, and a diagnostic system. The results indicated that the pulsed current parameters and the elemental compositions of the wire materials affected the explosion in several respects. In the case of the plasma radiation, the light intensity for non-refractory metals (Al, Cu, and Ag) decayed rapidly after the discharge ended. In contrast, for refractory metals (Mo, Ta, and W), the optical emission continued to increase and lasted for a relatively long period after termination of the discharge. In particular, the carbon plasmas appeared in the form of novel square-wave-like waveforms with high light intensity. In the case of the time-integrated spectra, the emitted radiation consisted of both line and continuous (bremsstrahlung-like) spectra. Moreover, as the atomic mass increased, e.g., from C to W, the intensities of the line spectra were gradually attenuated (under the energy level of SWE-2). It was also observed that much of the optical emission originated from the plasma formed within the explosion products themselves, and not from a possible surface flashover. A further notable feature was that the peak pressure of the shock waves was relatively low for refractory metals and high for non-refractory metals. Besides, there exists a positive correlation between the ambient gas pressure/stored energy and the peak pressure of the shock (pressure) waves.

CHARACTERISTICS OF NEGATIVE-POLARITY DC SUPERIMPOSED NANOSECOND PULSED DISCHARGE AND ITS APPLICATIONS

Hirofumi Yamashita[1], Yasuaki Torigoe[1], Douyan Wang[2], Takao Namihira[2]
1. Graduate School of Science and Technology, Kumamoto University - Japan
2. Institute of Pulsed Power Science, Kumamoto University - Japan

Non-thermal plasma generated by pulsed discharge is expected to efficiently treat combustion exhaust gases such as nitrogen oxide (NOx) and sulfur oxide (SOx) due to its high chemical activity. Nanosecond pulsed discharge which has voltage rise time and fall time of 2ns, pulse width 5 ns and peak value of 60 kV, has been developed by our group. Nanosecond pulsed discharge mainly consists of streamer discharge phase, so that heat loss which caused by glow discharge is less, and plasma impedance is kept almost constant during the streamer discharge phase. Therefore, impedance matching between pulsed power supply and discharge load is possible. Applications on ozone generation and NO treatment using nanosecond pulsed discharge are reported with high energy efficiency compared to other discharge methods. However, the discharge mode transit to arc discharge phase sometimes. Also, for industrial applications, the plasma processing capacity leaves room to improve. It has also been reported that negative polarity nanosecond pulse discharges give better results depending on the plasma processing applications. In this study, negative polarity DC superimposed nanosecond pulsed discharge is suggested in order to improve the better performance of the nanosecond discharge plasma. Results of ozone generation and NO treatment using negative polarity DC superimposed nanosecond pulsed discharge have also been introduced.

QUANTIFICATION OF OH RADICALS GENERATED BY NANOSECOND PULSED DISCHARGE PLASMA

Kiyotaka Okada[1], Kazuki Oishi[1], Shintaro Kodama[1], Douyan Wang[2], Takao Namihira[2]

1. Graduate School of Science and Technology, Kumamoto University - Japan
2. Institute of Pulsed Power Science, Kumamoto University – Japan

In conventional water treatment, waste water is purified by a biological method. However, this method has some problems, such as dissipation of time, high cost for treatment, necessity of large facilities, and existence of some pollutants that are not easily to be decomposed. Therefore, the development of advanced water treatment technologies that can solve those problems is required.

In recent years, discharge plasmas have been used as effective method for purifying environmentally polluted water. Some researchers reported that the species which have high oxidation potential, such as OH radical, O radical, O3 and etc., are produced by pulsed discharge plasmas generated in water surface. Among them, OH radicals have the highest oxidizing power.

In this work, OH radicals generated by the nanosecond pulsed discharge was evaluated using a chemical prove method. In this method, terephthalic acid (TA) was used as an OH radical scavenger and the given fluorescence of the resulted 2-hydroxyterephthalic acid (HTA) was measured. However, it can be estimated that the HTA in the reaction process could be destroyed by discharge afterwards. Furthermore, there is no report of OH radical measurement based on the amount of HTA destruction. This means, the accuracy of OH radical evaluation needs room to improve. Therefore, we measured the amount of HTA destruction by nanosecond pulsed discharge, and successfully examined the destruction amount of HTA. As the result, the generated OH radicals with consideration of HTA destruction is successfully evaluated.

ELECTRIC DISCHARGE DESTRUCTION OF REINFORCED CONCRETE SLEEPER IN THE SYSTEM OF SUPERIMPOSED ELECTRODES.

Evgeniy Petrenko, Igor Protopopov[1], Artem Yudin[1]
1. Tomsk Polytechnic University

Experimental data of the destruction of reinforced concrete sleeper in the system of electrodes placed on the sample were obtained. The tests were carried out at different modes: bipolar pulse, pulses with positive and negative polarities. The optimal charging voltage was determined, which was chosen according to the criteria for the occurrence of breakdown at the top or in the decay of a pulse signal without overvoltages in the system with the given interelectrode distance.

During the experiment, the sample was destroyed before the first layer of reinforcement, and it can be noted that the destruction near the reinforcement shows the worst result among all the stages of destruction, since the amount of consumed specific energy is more than in all other stages. Also, there is the smallest result in terms of the volume of the broken-off material. This happens due to the fact that a significant part of the impulses falls on the reinforcement, and not on the destruction of concrete.

As a result of destruction, the reinforcement can be completely removed without any additional effort.

SINGLE-STEP SYNTHESIS OF MOLYBDENUM CARBIDE NANOPARTICLES BY WIRE EXPLOSION PROCESS

Prem Ranjan[1], R. Sarathi[1], Ramkishore Kumar[2], P. Selvam[2], R. Jayaganthan[3], H. Suematsu[4]

1. Department of Electrical Engineering, IIT Madras, Chennai, 600036 India
2. Department of Chemistry, IIT Madras, Chennai, 600036 India
3. Department of Engineering Design, IIT Madras, Chennai, 600036 India
4. Extreme Energy-Density Research Institute, Nagaoka University of Technology, Nagaoka 940-2188, Japan

Molybdenum carbide (MoC) is used extensively in many industrial applications especially as catalysis replacing the expensive noble metals. Nano sizing of the material provides high surface area for reaction. Many processes are used to synthesize MoC nanoparticles (NPs). Those techniques involve multiple steps and a specific choice of precursors with long preparation time. In the present work, MoC NPs were synthesized by adopting wire explosion process (WEP), in single step. WEP utilizes the joule heating of wire by injecting high magnitude pulsed current obtained by discharging high energy capacitor. In the process, the wire sublimates to vapour/plasma, reacts with ambient and gets cooled down in ms time, to yield oxide, nitride, carbide NPs depending on the ambient used. To control the phase and morphology of NPs, two parameters are defined in WEP: energy ratio, K (ratio of energy supplied to wire and sublimation energy of wire) and pressure, P of ambient gas.

We propose the synthesis of MoC NPs with Mo wire as starting material and to carryout explosion in the methane gas medium, which acts as carburizing medium, as well as coolant, to bring down the local temperature rise to a value lower than the melting point of the material. XRD, TEM, SEM and XPS were used to characterize the synthesized NPs. Pure MoC was synthesized for $K = 5.8$ and $P = 170$ kPa. Carburization is more for high K/pressure. For low pressure case, one has to provide more K to get complete carburization. XPS confirms the formation of MoC. Spherical NPs were obtained with least mean particle size of 20 nm. Particle size decreases with increase in K and/or decrease in P. Formation mechanism of metal carbide NPs by WEP, will be discussed based on thermodynamical aspects.

DEVELOPMENT OF 3D ELECTROMAGNETIC THERMAL FLUID SIMULATION FOR ELUCIDATION OF MOVEMENT FACTORS IN VACUUM ARC

Soshi Iwata[1], Yusuke Nemoto[1], Ren Zhenwei[1], Yoshifumi Maeda[1], Toru Iwao[1]
1. Tokyo City University

It has been suggested that the movement factors of cathode spot are the electromagnetic force and force caused by pressure gradient. However, the quantitative force values causing movement has not been disclosed. In this paper, the movement factors of vacuum arc clarified that either electromagnetic force or force caused by pressure gradient is $9.98 \times 10^4 \sim 6.87 \times 10^5$ N/m^3 . The parameters of calculation were the external magnetic flux density and amount of metal vapor. In this simulation, the ion current was calculated from the behavior of ions in order to analyze the retrograde motion in the vacuum arc. The ion current is larger than the electron current in the cathode spot because the number density of ions is large in cathode spot. In addition, the direction of ion current is the cathode to anode caused by the pressure gradient. For these reasons, the phenomenon of retrograde motion increases with increasing the electromagnetic force and amount of metal vapor. Moreover, the two cathode spots were analyzed. The parameter is the distance between two cathode spots in order to elucidate that the electromagnetic force or force of pressure gradient dominates. As a result, one cathode spot was moved by the force of pressure gradient with the other cathode spot, but one cathode spot was not moved by the electromagnetic force with the other cathode spot. Thus, the force of pressure gradient is dominant. Therefore, the 3D electromagnetic thermal fluid simulation was developed in order to elucidate the movement factors of cathode spot in the vacuum arc.

ANALYSIS OF NITROGEN CONTAMINATION PROCESS INTO ARC AFFECTED BY LATERAL GAS FLOW VELOCITY IN ATMOSPHERIC PRESSURE

Yoshifumi Maeda[1], Toru Iwao[1]
1. Tokyo City University

The atmospheric pressure arc deflects and becomes unstable in the case of strong cross wind. For example, the weld defects such as the lack of penetration and blow hole caused by the contamination of nitrogen in weld pool are caused by arc deflection. It is necessary to elucidate the contamination process of nitrogen under consideration of flow field derived from cross wind in order to prevent the weld defects. The observation of nitrogen contamination process caused by the cross wind has been researched when the gas between the cathode and anode is covered by the shielding gas. However, the nitrogen contamination process has not been elucidated when arc is not generated between the electrodes. The measurement of flow field and nitrogen concentration distribution in arc is difficult because the mass density difference and strong radiation derived from the temperature increment of arc occur. For this reason, it is required to elucidate the nitrogen contamination process into the arc caused by cross wind using the numerical analysis of arc. The increment of shielding gas concentration caused by the magnetic pinch force near cathode has been researched using the numerical analysis. However, it is suggested that the nitrogen is contaminated by the arc in case of the high lateral gas flow velocity because the flow velocity to the direction of arc center increases.

In this paper, the analysis of nitrogen contamination process into the arc affected by the lateral gas flow velocity in atmospheric pressure was elucidated. As a result, the nitrogen concentration near anode increases with increasing the lateral gas flow velocity. This is because the flow velocity to direction of arc center near cathode increased with the lateral gas. Therefore, the flow velocity near cathode plays an important role for the nitrogen contamination process into the arc.

OPTICAL AND ELECTRICAL DIAGNOSTIC OF SURFACE ARCS

Suryakant Gupta[1], Keena Kalaria[1], Naresh Vaghela[1]
1. Institute for plasma research

In many plasma based applications, surface flashover cannot be avoided. Repetitive exposure of such surface flashover (also termed as an arc), can deteorate the surface properties of the material. Depending upon the arc locations, and arc frequency ultimately it may reduce the functional life of the material. Hence developing an understanding of such arcing phenomenon on various substrate's surface [i.e. insulator, conductor or semiconductor] is essential. Electric discharges or arcing prediction by simulations being still a technical challenge. Thus it is very important to capture the arc parameters such as arc locations precisely. This information helps to understand the reason behind arc initiation that helps in developing suitable arc mitigation techniques. Small duration arc events can be captured by using an advanced camera integrated with a trigger circuit but this is a cost intensive solution. Further surface flashover is a statistically happening event hence arc location and time cannot be predicted in advance. Therefore in various situations, this makes it difficult to integrate trigger circuits with advanced camera. In this paper a study of arc location on the satellite solar panel surface has been performed. We demonstrate the ability to precisely capture the ESD events and arc locations by using an infrared camera and an indigenously developed LabVIEW based automated test facility.

HOT ELECTRON EMISSION PROCESSES IN WAVEGUIDE INTEGRATED GRAPHENE

Rehan Kapadia[1], Fatemeh Rezaeifar[1], Ragib Ahsan[1]
1. University of Southern California

Photoemission plays a central role in a wide range of areas, from electronic structure measurements to free electron laser sources. In metallic emitters, photons with energy lower than the material workfunction can only drive photoemission through the multi-photon, or strong-field processes, both of which require large optical power densities, limiting the integration and deployment of these photoemitters despite their favorable properties. Here, we demonstrate a graphene emitter that is excited via a waveguide with 3.06 eV photons from a continuous wave (CW) laser exhibits two hot-electron processes that drive photoemission at peak powers orders of magnitude lower than previously reported multi-photon and strong-field metallic photoemitters. We use optical power dependent experiments combined with modeling to suggest that the observed behavior can be explained by considering two hot-electron emission processes: (i) non-equilibrium electron heating, and (ii) direct emission of excited electrons. These processes are dramatically enhanced in graphene due to the relatively weak electron-phonon coupling and the single layer structure.

By observing the optical power dependence as a function of electric field, we show that there is a cross-over from non-linear at low electric fields to linear at high electric fields. This crossover in optical power dependence is also reproduced in our model only when we consider both electron heating and direct emission of excited electrons. When LaB6 nanoparticles are used, the power dependence is linear regardless of the electric field, due to the low workfunction of the LaB6. Additionally, the integrated photonics approach demonstrates an efficiency three orders of magnitude greater than free space excitation. These results suggest the approach of integrated photonics combined with materials exhibiting low electron-phonon coupling and thin structures, such as 2-D materials or quantum dots, could provide a rich new area for electron emitters and integrated photonic devices.

ELECTRON EMISSION AND GAS BREAKDOWN: UNIFICATION OF THEORY FROM SCHRODINGER'S EQUATION TO PASCHEN'S LAW

Amanda Loveless[1], Adam Darr[2], Allen Garner[1]
1. Purdue University
2. Purdue University West Lafayette

The continued miniaturization of electronic devices for applications including micro- and nano-electromechanical systems (MEMS and NEMS, respectively) and microplasmas requires a thorough understanding of electron emission behavior at these length scales for various pressures. Paschen's law (PL) governs classical gas breakdown, but fails for microscale gaps, where field emission (FE) drives breakdown. Reducing the gap size below microscale further necessitates understanding the transitions from FE-driven breakdown to space-charge limited emission (SCLE) with Mott-Gurney (MG) at pressure, Child-Langmuir (CL) at vacuum, and quantum behavior at nanoscale. While piecewise connections of these breakdown and emission mechanisms have been studied, a complete analysis connecting all mechanisms remains incomplete.

This study aims to fill this gap by nondimensionalizing the governing equations with a consistent set of scaling parameters to obtain a single, material-dependent parameter retained in PL. Thus, this study provides a universal (material-independent) set of equations characterizing electron emission behavior from quantum scales up to, but not including, the traditional PL. The universality of the dimensionless equations highlights the underlying physics driving each mechanism and demonstrates the respective regions of importance. These dimensionless equations can predict the specific emission characteristics for a given set of experimental parameters and provide insight into device design.

This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-18-1-0218 and the by the Office of Naval Research under Grant No. N00014-17-1-2702. A. M. D. gratefully acknowledges funding from a Purdue Doctoral Fellowship. A. M. L. gratefully acknowledges funding from a graduate scholarship from the Directed Energy Professional Society and a fellowship from the Purdue Research Foundation.

MICROSCALE GAS BREAKDOWN VOLTAGE DEPENDENCE ON ELECTRODE SURFACE

Russell Brayfield[1], Andrew Fairbanks[1], Amanda Loveless[1], Shengjie Gao[1], Caleb Darr[1], Jacqueline Malayter[1], Wenzhou Wu[1], Allen Garner[1]
1. Purdue University

Surface structure, such as surface roughness and electrode geometry, can modify field enhancement and work function, which subsequently modifies field emission. This can significantly change gas breakdown voltage for microscale gaps at atmospheric pressure [1], where field emission drives breakdown rather than Paschen's law. This presentation uses a tungsten pin anode and a copper plate cathode polished to three different surface roughnesses to characterize the impact of surface roughness and subsequent cathode damage on breakdown voltage for interelectrode gaps of 1, 5, and 10 microns at atmospheric pressure. Changing the surface roughness did not cause a statistically significant change in breakdown voltage; however, it played a critical role in breakdown voltage and cathode conditions for repeated breakdown events. After treatment, the cathode contained small craters from 3 to 50 microns deep. The breakdown voltage for these subsequent breakdown events agrees with theoretical predictions for an effective gap distance equal to the sum of the interelectrode gap distance and the crater depth. These effective gap distances are sufficient to exceed the Meek criterion for streamer discharge, indicating potential breakdown mechanism transition for a single interelectrode gap distance. The implications of the impacts of electrode surface structure on breakdown before and after multiple breakdown events on microdevice operation will be discussed.

[1] S. Dyanko, A. M. Loveless, and A. L. Garner, "Sensitivity of modeled microscale gas breakdown voltage due to parametric variation," Phys. Plasmas, vol. 25, 2018, Art. no. 103505.

This material is based upon work supported by the Office of Naval Research under Grant No. N00014-17-1-2702. A. M. L. gratefully acknowledges funding from a graduate scholarship from the Directed Energy Professional Society and a fellowship from the Purdue Research Foundation.

QUANTUM EFFECTS IN ELECTRON EMISSION FROM NANODIAMOND

Stanislav Baturin[1], Oksana Chubenko[2], Andreas Schroeder[3], Sergey Baryshev[4]

1. PSD Enrico Fermi Institute, University of Chicago
2. Department of Physics, Arizona State University
3. Department of Physics, University of Illinois at Chicago
4. Department of Electrical and Computer Engineering, Michigan State University

Synthetic granular ultra-nano-crystalline diamond with high n-type conductivity via nitrogen doping ((N)UNCD) has emerged as a high efficiency photo- or field-emission source in that it has high internal and external quantum efficiency in near UV/visible or low turn-on field, respectively. It is widely anticipated that graphitic grain boundaries (surrounding diamond grains) are behind the high efficiency of (N)UNCD. Grain boundary effect hypotheses rest upon the fact that (N)UNCD emission efficiency can be largely "tuned" through the diamond-to-graphite ratio typically quantified by optical and x-ray spectroscopy techniques.

In addition to high efficiency, we have experimentally observed that (N)UNCD demonstrates some unconventional behaviors that attend electron emission. These are 1) output current saturation [1,2] and 2) light emission [3] during field emission, and 3) intrinsic emittance/mean transverse electron energy independent of the excess photon energy during photoemission [4]. In this talk, we will summarize our recent experimental and theoretical work that further corroborate the critical role of defect grain boundary states on electron emission from (N)UNCD. Specifically, we will outline the role of

1) Density of grain boundary states induced inside diamond fundamental band gap and electron transport properties on the Fowler-Nordheim and saturation regimes of field emission;

2) Electron effective mass on light generation and spectrum during field emission;

3) Ground state photoemission from spatially confined grain boundaries on transverse photoelectron momentum (intrinsic emittance).

We will also outline how the models implying quantum effects associated with graphitic grain-boundary-promoted electron emission can simultaneously account for high efficiency and unconventional behavior of (N)UNCD in a non-contradictory way.

[1] ACS Appl. Mater. Interfaces 9, 33229 (2017)

[2] arXiv:1812.05726 (2018)

[3] arXiv:1811.04186 (2018)

[4] arXiv:1812.00323 (2018), Appl. Phys. Lett., accepted (2019)

PARTICLE EMISSION INVESTIGATION FROM AN ANODE LIQUID SURFACE OF ELECTROLYTE IN ATMOSPHERIC PRESSURE DC GLOW

Yao Kovach[1], John Foster[1]
1. University of Michigan

Self-organization patterns observed on anode liquid surfaces in atmospheric pressure DC glow discharge represents both a mysterious and beautiful plasma physics phenomenon. The mechanisms underlying self-organization of plasmas in this context is still poorly understood. In this study, luminous particle emission from the liquid anode under self-organization condition has been observed. These particles have been collected in flight using witness plates. The particle impacts have the form of splats suggesting that they are molten. The splats were observed to have a great deal of structure including evidence of nano-precipitation. These resulting splats were examined using a scanning electron microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDX) diagnostics. In particular, the size range of molten particle droplets was theoretical estimated by converting from the size of impact splats. Furthermore, high-speed camera analysis was used to map the 2D trajectories of these particles in order to analyze both the emission force and the drag experienced by the particle during flight. This yields insight into mechanisms of emission. A thermal effect such as localized heating and evaporation is one potential mechanism driving the emission of particles that may be formed in the liquid. Here we examine the local temperature of the liquid water at the emission zone just below the surface. The actually temperature of this region is not well known and thus provides insight not only into the mechanisms of emission but also potentially the underlying processes driving the self-organization formation itself.

ENGINEERED TUNNELING ELECTRICAL CONTACTS

Sneha Banerjee[1], John Luginsland, Peng Zhang[1]
1. Michigan State University

Contact resistance and current transport are important to nano scale electrical contacts, such as those based on metal-insulator-metal (MIM) thin junctions, carbon nanotube (CNT) networks, and novel two-dimensional (2D) materials. Current tunneling and contact resistance across such contacts greatly influence the device properties and performance. Current crowding effects in these contacts can lead to localized overheating and the formation of thermal hot spots. To improve reliability and lifetime of the device, it is crucial to engineer these contact structures to mitigate the local heating. In this study, we propose a method to design nanoscale electrical contacts with controlled current distribution and contact resistance via engineered spatially varying contact layer properties and geometry. A lumped circuit transmission line model (TLM) [1] is used to get self-consistent analysis of contact resistivity, current and voltage distribution across tunneling contacts formed between similar/dissimilar contacting members separated by a thin insulating gap with varying thickness. It is found the nonhomogeneous current and voltage distribution in parallel tunneling contacts can be reduced by varying the specific contact resistivity along the contact length. This specific contact resistivity is either predefined (for ohmic contacts), or calculated from the local tunneling current in case of insulating tunneling layer [2].

1. S. Banerjee, J. Luginsland, and P. Zhang, “Two dimensional tunneling resistance transmission line model for nanoscale parallel electrical contacts”, under review, 2019.

2. P. Zhang, ”Scaling for quantum tunneling current in nano- and subnano-scale plasmonic junctions”, Sci. Rep., 5, 9826 (2015).

This work was supported by AFOSR YIP Award No. FA9550-18-1-0061.

A COORDINATE INVARIANT THEORY FOR SPACE CHARGE LIMITED EMISSION USING VARIATIONAL CALCULUS

Adam Darr[1], Allen Garner[2]
1. Purdue University West Lafayette
2. Purdue University

Classical theories of space-charge limited emission (SCLE) for coaxial cylindrical and concentric spherical diodes were first formulated by Langmuir and Blodgett (LB) [1,2]. Recent studies have improved upon the LB series expansion using analytical techniques [3,4]; however, they assume zero space-charge and cannot predict single-particle trajectories or solve for the shape of the potential function across the gap. This presentation applies variational calculus and the minimum energy principle to obtain fully analytic solutions for the potential and current-voltage behavior of these diodes. We obtained excellent agreement with previous simulations and experiments, with better agreement at more extreme ratios of anode to cathode radius compared to other theoretical approaches. The implications of these equations and the potential extension to multi-dimensional SCLE and other electron emission mechanisms will be discussed.

1. I. Langmuir and K. Blodgett, "Currents limited by space charge between coaxial cylinders," Phys. Rev., vol. 22, 347-356, 1923.

2. I. Langmuir and K. Blodgett, "Currents limited by space charge between concentric spheres," Phys. Rev., vol. 24, pp. 49-59, 1924.

3. X. Chen, J. Dickens, L. L. Hatfield, E.-H. Choi and M. Kristiansen, "Approximate analytical solutions for the space-charge-limited current in one-dimensional and two-dimensional cylindrical diodes," Phys. Plasmas, vol. 11, pp. 3278-3283, 2004.

4. Y. B. Zhu, P. Zhang, A. Valfells, L. K. Ang, and Y. Y. Lau, "Novel scaling laws for the Langmuir-Blodgett solutions in cylindrical and spherical diodes," Phys. Rev. Lett., vol. 110, 2013, art. no. 265007.

Work supported by a Purdue Doctoral Fellowship

MODELING A COMPACT A6 RELATIVISTIC MAGNETRON OPERATING WITH PERMANENT MAGNETS

John Leopold[1], Uri Dai[2], Yakov Krasik[1]
1. Physics Department, Technion, Israel Institute of Technology
2. DDR&D, IMOD

We present simulation results which demonstrate that a relativistic magnetron can be operated with permanent magnets. Using permanent magnets makes the magnetron a more compact device. In a recent paper (Leopold et al., IEEE-Trans. Plasma Sci., vol. 44, no. 8, pp 1375-85, 2016) we showed that the power balance in an A6 single radial output magnetron with its longitudinal slots covered by anode caps, is the result of a complex process involving the applied voltage and the distribution of the current between the axial leakage and magnetron currents. The axial magnetic field which is usually considered to be fixed and uniform in the interaction volume is an important parameter. The parameter space for pulse shortening and mode competition to occur has also been clarified. Replacing Helmholtz coils with permanent magnets is not though straightforward. It is possible to create sufficiently high axial magnetic fields by inserting magnets in the six vanes of an A6 magnetron, in the cathode or both. It is though difficult to use long enough permanent magnets for their edges to be far enough from the interaction region. On the other hand if the edges are too close, then the balance between the axial and magnetron currents is affected. Therefore it becomes more difficult to optimize the performance of such a magnetron.

MODELING THE WAKEFIELD EXCITATION BY A 28 GHZ MICROWAVE PULSE IN A PLASMA FILLED WAVEGUIDE

Y. Cao[1], Y. P. Bliokh[1], J.G. Leopold[1], V. Rostov[2], Ya. Slutsker[1], Ya.E. Krasik[3]
1. Physics Department, Technion, Israel Institute of Technology
2. 2 Institute of High Current Electronics, Russian Academy of Sciences, Tomsk, Russia
3. 1 Physics Department, Technion, Israel Institute of Technology

A simple 1D model of the propagation of an ultra-short ($\leq$ 1ns), TM01 mode, 28 GHz, $\sim$1 GW, microwave pulse produced by an SRBWO (Super Radiant Backward Wave Oscillator) in a $\sim 10^{10}$ cm^{-3} density plasma shows that a wakefield develops as a result of the radial ponderomotive and the Lorentz force. This is a scaled-down equivalent of a laser wakefield experiment with more manageable parameters. The model shows that for best results the waveguide radius needs to be such that the Lorentz and ponderomotive forces balance in a particular way. We simulate the system by the 3D PIC LSP code and confirm this model. Moreover, we simulate the experimental waveguide which has a slotted wall. These slots are required to be wide enough so that the plasma produced at larger radii penetrates the waveguide filling it uniformly, large enough to allow diagnostics, and sufficiently small, so that the microwave radiation is contained.

EFFECTS OF THE MESH ANODE TRANSPARENCY ON THE OPERATION CHARACTERISTICS OF THE VIRTUAL CATHODE OSCILLATOR

Se-Hoon Kim[1], Chang-Jin Lee[2], Kwang-Cheol Ko[1]
1. Hanyang University
2. Hanyang Univ.

An axial virtual cathode oscillator is experimentally analyzed depending on the transparency of the mesh anode. The axial virtual cathode oscillator is operated using a 140J/170kV Marx generator. A stainless steel cathode and stainless steel mesh anodes with different transparency are used as a high power microwave generating diode. The gap distance of the virtual cathode diode is 4 mm. To analyze the operation characteristics depending on the mesh anode transparency, the output power, voltage, and current are measured.

PARTICLES CHARGE DISSIPATION IN KU-BAND RELATIVISTIC HPM SOURCE

Antoine Chauloux[1], Jean-Christophe Diot[1], Stéphane Tortel[1]
1. CEA - Gramat

When designing relativistic high power microwave sources operating at high frequency one must combine high power handling with small structures in order to prevent from mode competition. This consequently leads to high power density levels with the risk of power breakdown inside of the microwave source. The triaxial configuration offers a solution to this tradeoff where the electronic beam is surrounded by both an inner and an outer conductor. Low power density levels can be achieved with wide structures and transverse electromagnetic mode propagation is ensured thanks to the coaxial design. However, electric potential and currents of the inner conductor rise up during a pulse and need to be dissipated. Metallic plots acting as short-circuits can be consequently positioned between outer and inner conductors to discharge the currents but specific attention has to be paid to the electromagnetic propagation. Moreover, Particle-In-Cell simulations revealed that surface currents on these plots can reach dramatically high values.

A novel approach is proposed to solve these drawbacks: The design of a Transit Time Oscillator (TTO) with an inverted output is firstly exposed. In this configuration, the electronic beam is collected directly by the Anode and not by the inner conductor resulting very low current level on the metallic plots. On the second solution, an antenna (with a design containing short-circuits) is connected at the output of a TTO (with no inverted output and no metallic plots). Electromagnetic simulations show that when the antenna is fed with transverse electromagnetic mode input signal combined with the continuous signal component coming from the electric potential of the inner conductor, the antenna operates conveniently with good radiation patterns and low input reflection coefficient.

FAST-WAVE AND SLOW-WAVE INTERACTIONS IN THE RIPPLED-FIELD MAGNETRON

Andrey Andreev, Edl Schamiloglu[1], Samuel Smith[1], Ahmed Elfrgani[1], Dmitrii Andreev[1], Stacie Hernandez[1], Artem Kuskov
1. University of New Mexico

The rippled-field magnetron is a compact millimeter wave source developed by Bekefi [1]. This source is driven by a rotating electron stream. The electron stream moves through an azimuthally periodic wiggler magnetic field oriented transversely to the flow and a uniform axial magnetic field. The advantages of this circular device compared to linear devices is that the beam circulates continuously, resulting in a long effective interaction. The anode-cathode gap is part of the magnetic wiggler interaction region.

The rippled magnetic field can be achieved by permanent magnet or wires carrying current (electromagnet). The rippled-field magnetron uses samarium-cobalt bar magnets positioned behind grounded stainless steel cylinders and held in place using a grooved aluminum holder. In this work, the magnet bars are replaced by azimuthally periodic longitudinal strips carrying high current. A combination of strips connected to the cathode and anode are considered. They carry currents in opposite directions in order to form the desired magnetic wiggler fields. This setup is similar to the inter-digital magnetron (Mitron) which raises the possibility of electrons interacting with Hartree harmonics. The slow-wave growth is similar to magnetron interaction which can be achieved even for a moderate relativistic beam. On the other hand, the fast-wave growth is a free-electron laser type of instability which requires MeV or higher electron beam energies.

1. G. Bekefi, “Rippled-Field Magnetron,” Appl. Phys. Lett., vol. 40, 578, 1982.

----

* Work supported by DARPA Grant #N66001-16-1-4042

FREQUENCY TUNABLE X-BAND RELATIVISTIC BACKWARD WAVE OSCILLATOR

jean-christophe diot[1], Antoine Chauloux[1], jeremy pothee[1], Thierry Chanconie[2], Stéphane Tortel[1]
1. CEA
2. CEA Gramat

Relativistic tubes are generally used for High Power ElectroMagnetic (HPEM) applications. Most of these tubes radiate high level electromagnetic fields but operate at a fixed frequency. Nevertheless, in most cases, a variable frequency is useful if not required. In a precedent study, CEA worked on a very compact HPEM source named CLAIRE. The used tube was an optimized X-band sub-gigawatt relativistic resonant Backward Wave Oscillator (BWO) using low-level magnetic field. A new BWO design (based on the previous one) has been achieved with frequency tunable capability. This tube is cautiously designed to be compatible with the CLAIRE generator and to provide at least 500 MHz frequency range. Pros and cons of mechanical and electrical tunability are firstly evaluated. Particles In Cell Simulations (PIC) were carried out and revealed that an optimized mechanical solution provides the desired performances. Desired tunable frequency range is obtained by changing the distance “D” between the resonant reflector and the Slow Wave Structure (SWS). Finally, a prototype is realized. The distance “D” is mechanically actuated by moving the resonant reflector of few millimeters. A particular attention has been paid on the realization for two reasons. Firstly, operating in X-band implies high mechanical accuracy in order to achieve great performances. Secondly, it’s necessary to maintain good vacuum state while mechanically moving the resonant reflector. This paper presents the design, numerical PIC simulations, and first experiments.

EXAMINATION OF STABILITY AGAINST BEAM PARAMETERS IN A KU BAND HELIX TWT

Necati Haytural, Ferhat Bozduman, Lutfi Oksuz[1]
1. Suleyman Demirel University

A Ku band tape helix TWT with a center frequency of 13.25 GHz which was chosen for the RF driver present in our lab for a future prototype, was modeled and simulated using CST MWS and CST PS. Connectors for the RF input and output were also modeled in two different types. Firstly, a 50 Ohm coaxial connector was modeled and directly coupled to the helix and secondly an impedance matching section starting with a 50 Ohm and gradually increasing until coupling section to the helix was modeled. Beam parameters such as voltage, current and radius were swept while the other two were held constant. Aim of the study was to investigate the beam parameters for optimum operation and effects of matching were also studied in simulations. It was observed that a system that breaks down due to oscillations could, in some cases, be recovered just by proper matching.

METAMATERIAL BASED RF SOURCE

Rebecca Seviour[1], Simon Foulkes[2]
1. Supervisor
2. University of Huddersfield

We present our current progress towards the development of a novel RF source utilizing a low-loss, dispersion engineered, artificial EM material, based upon a complementary split ring resonator that supports both forward and backward wave propagation. The frequency dispersive media was designed numerically to yield specific constitutive parameters, determined using a Nicholson Ross Wier based retrieval approach. The media is designed to reduce EM wave propagation to approximately 0.2 c, facilitating interaction with a 20 keV electron beam.

To explore the beam - wave the interaction a cylindrical waveguide loaded with the artificial material is considered and modeled using the FDTD-PIC simulation software MAGIC. Where a 20 keV, 0.5 A electron beam acted upon by a 0.3 T external magnetic field propagates on axis, to excite a wave in the media. The simulation results demonstrate Beam-Wave energy transfer, producing a narrow band EM wave at 8.45 GHz. Results of the frequency spectrum and the power generated are presented, along with eigenmode simulation results for both the empty and the loaded system. FEM simulations show the artificial material is capable of supporting a 1 KW continuous wave propagating through the media.

COLD TEST VALIDATION OF METAMATERIAL BASED RECTANGULAR SLOW WAVE STRUCTURE FOR HIGH POWER BACKWARD-WAVE OSCILLATORS

Doğancan Eser[1], Şimşek Demir[2]
1. PhD Student
2. IEEE member

In this paper, novel S band metamaterial based rectangular slow-wave structure (RSWS) is proposed for high power backward-wave oscillator (BWO). The circular waveguide is loaded with R-SWS that shows negative permittivity and permeability. Since RSWS shows the negative permittivity and permeability which is the key characteristics of metamaterial, it can work below the cut-off frequency. A high frequency characteristic of SWS is analyzed using CST Studio Suite. Dispersion diagram of unit cell is observed with Eigen Mode Solver which is dedicated to simulation of closed resonant structure. Interaction impedance of the unit cell is also analyzed for future work. Since the beam-wave interaction occurs with TM mode, axial and absolute electric field is observed in the simulation. Slow wave structure composed of 8 unit cell is fabricated and measured in Network Analyzer. Cold-test measurement validates the TM mode propagation and dispersion diagram of RSWS. Hot test simulation is also achieved using CST Particle Studio. It is achieved for the 450 kV, 100 A annular electron beam under the 2 T analytical magnetic field with 10.7 MW peak power and % 23.8 peak efficiency at 2.49 GHz

SIMULATION OF AN INDUSTRIAL MAGNETRON USING CATHODE MODULATION

Andong Yue[1], Jim Browning[1], Mike Worthington[2], John Cippola[2]
1. Boise State University
2. L3 Technologies

Magnetrons can be phase-locked using external systems. Previous 2-D PIC simulations of a rising sun magnetron[1] have shown that phase-locking is possible using modulated electron injection to control the spoke formation. An experimental setup using Gated Field Emission Arrays (GFEAs) for the modulated electron injection offers a potential solution to this problem by permitting the injection of electrons into the interaction space. Current work focusses on extending previous simulation results into 3-D. A commercially available industrial cooker magnetron (the L3 CWM-75kW) has been successfully simulated by using the 3-D PIC code VSim under the magnetron's typical operating conditions (18kV, 5A, 1900G, 896-929MHz). The simulation generated results that are consistent with known experimental results in terms of power and frequency. Cavity oscillation starts within 100ns using 20ns of RF priming at half of the typical power. Preliminary results have shown that modulated electron injection has a significant effect on the working mechanisms of the magnetron in terms of spoke formation and start-up time, acting as a form of "cathode priming." It has been experimentally shown by L3 technologies that this magnetron is capable of operating at ∼9kV, 150 mA, and 900G. Future work will focus on the simulation of the magnetron under the aforementioned low-voltage-low-current conditions as well as further exploration of the effect of modulated electron injection on start-up and phase.

This work is supported by the Air Force Office of Scientific Research under award #FA9550-16-1-0083. Geometry drawings, the magnetron hardware, and experimental low-voltage-low-current parameters were generously provided by L3 Technologies. Technical support of the VSim code was provided by Tech-X Corporation

1. S. Fernandez-Gutierrez, J. Browning, M. Lin, D. N. Smith, and J. Watrous. "Phase-Control of a Rising Sun Magnetron Using a Modulated, Addressable, Current Source." Journal of Vacuum Science & Technology, vol. B 33, pp. 031203. 2015.

NLTL FREQUENCY CHIRP THROUGH DYNAMIC BIAS OF INDUCTOR CORES

Emily Schrock[1], D. Phillip Coleman[1], Seth Miller[2], John Borchardt[1]
1. Sandia National Laboratories
2. Sandia National Labs

Nonlinear transmission lines (NLTL) have demonstrated the ability to convert a low-frequency video pulse into a narrowband RF packet whose frequency may vary from pulse to pulse. Synchronous wave magnetic NLTLs achieve this via a DC current bias prior to the launch of a video pulse which sets the subsequent shock velocity and thus the RF frequency. This paper explores the idea that a dynamic (time-varying) bias waveform can yield NLTL RF output with a chirp frequency characteristic by varying the shock velocity along the length of the line. A low power NLTL was utilized to prototype the concept using 1 kV – 3 kV input drive, 0 – 150 V bias waveform, and 0 – 1 A DC bias current. The center frequency output of the low power NLTL ranges from 120 MHz – 260 MHz, which varies with bias current and drive voltage, and has RF pulse widths between 50 ns and 300 ns. The optimization of the input waveform required to produce a chirp output waveform and experimental characterization of various dynamic bias waveforms on a low power test bed are described.

THE INFLUENCE OF MAGNETIC FIELD PROFILE ON THE DOWNSTREAM ELECTRONS AND THE OUTPUT MODE OF MDO

Shen Shou Max Chung[1]
1. Department of Electrical Engineering, National Penghu University

Magnetron with Diffraction Output (MDO) possesses advantages like direct couple to axial output waveguide; hence it has higher output extraction efficiency. Like traditional magnetron, MDO also requires an axial magnetic field to force the explosive field emitted electrons to go into a spiral motion and form resonant fork, and unlike low power traditional magnetron where the B field is formed by permanent magnet, in high power pulsed relativistic magnetron the B field is usually formed by a pair of Helmholtz Coils that provides near constant Z axis B field if the radius and distance between the coils are large enough. Due to the nature of the pulsed power system that drives such high power MDO, the electrons tends to drift towards the output horn and the magnetic field profile in the horn region affects how the electrons propagate in this region. Using Particle-In-Cell (PIC) simulation, we found if the magnetic field is setup as a unit function, then the downstream electrons continue to drift in a straight line. If the magnetic field gradually decreases as in a real Helmholtz Coil, then the downstream electrons drift outwards in the vanes of the MDO. Due to the influence of the downstream electron positions, the output mode is slightly changed at the output horn end.

HYBRID KINETIC-FLUID SIMULATIONS OF A KU-BAND MILO

Peter Stoltz[1], John W. Luginsland[2], Anton Spirkin[1], Christine Roark
1. Tech-X Corporation
2. Confluent Sciences

There has been tremendous progress in the modeling and simulation of high-power microwave devices, especially in the lower frequencies, such as L-band (1-2GHz) and S-band (2-4GHz). Here we look at significantly higher frequency, 14GHz, while still studying a tube with GW-class power levels [Tao Jiang et. al. Phys. Plasmas 2015]. The choice of this Ku-band allows both high frequency and high power density (due to the smaller dimensions of the slow wave structure) to be investigated. Additionally, the tube under study is a magnetically insulated line oscillator, where the self-magnetic field from the intense relativistic electron beam population is sufficient to insulate the transmission of current across the vacuum gap. In this way, the Ku-band MILO offers physics and power densities approaching those seen in magnetically insulated transmission lines (MITL), a critical pulsed power technology for high-energy density physics (HEDP). We report on the application of fully electromagnetic particle-in-cell (VSim) and fluid models (USim) in modeling electron flow in the device. Additionally, due to the intense power loading experienced in this device, we also investigate various plasma production models that introduce ion space charge into the device. We use the combination of both kinetic and fluid simulations to study the interaction of electron and ion populations in a fully electromagnetic environment, as well as use the Ku-band MILO as a test bed for active and automated transition between PIC and fluid models during individual run to produce a hybrid model of the plasma physics in this device.

W-BAND 2D PERIODIC LATTICE OSCILLATOR

Colin Whyte[1], MacLachlan Amy [1], Robertson Craig[1], Cross Adrian[1], Zhang Liang[1], Donaldson Craig[1], Phelps Alan[1], Ronald Kevin[1]
1. University of Strathclyde

Two dimensional (2D) periodic surface lattices PSLs have been used successfully in both fast-wave sources [1] and in slow-wave sources [2-4]. Numerical simulation codes have been used to design an electron beam driven W-band millimeter-wave source, in which a cylindrical two dimensional (2D) periodic surface lattice (PSL) forms an over-sized mode-selective cavity. The 2D PSL consists of shallow periodic cosinusoidal perturbations in both the azimuthal and axial directions on the inner wall of a cylindrical waveguide. Electrochemical deposition of copper on a cylindrical aluminum former with the aluminum subsequently removed by dissolving in strong alkali solution was used to construct the 2D PSL. Analytical theory and numerical PIC simulations have been used to design the W-band oscillator that has been constructed. The ratio of the diameter of the cylindrical cross-section of the structure to the operating wavelength is $\sim$5. The performance of oscillator will be compared with the predictions of the numerical simulations.

ACKNOWLEDGMENT

Support from AFOSR under awards FA8555-13-1-2132 and FA9550-17-1-0095 is gratefully acknowledged.

REFERENCES

[1] N. S. Ginzburg, N. Y. Peskov, A. S. Sergeev, et al. , “Theory of free-electron maser with two-dimensional feedback driven by an annular electron beam”, J. Appl. Phys., vol. 92, pp. 1619-1629, Aug. 2002.

[2] A. W. Cross, I. V. Konoplev, A. D. R. Phelps, and K. Ronald, “Studies of surface two-dimensional photonic band-gap structures”, J. Appl. Phys., vol. 93, pp. 2208-2218, Feb. 2003.

[3] N. S. Ginzburg, E. V. Ilyakov, et al., “Theoretical and experimental studies of relativistic oversized Ka-band surface-wave oscillator based on 2D periodical corrugated structure”, Phys. Rev. Accel. Beams, vol. 21, (8), art. no. 080701, Aug. 2018.

[4] A.J, MacLachlan, C.W. Robertson, I.V. Konoplev, A.W. Cross, A.D.R. Phelps and K. Ronald, ‘Resonant Excitation of Volume and Surface Fields on Complex Electrodynamic Surfaces’, accepted for Phys. Rev. Appl., Feb 2019.

OPERATION OF A GYROMAGNETIC LINE WITH MAGNETIC AXIAL BIAS

Fernanda Yamasaki[1], Jose Rossi[2], Elizete Gonçalves Lopes Rangel[1],
Edl Schamiloglu[3], Leandro Carvalho Silva[1]
1. INPE
2. National Institute for Space Research
3. University of New Mexico

A growing interest has been rising around the use of Gyromagnetic Nonlinear Transmission Lines (GNLTLs) for Radiofrequency (RF) generation since recent results that were published has demonstrated great prospects for this end. The interest on this type of transmission line comes from the high RF conversion efficiency around 20.0% according to some works already elaborated, what shows a great capability of operates in a frequency range with considerable value, between 300.0 MHz and 6.0 GHz. The focus of this type of research is for the development of systems with greater reliability, efficiency and of course cheaper than those that already exist. Several authors used different approaches to study the gyromagnetic effect in order to understand the electron magnetic dipole precession movement of the ferromagnetic material, responsible for compress the pulse oscillation. The model proposed and studied here to analyze the GNLTL has a coaxial structure using NiZn ferrite beads distributed in a 20-cm coaxial line, for low and high voltage operation. Different measurements are compared in order to check the influence of the voltage injected onto the input, as well as the influence of the medium in which the coaxial line is and the use of a solenoid to create an axial magnetic bias. This work aimed the oscillation generated at the output caused by the presence of a magnetic field and by the changes in the system setup. For this, we analyzed the GNLTL behavior according to the results obtained from experimental tests, in order to observe the frequency response when the axial bias is present. It is expected that the results presented here will be useful as a basis to develop a system capable of generating RF for the use in space and mobile defense platforms.

Work funded by AFOSR under contract number FA9550-18-1-0111.

SIMULATIONS OF A W-BAND CIRCULAR TWT

Khandakar Nusrat Islam[1], Edl Schamiloglu[1]
1. University of New Mexico

We are exploring the amplification of W-band electromagnetic radiation using a dielectric-loaded traveling wave tube (TWT) by employing several particle–in–cell (PIC) codes. We are seeking to replicate recent results obtained by a Naval Research Laboratory's (NRL's) dielectric–loaded TWT design [1] consisting of a solid circular electron beam (26 kV, 100 mA and 0.185 mm beam radius) surrounded with dielectric material, ϵr=13.5, and coupled to a TM01 electromagnetic wave at a frequency of 94 GHz. NRL used a finite-difference-time- domain (FDTD) formulation in a 2–D cylindrical coordinate system to perform the dielectric–loaded TWT simulations. In our case, we have opted for PIC simulations comparing three different software tools–a 3–D Cartesian coordinate system 'FDTD–PIC method–based MAGIC', 'CST Electromagnetic and Multiphysics Simulation Studio Suite', and 'Improved Concurrent Electromagnetic Particle–In–Cell (ICEPIC)'. An earlier structure similar to that published by NRL, but at K-band and using a sheet beam and planar dielectric material, has been studied and confirmed by Los Alamos National Laboratory (LANL). We are seeking to confirm the results obtained by LANL at K-band using PIC simulations in a 3-D Cartesian system. Results from MAGIC and CST simulation will be presented.

1. J. P. Calame and A. M. Cook, "Design and large-signal modeling of W-band dielectric TWT," IEEE Trans. Plasma Sci., vol. 45, 2820–2834 (2017).

PULSED RF SIGNAL IRRADIATION USING A LOW VOLTAGE NLTL COUPLED TO A DRG ANTENNA*

Jose O. Rossi[1], Leandro Carvalho Silva[2], Lucas Reis Raimundi[1], Elizete Goncalves Lopes Rangel[2], Edl Schamiloglu[3]
1. National Institute for Space Research
2. INPE
3. University of New Mexico

Nonlinear Transmission Lines (NLTLs) has been used for RF generation with great success. Possible applications of NLTLs as an RF generator include aerospace radars, telecommunications, battlefield communication disruption, etc. The RF pulses generated by the NLTLs can be radiated using antennas connected to the output of the lines. Also, there has been a paucity in the literature considering experimental results on the extraction and radiation of the RF signals from the NLTL output. This work reports the results obtained with a low voltage lumped capacitive NLTL in which oscillations of about 230 MHz were produced and radiated using a Double-Ridged Guide (DRG) antenna. The RF signal from the NLTL output was extracted using a high-pass filter decoupling circuit. The pulsed RF signal measured on a resistive load connected to the line output was evaluated in time and frequency domains as well as the signals obtained from the DRG transmitting and receiving antennas. A SPICE line model has been implemented showing a good agreement between the simulation and experimental results.

*Work supported by SOARD/AFOSR under contract no. FA9550-18-1-0111.

E-BAND OVERMODED RELATIVISTIC BACKWARD WAVE OSCILLATOR

Liangjie Bi[1], Ahmed Elfrgani[2], Edl Schamiloglu[2]
1. University of New Mexico,University of Electronic Science and Technology of China
2. University of New Mexico

An E-band relativistic backward wave oscillator (RBWO) is proposed to generate megawatts of power. An overmoded rectangular slow wave structure (SWS) is chosen and combined with a relativistic hollow electron beam to increase the interaction impedance and avoid RF breakdown. To overcome the frequency limits of conventional fundamental mode version, a higher order mode is selected as the operating mode by using a mode selection technique. To demonstrate its capability, the RBWO based on the axisymmetric SWS has been designed and simulated using the particle-in-cell codes CST and MAGIC. The Gaussian output mode is obtained from the operating TM03 mode through a corrugated waveguide mode converter.

* Work at the University of New Mexico is supported through DARPA Grant #N66001-16-1-4042.

3D ICEPIC SIMULATION OF AN X-BAND RELATIVISTIC TWISTRON

Paul Gensheimer[1], Timothy Fleming[1]
1. AFRL/RDH

We present results of 3D ICEPIC simulations of a relativistic X-band (9.9 GHz) twistron based on a design reported in the literature. Here we report on progress made in our hot test simulations of this device. Full 3D ICEPIC simulations were made using the supercomputers of the DoD Supercomputing Resource Centers (DSRCs). Our hot test simulations used a 373 kV, 6.5 kA annular beam with 13.75 mm inner radius, 15.25 mm outer radius, focused with a 0.7 T axial magnetic field; the ICEPIC cell size used for our simulations were typically 0.25 mm. The 0.57 GW output RF power leaves the twistron as a TM01 mode via a downstream cylindrical waveguide. We have made some improvements to the twistron including adding a downstream beam catcher after the slow wave structure.

SIMULATIONS OF SURFACE INHOMOGENEITIES IN FIELD EMISSION

Kristinn Torfason[1], Ágúst Valfells[1], Andrei Manolescu[1]
1. Reykjavik University

Surface inhomogeneities can have a large impact on field emission, because it is strongly dependent on the local value of the surface electric field and work function of the metal. Within a given area the bulk of the emitted current may stem from a protrusion where the field is enhanced, or from a site where the work function is lower than in the surroundings. In systems that are large these effects tend to be obscured due to the large number of emitter sites, but for small systems there may be large variation in the performance because each aberration is a significant contributor to the total current emitted. Here we report on simulations done using our molecular dynamics code^{1,2} to simulate the emission from a planar cathode with non-uniform work function on the surface. The distribution, number of inhomogeneities and size are studied and how they affect the beamlet. This is done by calculating the beam emittance and electric current through the system during the simulation.

This work was supported by a grant form the Icelandic Research Fund under grant number 174127-053.

1. K. Torfason, A. Valfells, A. Manolescu, "Molecular dynamics simulations of field emission from a planar nanodiode", Phys. Plasmas 22, 033109 (2015).

2. K. Torfason, A. Valfells, A. Manolescu, "Molecular dynamics simulations of field emission from a prolate spheroidal tip", Phys. Plasmas 23, 123119 (2016).

BEAM-CURRENT LOSS IN EMITTANCE-DOMINATED HIGH-FREQUENCY TUBES

Muhammed Zuboraj[1], Bruce Carlsten
1. Los Alamos National Laboratory

The next generation high frequency tubes will face significant challenge in focusing the beam into small aperture for beam-wave interaction. The efficiency of such tubes will depend largely on available beam energy that will interact with electromagnetic wave as the beam is transported. Unlike low frequency tubes, emittance is emerging as a major concern since beam loss at the wall or at the surface of the slow wave structures are expected to increase appreciably as the frequency increases. To determine the beam loss for a certain pipe size, typically numerical analysis of particle simulation is conducted which is often expensive and tedious. In addition, there has not been any concrete analysis demonstrating how the current profile evolves as the beam is transported in such tubes. In this paper, we apply the beam physics developed for linacs to high-frequency tubes for the first time. We provide necessary theoretical tools to determine the fundamental limit of the beam pipe sizes for a desired limit of beam interception. Specifically, the effect of both space charge and emittance are incorporated into iterative solution of equilibrium distributions of charge densities in the presence of a uniform focusing axial magnetic field. The effect of phase-space rotation and evolution of beam current is demonstrated through the calculation of beam divergence and maximum excursion of particles. Hence, the numerical solutions and tools provided here are complete analysis and can be used to determine the beam pipe size for any beam emittance. The theoretical formulation and results are expected to be particularly useful for devices operating from mm-wave to sub-THz frequency regimes.

CONFINEMENT OF DUST BALLS IN NEON CRYOGENIC PLASMA

Valeria Shumova[1], Dmitry Polyakov[2], Leonid Vasilyak[1]
1. Joint Institute for High Temperatures of the Russian Academy of Sciences
2. Joint Institute for High Temperatures of Russian Academy of Sciences

The parameters of radial plasma-dust trap have been simulated for dust balls formed from micron sized dust particles in neon dc discharge at 77K. Simulation have been based on the diffusion/drift model of positive column of a glow dc discharge with dust particles [1]. At 77K individual dust particles formed dust clusters [2], which formed dust structures with high average number density of dust particles N. In dust balls N varied in the range between $4 \times 10^5 \mathrm{cm}^{-3}$ and $1.2 \times 10^7 \mathrm{cm}^{-3}$ [3]. In simulations the strong disturbance of electron concentration in a discharge by dust balls have been obtained. Even with the lowest N, there was observed formation of local minimum of electron concentration n on discharge axis. Dust balls were supposed to be confined in radial direction of dc dicharge by the action of radial electric field force, thermophoretic force and ion drag force. Formation of n caused the inversion of radial electric field and consequently ion drag force [4]. It has been found that for dust balls consisted of complex dust clusters, with the proper charge of dust cluster, these forces can form the potential trap with sizes close to that observed in experiment [3].

Work supported by the Russian Foundation for Basic Research, Grant 19-02-00454.

1. V. V. Shumova, D. N. Polyakov, L. M. Vasilyak, Plasma Sources Sci. Technol. 2014, 23, 065008.

2. D. N. Polyakov, V. V. Shumova, L. M. Vasilyak, Plasma Sources Sci. Technol. 2017, 26, 08LT01.

3. V. V. Shumova, D. N. Polyakov, L. M. Vasilyak, Plasma Phys. Rep. 2019, 45, (2), (in print).

4. D. N. Polyakov, V. V. Shumova, L. M. Vasilyak, V. E. Fortov, Phys. Scr. 2010, 82, 055501.

HYBRID QUANTUM-HYDRODYNAMICS/KINETICS MODEL FOR DENSE PLASMA MIXTURES

Lucas J. Stanek[1], Kris Beckwith[2], Jeffrey Haack[3], Michael S. Murillo[4]
1. Michigan State University and Sandia National Laboratories
2. Sandia National Laboratories
3. Los Alamos National Laboratories
4. Michigan State University

Fusion energy promises nearly unlimited, clean energy. One approach to fusion energy production is by means of inertial confinement fusion experiments where a fuel boundary exists (e.g., fuel-liner or fuel-ablator). Unfortunately, in the presence of a wide variety of energy loss mechanisms, obtaining a net gain in energy remains a challenge. The mixing of cooler materials into hot regions can spoil the production of fusion energy. Two ways that cooling occurs is from the mixing of two ion species, or by conduction from the electron species. An existing kinetic model for studying the mixing of ions, is the multi-component BGK (McBGK) equation which describes the ionic heat transfer. One way to add the effects of heat conduction from the electrons is by solving a kinetic equation which is not a computationally tractable approach due to the considerable difference in timescales for the electron and ion species. Instead, hydrodynamic equations of motion for the electron species are derived directly from the McBGK equation and are used to determine how the electrons transfer heat to the ion species. We plan to use our model to aid in the design and interpretation of experiments at Sandia National Laboratories that are being performed on the Z Machine, a large pulsed-power facility. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND Number: SAND2019-1736 A

MAGNETO-HYDRODYNAMIC SIMULATION FOR WIRE ARRAY UNDERWATER ELECTRICAL EXPLOSIONS

Zhigang Liu[1], Dun Qian[1], Xiaobin Zou[1], Xinxin Wang[1]
1. Tsinghua University

Based on the magneto-hydrodynamic (MHD) equations, a numerical simulation is carried out for underwater electrical explosions of a cylindrical wire array with different array radii and number of wires. The simulation model provides a self-consistent description of underwater electrical wire explosion (UEWE) by solving a circuit equation coupled with two-dimensional MHD equations with the help of appropriate material characteristics of the exploding wire. Comparison of the numerical results with the measured waveforms of current, voltage and pressure is shown, and the current and voltage waveforms calculated by numerical model agree well with experimental results. The simulation results also present the interaction details of the shock wave from different wire. Additionally, quantitative description is given for the operating conditions in which peculiar phenomenon, such as current pause and restrike, exists in UEWE system. When the total mass of the explosive wire is fixed, the influence of the number and relative position of wires on the intensity of the converging shock wave is discussed with present numerical model as well, which is of great significance for the structural optimization of wire array electrical explosion system.

This work was supported by the National Natural Science Foundation of China (No.51777113, 51790522).

PLASMA SIMULATION AND MODELING OF PSEUDOSPARK DISCHARGE FOR HIGH DENSITY AND ENERGETIC ELECTRON BEAM GENERATION

Varun .[1], Prasoon Shukla[2], Adrian Cross[3], Kevin Ronald[3], Udit Narayan Pal[4]
1. CSIR- CEERI, Pilani, India and AcSIR, Ghaziabad, India
2. 1Academy of Scientific and Innovative Research, Ghaziabad, U.P.- 201002, India
3. University of Strathclyde
4. CSIR-Central Electronics Engineering Research Institute, Pilani, India

Generation of high density and energetic electron beams of short duration are important in growing areas such as the generation of extreme ultraviolet/X-ray radiation, microwaves, THz radiation and for biomedical and radiography applications [1-2]. A pseudospark discharge (PSD) has the ability to produce the combined highest current density (>108A/m2) and brightness (∼1012Am−2rad−2) electron beams with fast current rise times (dI/dt ∼1011 A/s) [2]. Analysis of the PSD has been carried out for the generation of high density and energetic electron beams from single to multi-gap PSD configurations using plasma simulation codes OOPIC-PRO and COMSOL. The generated e-beams are strongly influenced by the gas pressures (20-80 Pa), electrode apertures (2-6 mm), number of gaps (1-4), trigger energy (1-4 kV) and applied voltages, etc. The generated e-beam currents decrease with the increase in electrode apertures while increase with increase in gas pressures. Detailed consideration is required in choosing suitable trigger energy for operation at higher gas pressures and lower cathode apertures in a multi-gap PSD arrangement [3-5]. It is found that there is a decrease in the breakdown voltage for increasing gas pressures and electrode apertures [3-4]. It has been found that potential distributions in the PSD source is very much responsible for confinement of the plasma and generation of high density and energetic e-beams of different peak currents and sizes.

[1] D. Bowes, et al. Nucl. Inst. Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, vol.335, pp. 74–77, 2014.

[2] A. W. Cross et al., J. Phys. D, Appl. Phys., vol.40, no.7, pp. 1953–1956, 2007.

[3] Varun et al., IEEE Trans. Electron Devices, vol.65, no.4 pp. 1542-1549, 2018.

[4] Varun, et al., IEEE Trans. Electron Devices, vol.65, no.10, pp. 4607–4613, 2018.

[5] Varun et al., IEEE Trans. on Plasma Sci., vol.46, no.6, pp. 2003-2008, 2018.

PIC-DSMC NUMERICAL GRID HEATING IN COLLISIONAL PLASMAS: APPLICATION TO STREAMER DISCHARGE SIMULATIONS

Chris Moore[1], Ashish Jindal[2], Andrew Fierro[2], Keith Cartwright[2], Matthew Hopkins[2]
1. Sandia National Labs
2. Sandia National Laboratories

Numerical heating due to the mesh size being larger than the Debye length is well understood for collisionless PIC simulations [1]. However, the importance of grid heating in collisional, partially ionized plasmas such as streamer discharges is less understood. In these plasma regimes the artificial heating of the plasma can, at least theoretically, be mitigated by collisional energy transfer to the dense background gas. On the other hand, elastic energy transfer is extremely inefficient and by inaccurately increasing the electron temperature both the electronic excitation and ionization rates will increase, potentially leading to significant error in the plasma evolution and the streamer channel density and temperature. To some extent, whether one cares about the numerical error introduced depends on the quantity of interest. Specifically, while the density and temperature of the streamer channel may not affect the streamer velocity or branching, it would most likely change the current carried through the channel. In the present work we investigate how numerical heating in collisional plasmas affect various quantities such as the electron energy distribution function and net ionization coefficient for several cases across a range of mesh sizes. The cases include a 0D, extremely low E/n plasma representing the streamer channel, a 1D fixed-field "electron avalanche" case representing the streamer tip region, and a 2D simulation of a streamer.

[1] C.K. Birdsall and A.B. Langdon, Plasma Physics via Computer Simulation (2005).

* Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

DISPERSION ENGINEERING FOR O AND M-TYPES HIGH POWER MICROWAVE SOURCES

Artem Kuskov[1], Dmitrii Andreev[1], Ahmed Elfrgani[1], Stacie Hernandez[1], Braulio Martinez-Hernandez[1], Edl Schamiloglu[1]
1. University of New Mexico

The design and the development of High-Power Microwave (HPM) sources today relies heavily on Particle-In-Cell (PIC) codes, which allow the source concepts to be virtually prototyped and optimized prior to being built experimentally. The current state of source development consists of developing the geometry of the structure, extracting the dispersion relation from the eigenmodes, evaluating the dispersion properties, and finally adjusting the geometry to obtain the desired wave dispersion [1]. O-type devices and amplifiers have an advantage in having axial symmetry, which can be simulated with a single slow wave structure and periodic boundary conditions [2-3]. The dispersion relation for M-type devices, however, cannot be constructed in the same way due to the entire period being 2π. The UNM HPM group found a methodology that can ease the extraction of the dispersion curve from M-type devices, such as the magnetron or Mitron (inter-digital magnetron), which can be a novel method for dispersion engineering of cross-field devices.

This work explores a methodology for deriving the dispersion relations for O- and M-type devices and attempts to simplify the process of dispersion engineering from the required dispersion characteristics to the corresponding geometry.

1. E. Schamiloglu, “Dispersion Engineering for High Power Microwave Amplifiers,” in Proceedings of the 2012 EAPPC-Beams Conference, Karlsruhe, Germany, Sept., 2012.

2. S.C. Yurt, Design of an O-Type Metamaterial Slow Wave Structure for High Power Microwave Generation (Ph.D. Dissertation, University of New Mexico, Albuquerque, NM, 2017).

3. R.K. Singh, “Cold Analysis for Dispersion, Attenuation and RF Efficiency Characteristics of a Gyrotron Cavity,” World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, vol. 6, 1233-1238, 2013.

FAST A-STABLE IMPLICIT SCHEME AND SCALABLE SOFTWARE MOLTN FOR ELECTROMAGNETICS

Mathialakan Thavappiragsam[1], Andrew Christlieb[1], John Luginsland[2], Pierson Guthery[1]
1. michigan state university
2. Confluent Sciences, LLC

Maxwell's equations based vector potential formulation of electromagnetism is widely used in classical and quantum physics. However, in PIC simulations, the community has primarily focused on Maxwell's equations in first-order form, exploiting the explicit Yee method for the fields with the Boris push for the particles. However, a challenge with this approach is geometry. The community has embraced CUT cells as a solution, however, both particle weighting and field updates on cut cells are problematic and the approximations used together can lead to instabilities, and the fields introduce a stability issue in terms of restrictive CFL. In this work, we are developing a new approach to overcome these issues, based vector potential formulation under the Lorenzo gauge. The scheme is based on the MOLT which first discretizes the operator in time and then solves the resulting boundary value problem using a kernel method. It is fast (O(N)), linear-time, high-order in space and A-Stable to all orders in time. ADI scheme is used for the extension to multi-dimensions, with each line solved independently. High-order is achieved using successive convolution to correct for the splitting error. It avoids the use of matrices, eliminating the main bottleneck in scaling implicit methods. An embedded boundary method is employed to deal with complex geometries, and It does not suffer from small time step limitations. The eventual goal is to combine this method with a novel particle method for the simulations of plasma. So far, the consistency and performance of the scheme are evaluated for EM wave propagation and scattering using different shaped objects including curved boundaries, and the introduction of true point sources that demonstrate how we will look to handle particles. We are developing an open-source code MOLTN which is hardware-independent, scalable software tool, using multi-node MPI, multi-core OpenMP, and GPU Cuda implementation.

ELECTROSTATIC FINITE ELEMENT NUMERICAL MODELING OF SPARK GAP AND RELATED ACCELERATOR STRUCTURES

Greg Dale[1], Salvador Portillo[2], Rena Berdine[2]
1. Los Alamos National Labs
2. University of New Mexico

L3 Applied Technologies is developing series pulsed forming water transmission lines for Los Alamos National Laboratory. The Series Pulse-Line Integrated Test Stand (SPLITS) consists of a set of four, 5.5 ohm coaxial water pulse forming lines in series. Each water line is capable of producing a -300 kV pulse when driving a matched resistive load.

As part of this effort, the University of New Mexico is carrying out a 2d and 3d Finite Element Electrostatic modeling of the main spark gap switch design in support of advanced laser triggered switch resistivity studies. This paper presents results of 2d electrostatic modeling of the main spark gap geometries using the FEM tool ESTAT. 3 dimensional models of these structures using FEM code HiPhi will also be shown as well as some preliminary electrodynamic time domain models for selected geometries.

MODELING OF GAS RECIRCULATION EFFECTS IN NANOSECOND-PULSED HIGH-FREQUENCY DISCHARGES

Steve Adams[1], Jared Miles[1], Asher Straubing[2], Kristina Lemmer[3], Hannah Watts[3]
1. Air Force Research Laboratory
2. University of Dayton Research Institute
3. Western Michigan University

Gas recirculation effects have been modeled following a nanosecond-pulse high-voltage discharge across a pin-to-pin air gap, where subsequent pulses in a burst have been found to couple very efficiently if the repetitive pulses occur above a critical frequency. Previous data from the same pulse discharge system indicated that the inter-electrode gas temperature increased rapidly following the first pulse up to several thousand Kelvin, but the inter-electrode region was rapidly cooling by 4 μs after the first pulse, presumably due to recirculating fresh gas. For this system, repetitive pulses at frequencies of 20 kHz and above exhibited strong thermal coupling, indicating that fresh gas recirculation does not cause a de-coupling of the following discharge until about 50 μs after the first pulse. The model developed is a computational fluid dynamics code that simulates the pulse energy deposited by the initial 10 ns arc into the inter-electrode gas and then computes the evolution of the resulting gas density and temperature profile after the pulse. The grid is set up to be two-dimensional and axially symmetric about the inter-electrode axis with the shape of the electrodes accurately represented. The simulated density profiles as a function of time are compared to experimental measurements which used Rayleigh laser scattering to determine the gas density along several different radial lines through the inter-electrode space. The Rayleigh scattering technique employed a pulsed 532 nm laser and gated intensified CCD camera that allowed both temporal and spatial resolution of the gas density after the pulse discharge.

STUDY OF TWO-SURFACE MULTIPACTOR SUSCEPTIBILITY USING MONTE CARLO SIMULATION

Zizhuo Huang[1], Peng Zhang[1]
1. Michigan State University

Multipactor is a nonlinear phenomenon driven by an rf electric field in which secondary electron emission from metallic or dielectric surfaces, leads to an exponential growth of charge. It is harmful to satellite communications and microwave systems [1]. Here, we apply Monte Carlo (MC) simulation [2] to study the multipactor susceptibility in a gap between two parallel metallic electrodes. For a given fD (f is the frequency of rf field, D is the gap distance between the two surface), we scan the average secondary electron yield (SEY) for a range of magnitude of the input microwave voltage V using MC simulation, to obtain the multipactor susceptibility diagram in the V-fD plane. The results are obtained for secondary emission processes with SEY based on Vaughan's model [3], with fixed emission energy and normal emission angle, and with random initial energy and angle following a preassigned distribution. For both cases, the MC results are different from the analytical theory [2,3]. Analysis of the electron trajectories reveals that the deviation from the analytical theory is due to the presence of mixed multipactor mode.

1. Special sessions on Multipactor, I and II, ICOPS, Denver, CO, June 2018.

2. R. A. Kishek, Y. Y. Lau, L. K. Ang, A. Valfells, and R. M. Gilgenbach, Phys. Plasmas 5, 2120 (1998).

3. J. R. M .Vaughan, IEEE Trans. Electron Devices 35, 1172 (1988).

Work supported by AFOSR MURI Grant No. FA9550-18-1-0062.

HIGH POWER RADIO FREQUENCY PULSE SHAPING FOR A 1.5MW S BAND MAGNETRON SOURCE

Michael Abdalla[1], Dirk Frew[2], Nick Myers[2], Michael Skipper[1], jane Lehr[3], Michael Butcher[2], Manuel Alan[2]
1. ASR Corporation
2. Verus Research
3. University of New Mexico

Verus Research designed and modeled a novel plasma switch assembly to optimize the mechanical and electrical characteristics required to create an efficient and reliable family of switches for megawatt sources. There is a need in the high-power community for a fast rise-time High Power Radio Frequency (HPRF) pulse shaping tool to augment slow risetime HPRF sources, such as magnetrons, to support physics and engineering tests. We developed an efficient High-Power Pulse Shaping (HPPS) capability that can be incorporated into an existing source without the need to procure a different source or pulsed power system, providing test facilities with a tunable, cost-efficient capability. Our augmented capability is used for applications requiring adjustable pulse width while achieving a fast risetime and maintaining pulse repetition frequency; applications include electronics testing, antenna testing, model verification of RF coupling, among others. The use of a high-power circulator combined with HPPS isolates the HPRF source from reflected power created during the pulse shaping process. We discuss optimization of the HPPS design with emphasis on maximizing the ratio of the shaped, output-pulse, peak power to the input peak power. A rise and fall time of less than 10 ns was observed during initial testing with a pulse width of less than 100 ns. We present results from extensive parametric modeling of S-band configurations utilizing a WR284 waveguide, examining the effect of materials properties, gap spacing, and dielectric strength.

FEASIBILITY STUDY OF GUIDING HIGH POWER MICROWAVE WITH LASER CREATED PLASMA RING CHANNELS OR PHOTONIC CRYSTALS IN AIR

Shen Shou Max Chung[1]
1. Department of Electrical Engineering, National Penghu University, Penghu, Taiwan, R.O.C.

High Power Microwave (HPM) is a proven effective mean to suppress electronic system or disable Unmanned Aerial Vehicle (UAV) because the power level can be as high as GW, however, due to basic limitation from antenna theory, the power per unit area quickly decline when the distance to target increases, therefore difficult to extend the effective range to more than a few km. Elaborately designed phased array can ameliorate this situation but comes with its own tradeoffs. Recently substantial progress has been made in High Energy Laser (HEL) such that 50-100 KW DC or pulsed lasers are possible, and it is also used in destroying UAV but with heating mechanism. It seems there is a possibility to combine these two directed energy technologies together to form a new weapon. A ring plasma channel with different reflective index can be formed in air with DC or pulsed HEL, and the HPM can be confined inside the plasma channel to travel to a greater distance without as high attenuation as in open air. Also possible is several plasma photonic-crystal structures can be formed by HEL to trap the HPM inside such structures to transfer the HPM to a longer distance. Each approach comes with its own tradeoffs in total energy efficiency and performance. This HEL outside, HPM inside directed energy weapon can have both the heating mechanism of the HEL and the breakdown mechanism of HPM and maybe described as “Photon Torpedo”. Simulations are used to estimate the field confinement effect of such Photon Torpedo.

INVESTIGATION INTO THE PROPAGATION OF ELECTRON BEAMS OF DIFFERENT SHAPES THROUGH GAS-FILLED SPACE USING PIC SIMULATIONS

Prasoon Shukla[1], Varun .[2], Udit Narayan Pal[3], B. N. Basu[4]

1. 1Academy of Scientific and Innovative Research, Ghaziabad, U.P.- 201002, India
2. CSIR- CEERI, Pilani, India and AcSIR, Ghaziabad, India
3. CSIR-Central Electronics Engineering Research Institute, Pilani, India
4. Sir J. C. Bose School of Engineering, Supreme Knowledge Foundation Group of Institutions, Mankundu, W.B.-712139, India.

The propagation of moderately high energy (10-100 keV) electron beams through gas-filled tubes has been being long studied for various potential applications, such as microwave generation, EUV/X-ray radiation and surface modification [1-3]. However, it appears that not much attention has been paid to understand the mechanism as to how the e-beam cross-sectional shape affects the breakdown of a gas by beam electron impact ionization and how the self-focusing of e-beam by ion channel as well as eventual formation of instabilities under certain conditions takes place [3].This paper attempts to develop the understanding of such a mechanism by making a comparative investigation into the elecron beam propagation of solid cylindrical and annular electron beams through a gas-filled tube, using PIC simulation, under typical operating pressures (5-50 Pa), beam energies (10-50 keV) and beam currents (10-100 A). Analytical formulation of space-charge limiting current for different beam shapes along with the spatial and temporal evolution of beam envelope and cross-section is presented. It has been found that the accumulation of ion channel triggers instabilities deteriorating the beam quality, which happens much earlier in a solid cylindrical beam than in an annular beam. This has been quantitatively inferred based on the dependene of self-focusing behavior, controlled by the space-charge potential and charge-neutralization factor, on beam shapes. Several results investigating the role of beam and plasma parameters in the electron beam propagation through a gas-filled space have also been preented. It is worth extending the scope of the present simulation to study an e-beam penetrating through such a gas-filled space for beam-plasma convective instability in a beam-plasma amplifier.

[1] Varun et al., IEEE Trans. Plasma Sci., vol.46, no.6, pp.2003-2008, 2018.

[2] N. Kumar, et al., Appl. Phys. Lett., 111, 213502, 2017.

[3] U. N. Pal, et al., IEEE Trans. Plasma Sci., vol.45, no.12, pp.3195-3201, 2017.

ELECTRON TEMPERATURE AND DENSITY MEASUREMENTS OF PLASMA GENERATED AT THE FOCUS OF A CW MICROWAVE BEAM

Adrian Lopez[1], Remington Reid[1], John Foster[2]
1. Air Force Research Laboratory
2. University of Michigan

An experimental setup to study plasma generated at the focus of a continuous-wave (CW) microwave beam was designed and constructed at the Air Force Research Laboratory at Kirtland AFB, NM. Experimental studies of free space plasma are of interest because they can help validate and improve theoretical models, such as the Improved Concurrent Electromagnetic Particle-In-Cell (ICEPIC) code. Free space plasma does not interact with bounding wall surfaces, which help prevent non-ideal effects, such as contamination and secondary electron emissions, from influencing the experimental results. In our experimental setup, free space plasma is generated by a multi-kW, 4.7 GHz CW microwave system at pressures ranging from 100 to 200 mTorr. A precision mass flow system controls the composition of the gas used to generate the plasma. Gas pressure, gas composition (a mixture of Ar, N2, and O2), and the power of the microwave beam are varied to study their effects on the stability, uniformity, and parameters of the plasma. Invasive and non-invasive plasma diagnostic methods were implemented to measure the electron temperature and density of the plasma. In addition, simulations of the plasma generated in our experiment were conducted with GlobalKin, a zero-dimensional global-kinetics model, using estimates of the total power absorbed by the plasma generated under different conditions. The results from the experiments and simulations conducted to date will be presented.

MULTIPACTOR IN COAXIAL TRANSMISSION LINES

Nicholas M. Jordan[1], Flynn B. Darby[1], Stephen V. Langellotti[1], Y. Y. Lau[2], Ronald M. Gilgenbach[2]

1. University of Michigan

2. University of Michigan, Ann Arbor, MI 48109, USA

Despite decades of research, understanding and prediction of multipactor in complex geometries remains predominantly empirical. This results in large safety margins in RF design, driving up production and deployment costs to prevent costly operating disruptions or complete device failure.

As part of a Multi-University Research Initiative (MURI) led by Michigan State University, the University of Michigan is investigating multipactor discharges in coaxial geometry. The asymmetric field intensity of coaxial geometry results in different transit times for electrons born on the inner or outer surface of the coaxial line, altering the resonant conditions typically observed in parallel plate multipactor. Minimal experimental data on coaxial multipactor exists in the public domain [1,2]. The published data are for a limited set of materials, and for frequency-gap products, fd, below 3 GHz-mm.

To characterize and mitigate multipactor, we have built a coaxial test chamber comprised of OFHC copper tubing with a replaceable test region. The inner conductor is increased in diameter in the test region using $\frac{1}{4}$-wave step transformers to allow a range of gap distances, d, to be explored. Coupled with frequencies, f, ranging from 0.9 to 2.835 GHz, this test setup will acquire multipactor susceptibility information for fd $>$ 3 GHz-mm, validating concurrent analytic and computational work. Initial coaxial multipactor susceptibility data will be presented.

[1] R. Woo, “Multipacting Discharges between Coaxial Electrodes,” Journal of Applied Physics, vol. 39, no. 3, pp. 1528–1533, Feb. 1968.

[2] T. P. Graves, “Experimental investigation of electron multipactor discharges at very high frequency,” Ph.D. Thesis, Massachusetts Institute of Technology, 2006.

DIAMONAD FILM GROWTH UISNG A MICROWAVE PLASMA JET CHEMICAL VAPOR DEPOSITION

Chun-Yu Lin [1], Jing-Shyang Yen[2], Jwo-Shiun Sun[2], Hua-Yi Hsu[3], Ming-Chieh Lin[4]

1. Department of Mechanical Engineering, National Taipei University of Technology

2. Department of Electronic Engineering, National Taipei University of Technology

3. Department of Mechanical Engineering National Taipei University of Technology

4. Department of Electrical and Biomedical Engineering, Hanyang University,

The research and development of a microwave plasma jet chemical vapor deposition for diamond film growth have been carried out in this study. A 3-D electromagnetic model of microwave plasma interactions is constructed to get more understanding the operating characteristics of diamond film growth. An adaptive finite element method has been employed in the 3-D model. Microwave plasma simulation has been considered as a numerically stiff problem because of the strong nonlinearity and multi-scale properties. The whole system has been simulated self-consistently. In addition, a thin diamond film has been successfully fabricated according to the identical conditions predicted in the simulations. The SEM image shows that the deposited diamond particles are uniformly distributed on the substrate with the size of 1 micrometer which might find application in surface hardening and field electron emission.

1. G. Shivkumar, S. S. Tholeti, M. A. Alrefae, T. S. Fisher, and A. A. Alexeenko, “Analysis of hydrogen plasma in a microwave plasma chemical vapor deposition reactor”, J. Appl. Phys. 119, 113301 (2016).

2. A. Massaro, L. Velardi, F. Taccogna, and G. Cicala, “Experimental and numerical studies of microwave-plasma interaction in a MWPECVD reactor”, AIP Advances 6, 125001 (2016).

SUPPRESSING SINGLE-SURFACE MULTIPACTOR DISCHARGES USING NON-SINUSOIDAL ELECTRIC FIELD

Deqi Wen[1], Asif Iqbal[1], Peng Zhang[1], John P Verboncoeur[1]
1. Michigan State University

Multipactor discharge is a major concern in a multitude of electromagnetic devices, often requiring suppression to properly operate devices and avoid damage. The factors affecting multipactor discharges are mainly from the dielectric window properties and the field distribution. Modifying the window geometry including periodic grooves on the window surface in rectangular or triangular shape, and applying an external dc electric field pointing into the dielectric window or an external dc magnetic field parallel to the surface (perpendicular to the tangential rf field) were discovered to effectively reduce multipactor in the previous studies [1-4]. In our work, both particle-in-cell (PIC) and Monte-Carlo simulations demonstrate that applying a temporal Gaussian-type electric field can suppress single surface-multipactor discharge. Decreasing the half peak width of the Gaussian electric field can reduce the time-averaged multipactor intensity by an order of magnitude at fixed input power. PIC simulation reveals the underlying physical mechanism by examining the electron

impact energy and angle distribution, as well as the dynamic secondary electron yield (SEY). At smaller half peak width, more electrons striking the surface have energies below the first crossover energy of the SEY curve, and a small fraction of electrons have energies higher than the second crossover of the SEY curve with fixed input power, giving rise to weaker secondary electrons emission and a weaker multipactor discharge.

Acknowledgment: This work is supported by AFOSR MURI Grant No.FA 9550-18-1-0062.

[1] A. Neuber, G. Edmiston, and J. Krile et al, IEEE Trans. Magn. 43, 496 (2007).

[2] G. Edmiston, A. Neuber, and H. Krompholz et al, J. Appl. Phys. 103, 063303 (2008).

[3] C. Chang, G. Liu, and C. Tang et al, Appl. Phys. Lett. 96, 111502 (2010).

[4] A. Valfells, L. K. Ang, and Y. Y. La et al, Phys. Plasmas 7, 750 (2000).

LINEAR PLASMA EXPERIMENT FOR NON-LINEAR MICROWAVE INTERACTION EXPERIMENTS

colin whyte[1], Kieran Wilson[1], Alan Phelps[1], Adrian Cross[1], Alan Cairns[2], Robert Bingham, Bengt Eliasson[1], Mark Koepke[3], David Speirs[1], Craig W. Robertson[1], Philip MacInnes[1], Ruth Bamford[4], Kevin Ronald[1]

1. University of Strathclyde
2. University of St Andrews
3. West Virginia University
4. STFC Rutherford Appleton Laboratory

As a non-linear medium, plasma can exhibit diverse dynamics when excited by multiple EM waves. Electromagnetic waves are vital to the introduction of energy in laser plasma interactions and the heating of magnetically confined fusion reactors. In laser plasma applications Raman coupling via a Langmuir oscillation or Brillouin scattering mediated by ion-acoustic waves are of interest. Signals with normalised intensities approaching those used in some recent laser plasma interactions can be generated using powerful and flexible microwave amplifiers, interacting in relatively tenuous, cool and accessible plasma. Other multi-wave interactions are interesting for magnetic confinement fusion plasmas, for example beat-wave interactions between two microwave signals coupling to cyclotron motion of the ions and electrons or the lower hybrid oscillations may be useful in heating the plasmas or for driving currents.

A linear plasma experiment is being built to test such multifrequency microwave interaction in plasma, based on prior research on geophysical cyclotron wave emission and propagation [1,2]. The main section of the plasma will be magnetised at up to 0.05T, with the plasma created by an RF helicon source to generate a dense, large, cool plasma with a high ionisation fraction. A range of frequency-flexible sources will provide microwave beams to enable multi-wave coupling experiments. The paper will present progress on this apparatus and experiments.

The authors gratefully acknowledge support from the EPSRC, MBDA UK Ltd and TMD Technologies Ltd.

[1] Ronald K., Speirs D.C., McConville S.L., Phelps A.D.R., Robertson C.W., Whyte C.G., He W., Gillespie K.M., Cross A.W., Bingham R., 2008, Phys. Plasmas, 15, art.056503

[2] Speirs, D.C., Bingham, R., Cairns, R.A., Vorgul, I., Kellett, B.J., Phelps, A.D.R., Ronald, K, 2014, Phys. Rev. Lett., 113, art 155002

AIR-PLASMA CHARACTERIZATION AT THZ FREQUENCY RANGE

Yin-Dong Huang[1]

1. School of Electronic Science and Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

Nowadays, air-plasma prepared by the symmetry-broken dual-color laser fields is extensively studied as a convenient and low-cost source for terahertz wave generation. In the picture of current model, electrons formed drifting current are contributed to the emissions of THz wave. However, less attention has been paid to the propagation of the THz wave within the air-plasmas. Simple questions, such as what inherently happens during the THz wave propagating through the plasma, are still not well answered. To give a more comprehensive picture of the generation process,the lacking knowledge of the THz propagation within the air-plasma should be added.

Meanwhile, the diagnostics of plasmas could be carried out by measuring the optical properties, due to its unique dispersion relied on the plasma frequency. Different diagnostic light source are naturally limited due to the spectral region of the detector. If the frequency of the probing light is far from the plasma frequency,the phase shift of the detecting pulse may be too low to be observed, introducing a bad dynamic range of detection and a rough estimation of the plasma frequency. Therefore, THz-based plasma diagnostics could be applied as a unique tool for characterizing the property of air-plasma. Meanwhile, it could be performed to reveal more physics locating at THz frequency range by offering both the intensity damping and the phase information.

ELECTRIC FIELD PROFILES IN HIGH GAIN GAAS PHOTOCONDUCTIVE CLOSING SWITCHES

Maksim Verkholetov[1], Ilya Prudaev[2]
1. Tomsk State University
2. Tomsk State University

Electric field profiles in high gain GaAs photoconductive closing switches

Verkholetov M.G.1, Prudaev I.A.1

1 Tomsk State University, Tomsk, Russia

Closing high-gain photoconductive semiconductor switch (HG PCSS) are able to switch electric power of megawatt range with switching times of about 1 ns under triggering with optical pulse. The operational principle of HG PCSS is similar to optothyristor one. The task of this work was the calculation of stationary charge carrier transport in HG PCSS including deep level recharging process at high electric field conditions. The motivation was to optimize the GaAs HG PCSS by using commercially available TCAD software. Thus, this work presents the results of calculation of electrical characteristic profiles (distributions of electric field, charge density, etc.) in different GaAs HG PCSS structures. Two types of deep centers were examined (EL2 donor and Cr acceptor). Also, different structure types were investigated (n-i-n, p-i-p, p-i-n, structures with metal ohmic contacts and Schottky barriers).

We found that the recharging of deep centers leads to nonuniform distribution of electric field. The degree of nonuniformity is strongly depends on contact type and deep levels which are used. For example, for the structures with Schottky barriers the using of chromium deep level is more preferable. In GaAs doped with Cr (GaAs:Cr) the electric field distribution became uniform at the field of 0.1-1 kV/cm. In contrast, the using of EL2 deep donor does not allow to obtain the uniform field distribution: the high electric field domain with the maximum field of 10 kV/cm is formed at the cathode of HG PCSS due to strong field dependence of electron capture cross section of EL2. The rate of field domain expansion is about 1 mm/kV. In this structures the efficiency of switching is relatively low in comparison with GaAs:Cr.

STUDY ON TRANSFORMER NEUTRAL POINT DC ISOLATION DEVICE BASED ON PLASMA-JET TRIGGERED GAS SWITCH

Shuhan Liu[1], Zheng Zhao[1], Yi Sun[1], Qingyu Li[1], Xinyun Zhang [1], Dongdong Huang[1], Jiarui Ren[1], Jiangtao Li[1]
1. School of Electrical Engineering, Xi'an Jiaotong University

With the development of the power industry and urban construction, the scale of projects such as direct current transmission, high-speed railway and underground railway is increasing, and some direct current will leak into the earth. If there is a power transformer on the DC current return path, the power transformer will have a shift in the operating point, causing a malfunction such as abnormal vibration of the transformer. The method of series capacitance in the neutral point of the transformer is widely used. However, the current technical route is flawed because of the fast protection switch is unable to meet the requirements of quickness and reliability.

In this paper, a transformer neutral point DC isolation device based on the plasma-jet trigger switch is designed, including control and trigger system, first ground knife, second ground knife, fast protection switch based on jet plasma trigger switch, and metallic contact. Protection switch, DC blocking capacitor, voltage detector for detecting voltage across the DC blocking capacitor, current detector, control and trigger system for detecting DC blocking current. A starting system based on a magnetic switch is designed to trigger the switch conduction reliably. Also, the structure of the switch is highly improved.

The neutral point DC isolation device based on the plasma-jet trigger switch has short protection time, generally in the microsecond range. Meanwhile, it avoids the shortcomings of insufficient current conduction capability caused by power electronic switches. Without components such as inductance and resistor in the circuit, low neutral impedance of the neutral point of the transformer is ensured. Therefore, the whole device has advantages of short operating time, strong current conduction capability, low switching operating voltage and low impedance of transformer neutral point.

PERSPECTIVES OF SUPERCRITICAL FLUIDS FOR SWITCHING APPLICATIONS

Guus Pemen[1], Tom Huiskamp, Bert van Heesch[2], Wilfred Hoeben[1]
1. Eindhoven University of Technology
2. TUe

Introduction

Fast and repetitive switching in high-power circuits is a challenging task where the ultimate solutions still have to be found. Areas of application are power switches in high-voltage networks and heavy duty switches for pulsed power applications.

Supercritical switch media

We propose a new approach: the use of supercritical fluids as switching medium. Supercritical fluids have insulation strength and thermal properties like liquids and fluidity, self-healing and absence of bubbles like gases. These properties are very beneficial of power switching, and in particular allow very high breakdown voltages (thus compact switches) and very fast recov-ery behaviour (thus repetitive switches). We will pre-sent the concept of a supercritical switch, and data of breakdown behaviour of a prototype supercritical switch. In addition, a model for calculating the re-covery time will be presented, supported by experimental data on the recovery behaviour of supercritical nitrogen.

HIGH PERFORMANCE TRIGGERING TRANSFORMER FOR STACK OF SERIES CONNECTED THYRISTORS

Viliam Senaj[1], David Cabrerizo Pastor[1], Thomas Kramer[1]
1. CERN

Large Hadron Collider (LHC) - the world biggest and highest energy proton accelerator/collider is built on Switzerland/France border at ∼100 m underground. Its circumference is 27 km and it will accelerate up to 4e14 protons per beam to a peak energy of 7 TeV. Under these conditions energy of each beam will be 360 MJ. Safe dumping of the beam with such energy is crucial for the safety of the LHC.

LHC beam dumping system (LBDS) consists of 30 extraction and 20 dilution generators delivering altogether ∼1MA. Extraction generator operates at up to 29 kV and delivers up to 18 kA peak current with pulse duration of 91 us. It employs 2 parallel stacks of 10 series connected fast thyristors with 80 kA rating. Thyristor commutation speed depends on the triggering pulse performance with recommend triggering current peak value 2 kA with slew rate of 5kA/us. Triggering is ensured by a triggering transformer (TT) with a primary driven by two triggering generators operating at 3.5 kV and with multiple floating secondaries individually supplying each thyristors within the stack. Presently used TT (custom designed) limits the triggering current to 500 A peak with slew rate of 400A/us. Ongoing upgrade of LHC calls for increasing of the whole LBDS reliability including triggering system. Main modifications target reduction of TT and cabling inductances. The new TT has fully coaxial design with common primary and ten single turn secondaries with independent magnetic circuits. HV triggering cables are made of 12 parallel twisted pairs with common shielding. Significantly reduced total stray inductance resulted in more than 3x higher peak current and 10x higher dI/dt (1.8kA, 4kA/us respectively) with the same trigger generator voltage. The whole thyristors stack turn-on delay and rise time were reduced by more than 200 ns with proportionally reduced turn-on losses.

DATA ACQUISITION SYSTEM FOR HEH MONITOR

David Cabrerizo Pastor[1], Viliam Senaj[1], Thomas Kramer[1]
1. CERN

Reliable operation of the Large Hadron Collider Beam Dumping System (LBDS) is vital for the machine safety. The role of the LBDS is to extract two counter rotating beams and to dispose of them safely on their respective 8 m long graphite dump blocks. The LBDS consists of 50 pulse generators located in the LHC galleries: each generator is connected to a kicker magnet by, 30 m long, coaxial cables. The pulse generators contain High Voltage (HV) semiconductors, which are susceptible to Single Event Burnout (SEB) - a catastrophic phenomenon for HV semiconductors - due to High Energy Hadrons (HEH). In order to better assess the HEH flux and impact, the development of an HEH monitor, based on the SEB phenomenon in HV Si diodes, is ongoing. This will improve the accuracy of SEB related failure rate estimates and will help to guide mitigation measures. A low cost acquisition system for the HEH monitor was developed. The acquisition system is based on a micro-controller continuously checking new events in up to 16 independent channels each with up to 30 HV diodes per channel: the number of channels and diodes per channel are adaptable according to the sensitivity required. To avoid false counts and coupling effects an adjustable ‘dead-time’filter is used for each channel. Periodic ‘alive’signals and HEH events related information, such as total number of counts, HV value, temperature and total current consumption measurements are both sent to a database, via Ethernet or Wi-Fi connection, and stored in an internal USB or SD card as a backup. In addition, the system allows remote control of the sensitivity of the monitor by modifying the voltage applied to the HV diodes. The whole system has already experienced several irradiation campaigns without any malfunction.

DEVELOPMENT AND SWITCHING CHARACTERIZATION STUDY OF HOT CATHODE THYRATRON FOR PULSE MODULATOR APPLICATIONS IN LINEAR ACCELERATOR

Udit Narayan Pal[1], Mahesh Kumar[2], B. L. Meena[3], Ram Prakash Lamba[3], Harish Kumar Dwivedi[4], A. R. Tillu[5]

1. CSIR-Central Electronics Engineering Research Institute, Pilani, India

2. Microwave Devices Area, CSIR- Central Electronics Engineering Research Institute (CEERI), Pilani, Rajasthan-333031, India

3. Microwave Devices Area, CSIR- Central Electronics Engineering Research Institute (CEERI), Pilani, Rajasthan-333031, India

4. Maharishi University of Information Technology, Lucknow, India

5. Bhabha Atomic Research Centre (BARC), Mumbai, India

High power plasma switches, such as, hot and cold cathode thyratrons have always been the key components of pulsed power systems including pulse modulators, linear accelerators, synchrotron sources, crowbar circuits, cargo scanning systems, sterilization, etc. These switches are classified by their unique pulse characteristics and performances. The unique features of hot cathode thyratron are long lifetime, higher efficiency, moderate rate of current rise (1010A/s), better jitter and high stability. The paper has represented the recent technological efforts made by CSIR-CEERI, India for the design, development and switching characterization of high power 35kV/3KA hot cathode thyratrons for their potential applications in pulse modulators in linear accelerator. The proposed thyratron is a multi-gridded geometry which mainly consists of oxide coated cathode, reservoir/getter, pre-ionize grid, control grid, cathode and anode. The characterization and emission study of the oxide coated cathode in the pre-ionize grid assembly have been performed at different operating conditions in a suitable diode assembly. This has assured for the proper and uniform emission of the electron from the cathode. Deuterium gas has been used in place of hydrogen to improve the hold-off voltage characteristics. The parts and assemblies of the pre-ionizing grid, control grid and anode are designed and fabricated in such a way to have low misfire and quenching free switching at the designed and operating parameters. The switching characterization of the thyratron have been performed for its maximum peak parameters (35kV, 3kA), pulse width of $\sim$5 μs at different operating conditions. The switching performances have been optimized for the range of different parameters, such as, pressure, cathode current/voltage, reservoir current/voltage, etc. It is showing less than 5 ns jitter which makes it suitable of above mentioned applications. The design, fabrication, processing, development and characterization issues of the thyratron plasma switch have also been presented.

DIFFERENT PATTERNS OF CURRENT QUENCHING PHENOMENA DURING PSEUDOSPARK DISCHARGE

Jiaqi Yan[1], Saikang Shen[1], Weidong Ding[1], Lanxi Li[1]
1. Xi'an Jiaotong University

Pseudospark discharge are widely used in high power switches, intense electron beam generation and extreme ultra violet light source. Current quenching is one of the most important problems that seriously hamper the applications of the pseudospark discharge, which is characterized by the appearance of sudden current interruption and inductive voltage spikes at the same time. In this paper, current quenching phenomena are studied experimentally by testing the pseudospark discharge device under various conditions. It is observed that current quenching may occur at the starting, rising, peak, descending and zero-crossing phases of the current waveforms. Four main patterns are summarized from the testing results. The first kind occurs at the transition of current from hollow cathode discharge phase to high current conduction phase; the second kind is the oscillation superimposed on the whole current rising edge; the third kind is the temporary extinction of current at zero crossing; and the last one occurs in the high current conduction phase. Previous studies have focused on quenching correlated with the transition two discharge phases at current rising edge. Its mechanism is mostly believed to be the ion depletion near the cathode surface, while it might need amendment for the other quenching patterns. The details related to specific pattern are discussed. The results in this study could provide further understanding for current quenching.

PERFORMANCE OF 20-KV, 20-A SILICON CARBIDE HIGH-VOLTAGE MODULES

Miguel Hinojosa[1], Aderinto Ogunniyi[2]
1. Army Research Laboratory
2. Army Research Lab

This work describes laboratory measurements of recently-fabricated, state-of-the-art Silicon Carbide (SiC) Insulated-Gate Bipolar Transistors (IGBTs) developed for medium-voltage converters and pulsed-power applications. These next-generation, monolithic devices, have an active area of 0.3 cm2, a drift region of 160 μm, and are rated for 20-kV and 20 A. The IGBTs were co-packaged with SiC JBS/PiN anti-parallel diodes in a half-bridge configuration and utilize Al2O3/SiN substrates for improved thermal performance. In this paper the characteristics of the modules are presented with a focus on switching and conduction losses, power dissipation, burst-mode, and continuous operation. This work supports the U.S. Army Research Laboratory mission to push existing state-of-the-art SiC IGBT technology beyond its current state, to drive innovation in device process, fabrication, design, and packaging, to steer design of SiC IGBTs for pulsed power and low-duty-cycle continuous power Army applications, and demonstrate latest SiC technology with small scale prototypes.

SURFACE PASSIVATION OF GAAS PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHES WITH SILICON RESIN

Yong-Pyo Kim[1], Pyeung Hwi Choi[1], Min-Seong Kim[2], Jiheon Ryu[2], Sung-hyun Baek[2], Sung-Min Hong[1], Sungbae Lee[1], Jae-Hyung Jang[1]
1. Gwangju Institute of Science and Technology
2. Agency for Defense Development

The surface defect states of GaAs substrate may cause surface flashover which results in the immature breakdown of the GaAs based photoconductive semiconductor switch (PCSS) devices. It is also expected that the shorter carrier life time and the high surface recombination velocity at the GaAs surface have impact on the performance of GaAs based PCSS devices.

In this study, the surface passivation effect on the performance of the lateral type 2-mm-gap GaAs PCSS is investigated. The 200-nm-thick SiNx grown by plasma enhanced chemical vapor deposition, and drop casted 1-cm-thick silicon resin have been considered as passivation materials on the GaAs PCSS surface. The operational characteristics of the GaAs PCSS were measured by using 1064-nm triggering laser exhibiting a nominal illumination optical energy of 135 μJ and an optical pulse width of 700 ps. It is shown that the surface passivation can increase the carrier lifetime and decrease the surface recombination velocity by reducing the density of the surface states at the GaAs surface. Thereby, the surface passivated PCSSs exhibit the higher pulse height and the longer pulse width compared to non-passivated devices. It is also noted that the surface passivation of the PCSS retards the onset of surface flashover of the PCSS leading to the higher voltage operation capability. The PCSS without surface passivation suffers from flashover at 2.4 kV and permanently fails after 200 times of operation due to the cracks formed on the surface. The PCSS passivated with silicon resin successfully operates without surface flashover up to the bias voltage of 4 kV. The output characteristics of the GaAs PCSS with and without passivation will be compared in terms of the onset voltage of surface flashover, the height and the width of the electrical pulses. This work was supported by KEPCO (R18XA06-79) and Korea Agency for Defense Development.

COMPARISON OF LATERAL AND VERTICAL PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHES FABRICATED ON 4H-SIC

Pyeunghwi Choi[1], Yong-Pyo Kim[2], Min-Seong Kim[3], Jiheon Ryu[3], Sung-Hyun Baek[3], Sung-Min Hong[4], Sung-Bae Lee[4], Jae-Hyung Jang[4]

1. GIST(Gwangju Institute of Science and Technology)

2. Gwangju institute of science and technology

3. The 4th R&D Institute, Agency for Defense Development

4. Gwangju Institute of Science and Technology(GIST)

Silicon carbide (SiC) based photoconductive semiconductor switches (PCSSs) are interesting because of their potential for higher voltage operation originating from the excellent material properties of SiC. However, the experimentally demonstrated performances of the SiC based PCSSs are still far inferior to those of the GaAs counterpart. To harness their potential inherited from the excellent material properties, more researches are required to improve the device performances.

In this study, the lateral- and vertical-type 4H-SiC PCSSs are fabricated and their performances are compared. The 500-μm-thick, high purity semi-insulating 4H-SiC substrates are utilized to fabricate two different types of PCSS devices. The optoelectronic conversion characteristics of the two types of PCSS devices were measured by using 532-nm-wavelength triggering laser under the applied bias voltages up to 3 kV. The vertical-type PCSS outperforms the lateral type PCSS in various aspects. The vertical-type PCSS exhibits 12-times higher output voltage and 3-times wider full-width-half-maximum (FWHM) pulse width when compared with the lateral-type PCSS for same bias voltage and same irradiation conditions. The vertical PCSS enjoys longer optical path length leading to higher photocurrent. The current conducting channel is formed in the bulk of the vertical PCSS, but the dominant channel of the lateral-type PCSS is formed along the top surface of the device. The high recombination velocity at the SiC surface makes the electron-hole pairs generated close to the surface hard to be collected by the anode and cathode electrodes, which lowers the peak voltage and shortens the output pulse width. It is also noted that the vertical-type PCSS outperforms lateral-type PCSS in terms of high voltage operation capability. The vertical PCSS structures effectively suppress the effect of the imperfect SiC surface and achieves better performance compared with the lateral PCSS structures. This work was supported by KEPCO (R18XA06-79) and Korea Agency for Defense Development

RECOVERY CHARACTERISTICS OF A PLASMA CLOSING SWITCH FILLED WITH AIR, N2, CO2, AND AN AR/O2 MIXTURE

Yuan Yao[1], Igor Timoshkin[1], Scott MacGregor[1], Mark Wilson[1], Martin Given[2], Tao Wang[1]

1. University of Strathclyde

2. University Strathclyde

Gas-filled plasma closing switches (PCSs) are widely used as switching components in pulsed power systems with practical applications in different areas including physical research, environmental and biomedical applications. PCS's have exceptional capabilities to operate in high current (10s kA), high voltage (10s-100s kV) regimes, providing impulses with fast rise time and low jitter. However, the recovery time and recovery voltage can be major limiting factors on the potential use of PCS's in high pulse repetition rate regimes. The present paper reports on an investigation of the voltage recovery of a customised PCS. The two-impulses method was used in this study: after a breakdown by the first impulse, the second impulse was used to determine the recovery voltage in the spark gap. The recovery voltage of the PCS filled dry air, N2, CO2, or a 90%/10% Ar/O2 mixture was obtained for the pressure range from 0 bar to 9 bar (gauge).

THE INFLUENCE OF ELECTRODE PROFILE ON REPETITION PERFORMANCE OF CORONA-STABILIZED SWITCH

Longjie Li[1], Yongsheng Wang[1], Jiangtao Li
1. Xi'an Jiaotong University

Gas-discharge closing switches usually have more poor repetition performance than semiconducting switches. This is due to the recovery of gaseous insulation takes a lot of time, and can restrict the use of the gas switch in repetitive applications. The corona-stabilized switch is a potential plasma closing switch that has excellent PRF (pulse repetition frequency) capability. The electric field inhomogeneity of the switch is considered to have an important influence on the stabilization effect of corona plasma. In this paper, effects of electric field inhomogeneity on recovery rate and repetition performance of gaseous insulation are studied.

A double-pulse power supply, which is capable of generating two continuous voltage pulses with adjustable voltage amplitude and interval time, is used. A corona-stabilized switch with a single rod-plane electrode and gaseous medium of SF6 is investigated. Recovery rate of gaseous insulation in switch is obtained by comparing the breakdown voltage of the first pulse to that of the second at different pulse intervals (from 20μs -1s). Several rod electrodes are tested and the results are compared. Repetition performance under different electric field inhomogeneity is investigated by a repetition rate pulse generator. Charging and breakdown waveforms under a continuous repetitive mode are recorded. The repetition performance of the switch can be indicated by divergence of breakdown voltage. The results are explained by calculating corona critical volume under different electrode profiles. Further, physical model of corona stabilization at negative impulse in SF6 are proposed to help one to better understand the breakdown and recovery characteristics of electric field inhomogeneity dependence, relates the spatial extension of the corona plasma in an inhomogeneous field gap to the inhomogeneity of electric field. The trend of breakdown voltage according with pulse number indicates the relationship between electric field inhomogeneity and cumulative effect that result from continuous repetitive gas-discharge discharge.

POLARITY EFFECT OF REPETITIVE CORONA STABILIZATION BREAKDOWN

Longjie Li[1], Zheng Zhao[1], Jiangtao Li[1]
1. School of Electrical Engineering, Xi'an Jiaotong University

Gas-discharge closing switches have poor repetition performance, which is due to the gaseous insulation will decrease for a short time after the last breakdown , and therefore the gas switch will usually close at a much lower voltage than the initial breakdown voltage. The corona-stabilized switch is based on corona stabilization phenomenon that a space charge develops around the highly stressed electrode and prevents premature breakdown to take place. This means the switch can readily operate with high repetition rates at high operating voltages.

Polarity effect in highly non-uniform electric field is a well-documented discharge feature. The electrode arrangement of the corona-stabilized switch results in a typical highly non-uniform electric field. In this electrode gap, ionization always begins from the rod electrode. But the drifts of space charge under positive and negative impulses have significant difference, which leads to different corona stabilization effects. And the difference is supposed to have a noticeable impact on corona stabilization breakdown. In this paper, polarity effect of repetitive corona stabilization breakdown is investigated. Double-pulse method is employed to investigate the insulation recovery rate between single rod and plane electrode. Recovery rate curves for hold-off voltage are obtained under both positive and negative pulses. Indexes for Repetition performance of corona stabilization breakdown, such as divergence of breakdown voltage, failure rate and cumulative effect, under different external impulse polarity are also investigated by a repetition rate pulse generator. Kinematic law of space charge in corona stabilization breakdown process is studied. The physical model of corona stabilization breakdown in gas switch is established under both positive and negative pulses.

ON THE PERFORMANCE OF TRIGGERED CLOSING SWITCHES DEPLOYED IN HIGH EXPLOSIVE PULSED POWER EXPERIMENTS*

Andrew Young[1], Ronnie Speer[1], Antonio Ferriera[1], Gary Mease[1], Aric Pearson[1], Ashton Ray[1]
1. Lawrence Livermore National Laboratory

High explosive pulsed power experiments conducted by Lawrence Livermore National Laboratory employ several different triggered closing switches. Since experiments are single-shot events, failure in any one of these switches can be catastrophic to the experiment outcome. Thus, repeatability and reliability are key metrics in the assessment of closing switch performance. Presented in this paper are efforts to improve the performance of a triggered closing switch system used in a 450 kilojoule capacitor bank, which is used as a seed current source for magnetic flux compression generator experiments. The capacitor bank switch utilizes two different triggered closing switches: a commercial-off-the-shelf pressurized spark gap and a Livermore-designed solid dielectric puncture switch. Discussion of the commercial spark gap will focus on the results of an experimental investigation into switch reliability - specifically to determine the pre-fire probability. A campaign aimed at improving the repeatability of the solid dielectric puncture switch will be detailed, where almost a two-fold decrease in the average switch function time was observed by reducing the thickness of the solid dielectric. Data captured during the preparation and execution of high explosive pulsed power experiments will also be shown, encompassing the results of these improvement efforts.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

MODERNIZATION OF THE MARX AND RIMFIRE TRIGGERING SYSTEMS FOR THE HERMES-III ACCELERATOR

Chris Grabowski[1], Nathan Joseph[1], SEAN COFFEY[2], Guillermo Archuleta[1], Ethan Gutierrez[1], Benjamin Hughes[1], John Lott[1], Robert Natal[1], Israel Owens[1], John Santillanes[1], Andrew Shay[1], Brent Smart[1], Gary Tilley[1], Keith Tunell[1]

1. Sandia National Laboratories

2. SANDIA NATIONAL LABORATORY

HERMES III is a 20-MeV linear induction accelerator that was constructed at Sandia National Laboratories in the late 1980's and continues operation to this day. The accelerator utilizes 10 Marx banks for its initial energy storage and pulse formation. These Marx banks discharge their energy into 20 intermediate storage capacitors which, in turn, feed 80 pulse forming lines that further condition the pulse. Transmission line feeds from the pulse forming lines then deliver the electrical energy to 20 induction cavities arrayed along the axis of the machine to build the final output pulse along a central magnetically insulated transmission line (MITL). There are two triggering systems within the accelerator that work together in this energy discharge process. One simultaneously triggers the initial energy discharge of energy from each of the 10 Marx banks; the other staggers the triggering of the Rimfire gas switches following each intermediate storage capacitor to synchronize the energy delivery to the downstream cavities with the pulse already propagating along the MITL from the upstream cavities. Until recently, these triggering systems were the original systems dating back to the initial commissioning of the accelerator, however both have now been replaced with new and more modernized systems. Design details for both triggering systems will be presented, along with an overview of some of the initial operational data from the HERMES III accelerator using these new triggering systems.

SILICON CARBIDE DRIFT STEP RECOVERY DIODE STRUCTURES EVALUATED AS >10KV NANOSECOND PULSE POWER SWITCHES USING MIXED-MODE SIMULATION

Stephen Arthur[1], Reza Ghandi[1]
1. GE Global Research Center

Mixed-Mode modeling, is a combination of SPICE circuit and finite element device physics, is used to evaluate SiC drift step recovery diode structures for optimal operation as opening switches for the generation of narrow high voltage pulses in a single loop resonant LC circuit. This comparison is made as a practical means to define device design elements and process steps prior to the fabrication of actual SiC devices.

Parameter entitlements of single devices are made for diodes in the 2000 – 3000 voltage rating range, anticipating serial stacks of these devices to achieve $>$ 10 KV peak nanosecond voltage pulses. Epitaxial structures, high voltage terminations, and carrier lifetime are explored as device variables, with resultant peak voltage, rates of rise, and voltage gain are calculated across a 50-ohm resistive load.

Model results to date indicate for single devices with peak voltages of $\sim$ 2600 volts, dV/dt (90 to 10% of peak) $\sim$2100 volts/nanosecond are possible, pulse FWHM of 2 nanoseconds, and voltage gains (Vpeak/Vsupply) in the range of 12 to 17 can be achieved.

Such devices have potential uses in a variety of pulse power applications e.g. ignition, cell membrane modifications, and environmental (pollution) control.

SKIN EFFECT AND ENERGY LOSSES IN TOROIDAL CORE OF PULSE TRANSFORMER

Boris Fridman[1], Konstantin Lobanov[2]
1. Efremov Institute of Electrophysical Apparatus
2. Efremov Institutte of Electrophyssical Apparatus

The process of pulse magnetization of toroidal cores of pulse transformers is considered taking into the account the viscous type energy losses and eddy currents in the core. The energy losses in the core increase with growth of rate of induction change, and the magnetization current in the primary winding of the transformer increases also. The computational model of the dynamic processes with pulse magnetization is studying; the algorithm of calculation of magnetic field distribution in the core straps is described; the conditions of convergence and stability of the iteration process for the finite difference scheme of the magnetic field calculation are defined. The results of numerical calculations were checked on the experimental examples of the toroidal cores made from cold- rolls transformer steel. The limit conditions for pulse modes of the transformers are considered.

A HIGH-GAIN NANOSECOND PULSE GENERATOR BASED ON INDUCTOR ENERGY STORAGE AND PULSE FORMING LINE VOLTAGE SUPERPOSITION

Jianhao Ma[1], shoulong dong[1], hongmei liu[1], liang Yu, Chenguo Yao
1. Chongqing University

Pulsed gas discharge is an important means of generating low temperature plasma. Short pulses with fast frontier show superior performance in terms of increasing the active particle content, ionization coefficient and electron conversion rate due to its higher voltage rise rate. The common nanosecond pulse generator is based on capacitive energy storage. Compared with the nanosecond pulse generator based on capacitive energy storage, the inductive energy storage has outstanding advantages in energy storage density, miniaturization of the device, and less influence of loop inductance. However, the inductive energy storage also suffers from problems such as limitation of disconnect switch, uncontrollable outputs and waveform distortion.

In this paper, the inductance unit in the transmission line is used as the energy storage inductance, and combined with the characteristics of the rectangular pulse output of the transmission line, and the modular voltage superposition is carried out by using the propagation delay of electromagnetic wave in the transmission line to achieve high-gain rectangular nanosecond pulse output.Then we expand the design of the terminal superposition structure, optimize the magnetic field distribution between the lines to reduce the waveform distortion, and output the nanosecond short pulse.Finally, the paper analyzes the load matching characteristics of the designed pulse generator and provides experimental support for the actual application of the generator.In this paper, the superposition experiment of 10-stage inductive energy storage modules was carried out. The experimental results show that the time-delay isolation method of transmission line can effectively isolate the pulse voltage at the front and rear. The volume of the 10-stage circuit module is 25 cm*6 cm*12 cm, rectangular waveform output, the charging voltage is DC 58 V, the voltage amplitude is 8.2 kV, the voltage gain is about 140 times, the pulse duration is 23 ns and the rise time is 8 ns.

A COMPENSATED LOW-FREQUENCY METHOD FOR THE EXCITATION CHARACTERISTICS MEASUREMENT OF FERROMAGNETIC COMPONENTS

Xin Liu[1], Cheng Zhang[2], Shibin Liang[3], Chenguo Yao
1. China Academy of Engineering Physics
2. Institute of Electronic Engineering, China Academy of Engineering Physics
3. Electric Power Test&Research Institute (group) Co., LTD

It needs a high-voltage, large-capacity, nominal-frequency (NF) power supply to measure the excitation characteristics of ferromagnetic components for field or factory tests, such as current transformers (CTs) and power transformers.However, the high test voltage may damage the insulation of some high knee point voltage CTs and the test equipment are huge for power transformers. A compensated low-frequency (LF) method was proposed in this paper to reduce the test voltage and capacity of power supply for portable application. In this method, the core loss under several LFs are first obtained by sinusoidal power supply excitation. Then the eddy current under LF can be calculated based on Steinmetz core loss separation and least square method.The excitation current and voltage referred to NF are finally determined by compensating the eddy current increment which is caused by frequency increasing. Furthermore, experiments were conducted on a CT and a single-phase power transformer, respectively. Both the results verify that the proposed method is more accurately than the specified Chinese Standard recommended LF method compared with traditional NF method. And it also significantly reduces the test voltage and capacity of the power supply.

STUDY ON SHEATH INDUCED VOLTAGE AND SPATIAL TEMPERATURE FIELD OF LONG-DISTANCE 330/110KV CABLE SHARED THE SAME PIPE JACKING

Shuhan Liu[1], Yi Sun[1], Chenjie Li[1], Yifeng Wang[1], Xin Feng [1], Yuhao Liu[1], Jiangtao Li[1]

1. School of Electrical Engineering, Xi'an Jiaotong University

Cable is the main component of the network of power system. It is usually laid in the underground corridor and its function is to transmit and distribute electrical energy. As with further development of urban construction, cable usage is inevitablty getting higher and higher in hub substation with 110kV or higher voltage levels. Meanwhile, high voltage single-core XLPE insulated power cables will be widely used. In engineering, high voltage level and low voltage level cables share a tunnel or pipe jacking is very common, which can significantly increase the current carrying capacity of the cable. However, the induced voltage of the metal sheath of the single-core cable and the spatial temperature field will be significantly changed.

In this paper, long-distance 330/110kV cable shared the same pipe jacking is taken as example to compare the two types of cross-interconnected methods. First, the appropriate segment length is determined based on the value of sheath induced voltage under steady state. Then, the sheath induced voltage of transient fault is analyzed, including many single-phase ground faults which occur in different places of the cable. Finally, the influence of cable length growth under steady state and transient conditions is discussed.

It is found that the steady-state induced voltage of the sheath increases linearly with the increase of the length of the cross-interconnected small segment. No matter where the fault occurs, the transient induced voltage at the cross-interconnected point closest to the fault point is the highest. If the distance from the fault point increases, the induced voltage will gradually decrease. When fault occurs in the 330kV cables, the sheath induced voltage of the 110kV cables will have a great impact.

A COMPREHENSIVE DESIGN PROCEDURE FOR HIGH VOLTAGE PULSE POWER TRANSFORMERS

Michael Jaritz[1], Reto Christen[1], Matthias Bucher [1], Jasmin Smajic[1], Andreas Stöckli[2], Michael Bader[2], Thomas Franz[1]
1. University of Applied Scienes Rapperswil
2. Astrol AG

Typical pulsed power applications cover the field as e.g. collision and fusion experiments or the generation of high temperatures, as well as the generation of X-rays in medical applications [1]. In these applications, pulsed power modulators are used for generating highly accurate high voltage pulses with very fast rise and fall times and pulse widths from microseconds to milliseconds. In order to produce such very fast rising voltage pulses, pulse transformer based modulator systems are utilized. The rise and fall times can be directly adjusted by the leakage inductance and the stray capacitance of the transformer. Therefore, the proposed design method combines calculation of parasitics with isolation design and dynamic voltage distribution design within the windings.

In the considered application, the required nominal pulse voltage amplitude is 44.2 kV with a pulse power of 4.42 MW, a pulse length of 5 us and a maximal rise time of 1us. In this paper, a comprehensive design procedure for high voltage pulse power transformers is presented. The procedure is based on the finite element method (FEM) and contains an electrical model, a magnetical model, a thermal model of the transformer and a procedure for the isolation design. In addition, to avoid over voltages within the winding, a model for the dynamic voltage distribution is included in the approach as well. For validation of the models and the design procedure, a prototype has been built and is tested under full load conditions. There, the main focus is on evaluating the parasitics, which are crucial for the shape of the output voltage pulse. Further, the isolation design will be proofed by high voltage impulse tests.

[1]. . . D.A.Gerber, ”Ultra-Precise Short-Pulse Modulator for a 50 MW RF Output Klystron for Free-Electron Lasers,” Ph.D. dissertation, ETH Zürich, 2015

STUDY ON AGING CHARACTERISTICS OF DC TRANSMISSION LINE ARRESTER CONSIDERING IMPACT LOAD

Mengzhen Li[1]
1. Xi'an Jiaotong University

Metal oxide arrester (MOA) is the main equipment to limit overvoltage in power system. It has been widely used in UHVDC project in China. The UHVDC system has longer deliver distance. Under the influence of various external factors, the state characteristic parameters of MOA will change and its performance will decline, which is called the aging problem. Unlike the arrester in AC system whose continuous operating voltage is power frequency voltage, the aging of MOA resistors in DC system is more complicated. Based on a $\pm$1100kV UHVDC system in China, this paper studies voltage load waveforms of transmission line arrester in UHVDC system under different operating conditions, and analyzes its amplitude by mathematical methods. Based on simulation results, the impedance characteristics and power consumption characteristics of DC line MOA proportional components under multi-factors were studied. Considering the influence of impact load, the long-term integrated DC aging characteristics of MOA were studied. The comprehensive aging test results show that the DC reference voltage of the mainstream formula has an increasing trend of DC reference voltage after aging, which increases by a maximum of 6.05%; the DC leakage current shows a decreasing trend with a maximum reduction of 76%; the power loss shows a decreasing trend with a maximum of 71.4%. The AC reference voltage shows an increasing trend. The full current, resistive fundamental wave, and third harmonic show a decreasing trend. The capacitance and tanδ decrease slightly, and the residual voltage does not change significantly. The influence of different impact loads on DC aging of MOV is square wave>lightning wave>high current. It is found that there is a polarity effect in DC aging, and the regularity of the positive and negative characteristic parameters of MOV is opposite.

RESEARCH ON DISTRIBUTION PROBLEM OF OVERVOLTAGE ONLINE MONITORING DEVICE ON DISTRIBUTION LINES

Yuhao Liu, Jiangtao LI, Shuang He, Xin Feng[1]
1. Xi'an Jiaotong University

The safety of the power system is related to the magnitude of its overvoltage. Therefore, an overvoltage online monitoring device needs to be installed for monitoring. In order to obtain the lightning overvoltage information of distribution lines and realize effective monitoring of lightning parameters in the area, an overvoltage monitoring device needs to be installed on distribution lines. Considered the wide distribution of distribution lines and many branches, the overvoltage monitoring device cannot achieve full coverage monitoring on distribution lines. Therefore, it is necessary to select lines suitable for installing an monitoring device.

Combined with the data collected by the lightning positioning system and the lightning trip rate of distribution lines, a method for selecting distribution points in distribution lines of monitoring devices is proposed.

Calculate the influence of ground lightning density on p-value and m-value of lightning current amplitude of each line, and counts lightning strike failure rate q of each line.And calculate undefined1, undefined2, undefined3 of the three influencing factors by analytic hierarchy process according to the key factors of the actual lines, and calculates the priority c of each line (c = undefined1 * p + undefined2 * m + undefined3 * q), and lines the device installed on are determined by c. The p-value is calculated according to the flash density grid distribution map of the line region, and the total ground density value p of each line is calculated.The m-value is calculated according to the magnitude of lightning current of the line region, and the total magnitude of lightning current value m of each line is calculated. The q-value is to consider the historical lightning strike failure rate, and the lightning strike failure rate of each outlet is counted q. The final p,m, q is then the result of the normalization process.

DESIGN OF A LONG PULSE HIGH ENERGY WATER TRANSMISSION LINE TO DRIVE HPM SOURCES

Ian Chavez[1], Edl Schamiloglu[2], Kostyantyn Ilyenko[3], Yatsenko Tetyana[3], Salvador Portillo[4]

1. University of New Mexico- Electrical and Computer Engineering Department
2. University of New Mexico
3. Department of Vacuum Electronics of the Institute for Radiophysics and Electronics of National Academy of Sciences of Ukraine
4. University of New Mexico - Electrical and Computer Engineering Department

The University of New Mexico has designed and built a 10-stage high energy Marx generator with a pulse length of 1.5 Microseconds. This Marx generator has the capability to drive low impedance HPM loads such as the Magnetically Insulated Line Oscillators as well as HEDP loads like a DPF. A transmission line coupling the Marx to the load is the typical energy transfer mechanism for such a system. However, these loads require both fast rise times as well as relatively flat top peaks as both coupling of electromagnetic fields to cavities and plasma density during stagnation are sensitive to the onset of peak fields and to peak voltage variations. Additionally, both loads are sensitive to capacitive coupling of the Marx charge voltage to the load-leading to premature plasma production and possibly leading to instabilities in the run down phase of DPF devices as well as early onset of neutral desorption in HPM sources. All of these problems must be addressed by careful transmission line design. To this end, this presentation discusses time- and frequency-domain finite element electromagnetic numerical simulations of a 2.5-meter-long, high dielectric constant (81) water transmission line with a spark gap peaking switch, as well as with an additional pre-pulse peaking switch.

A 1 MV TESLA PULSED TRANSFORMER

Matthew Woodyard[1], Bucur Novac[2], Peter Senior[2]
1. Loughborough Univesrity
2. Loughborough University

A 1 MV transformer, based on Tesla technique, was designed and most of its components were already manufactured. The paper will present the calculations performed for obtaining an optimum design for the major components of the arrangement, such as the windings and the 1 MV switch connecting the load.

COMPARISON OF DECOMPOSITION BY-PRODUCTS OF C4F7N/CO2 MIXED GAS UNDER AC DISCHARGE BREAKDOWN AND PARTIAL DISCHARGE

Yongyan Zhou[1], Chenwei Li[2], Nian Tang[1], Boya Zhang[2], Li Li[1], Xingwen Li[2], Xiaodian Li[1]
1. Electric Power Research Institute of Guangdong Power Grid Co. Ltd
2. Xi'an Jiaotong University

In recent years, C4F7N has been highly concerned due to its excellent dielectric performance and arc-quenching ability. As a potential alternative to SF6, the decomposition characteristics of C4F7N will directly affect its application prospects. However, there are few studies on the decomposition characteristics of C4F7N mixed gas at home and abroad. Therefore, we conducted AC discharge breakdown experiment and partial discharge experiment on C4F7N-CO2 mixed gas, and qualitatively and quantitatively analyzed the gas decomposition by-products of C4F7N-CO2 mixed gas respectively by gas chromatography-mass spectrometry (GC/MS). The results show that the major decomposition by-products under AC discharge breakdown are CF4, C2F4, C2F6, C2HF4-CN, C3F8, CF3-CN, C3F6, C4F6, C4F10, C2F5-CN, C2N2, C3HF7, HCN, C2F3-CN, HF, and CF3-CN's content is the largest. the major decomposition by-products under partial discharge are CF4, C3F8, CF3-CN, C3F6, C4F10, C2F5-CN, C2N2, C3HF7, HCN, C2F3-CN, HF. Compared with the partial discharge process, AC discharge breakdown produces more types of decomposition products, and the content is larger.

DESIGN OF A DIELECTRIC COMPRESSION BUSHING FOR COMPACT, HIGH-VOLTAGE APPLICATIONS

Michael Butcher[1], Manuel Alan[1], Dirk Frew[1], Michael Skipper[2], Michael Abdalla[2]
1. Verus Research
2. ASR Corporation

High voltage insulation methods that can easily be assembled and disassembled are of use on compact pulsed power systems. High voltage isolation systems are a key element for reliable pulsed power operation. Verus Research's Dense Plasma Focus (DPF) system, under development as a radiation test source for the U.S. Army, requires an electrical-mechanical interface that can withhold a minimum of 100 kV peak voltage in air, during nominal operation over a small distance. A solid dielectric compression washer was used to make a critical seal providing high voltage isolation. A layered design constructed of thin Kapton film was fabricated to provide a long tracking path and sufficient dielectric strength with minimal inductance to prevent failure of the bulk material and transfer electrical stress upon the high voltage compression region. A test apparatus was designed and fabricated to test the failure point, and to identify the failure mechanisms. Multiple materials, such as silicone and urethane, as well as different compression concepts were tested to failure using the test apparatus and a 1 stage MARX to generate a high voltage pulse up to 200 kV for the test. Results from electrostatic modeling and empirical testing of the high voltage designs are presented here, as well as findings for the leading breakdown failure mechanism.

This work is performed under contract through the U.S. Army's Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI) and funded by the Test Resource Management Center's Test and Evaluation/Science and Technology (TRMC T&E/S&T).

A SEQUENTIAL CHARACTERIZATION METHOD FOR THE INSULATION EVALUATION OF THE ROD-PLANE GAP UNDER REPETITIVE FREQUENCY NANOSECOND PULSES IN HIGH-PRESSURE NITROGEN

Zheng Zhao[1], Dongdong Huang[1], Jiangtao Li[1]
1. Xi'an Jiaotong University

The high voltage repetitive frequency nanosecond pulse (RFNP) generator is an important equipment in many industrial and scientific applications, including the plasma-assisted combustion and plasma-surface interaction. The gas-insulated gap, one of the typical insulation infrastructures, is required to withstand RFNP. It is usually accepted that the insulation capacity of the gas gap under RFNP is much lower than that under single pulse due to the accumulation of metastable species, electrons and positive/negative ions. However, little research has been devoted to systematically characterize the dynamic evolution of the insulation capacity under RFNPs in high-pressure gas. In this paper, a sequential characterization method and typical influential parameters were investigated. Every voltage and emission light intensity in a sequence were acquired in the sequential acquisition mode to achieve the pulse sequence resolution.

Under positive RFNP, the number of pulses before breakdown Ni from 0.1 to 0.4 MPa was obtained with the same voltage working coefficient. It was found that Ni dramatically and nonlinearly depended on the pulse repetitive frequency (PRF). The emission intensity of corona discharge under positive RFNP was found in the discrete mode in a sequence and the repetitive frequency of corona discharge was closely related with the PRF. On the contrary, under negative RFNP, the corona discharges in a sequence were in the continuous mode. The latter average emission intensity of corona discharges was lower than that of the first corona discharge. Meanwhile, the inception time of following corona discharges decreased with the PRF.

The chemistry and diffusion dynamics during the pulse-off period was found to be vital for the discharge characteristics under RFNP. The proposed sequential characterization method illustrated advantages for the complete description of insulation strength evolution of the rod-plane gap under RFNP in nitrogen and was beneficial for understanding the space charge behaviors.

EXPERIMENTAL APPROACH OF THE DIELECTRIC STRENGTH OF A VACUUM INSULATOR

Baptiste Cadilhon[1], Laurent Courtois[1], Eric Pasini[1]
1. CEA

One of the main limiting factors in the design of high-power vacuum systems is a surface flashover occurring over the insulator surface between two conducting regions separated by a high-voltage gap. To decrease the probability of this phenomenon, traditional approaches include an increase in the area of insulators, screening tricks of triple junctions and limitation techniques of the secondary electron multiplication.

The design of multi-pulse systems such as multi-MeV, multi-kA induction injector needs to consider radial vacuum insulator stacks which can withstand multiple (two or more) mechanical impulses and multiple electric stresses coming from the generation of multiple high-power pulses. Those high-voltage components are generally designed from J.-C. Martin and Bluhm laws describing the breakdown probability as a function of the electric field, surface concerned and time of exposure.

We take the opportunity of having a dual-pulse high-voltage generator to manage an experimental study on a dedicated setup in order to improve our understanding breakdown phenomena in such geometries and to verify the validity of Martin's law for a two times stressed insulator. The experimental setup is a vacuum chamber in which one can test different dielectric materials compressed between different electrode shapes and stressed by two 250kV-70ns high voltage pulses. Main results of the first campaign will be presented.

EFFECT OF DIELECTRIC COATING ON BREAKDOWN STRENGTH IN HIGH PRESSURE SF6

Chuyu Sun[1], Haiyang Wang[1], Linshen Xie[1]
1. Northwest Institute of Nuclear Technology

Ceramic coating can be used as electrical insulation in demanding conditions, like high-temperature ambience or other harsh environment. However, the breakdown characteristics of ceramic coating electrode have been little discussed. In this paper, the effect of alumina coating on breakdown strength has been investigated in 0.3 MPa SF6 under nanosecond pulses. Seven pairs of bare electrodes and coating electrodes were employed with varied thickness of alumina coating. It was shown that the breakdown strength of these electrodes presented tiny differences when the applied voltage was relatively low. However, as the applied voltage increased, the breakdown voltage gap between bare electrodesand coating electrodes started to become bigger. The different process of discharge initiation and time delay may be the main causes for this phenomenon. To investigate the effect of coating layer, the coating electrode was utilized respectively as cathode and anode. Aphotomultiplier with quick time response and sensitive light response was also employed to monitor the breakdown process.

INFLUENCE OF THE CREEPAGE DISTANCE ON SURFACE FLASHOVER OF THE EPOXY INSULATION UNDER AC VOLTAGE IN C4F7N-CO2 MIXTURES

Zhongbo Zheng[1], Weidong Ding[1], Zhichuang Li[1], Yishu Liu[1], Yue Li[1], Chongjian Ge[2], Jiayin Yan[1]

1. Xi'an Jiaotong University

2. Xi'an Jiaotong

With the increasing usage of sulfur hexafluoride, the disadvantages of its high GWP are becoming increasingly prominent. Therefore, looking for alternatives to SF6 gas to promote gas-insulated technology to an environmentally friendly direction has important engineering and practical value. The mixture green gas C4F7N/CO2 which is most potential to subscribe SF6 arouses the concern of the researchers worldwide. However, recent researches focus on the breakdown performance of gas gap and the flashover performance in this mixture gas is rarely studied.

In this paper, the surface flashover experiment platform is built and PR equation and Antoine equation are used to amend the mixing method and calculates the liquefaction temperature. The influence of creepage distance on power frequency flashover voltage under uniform electrical filed is studied. The gas pressure of the mixture is 0.1MPa, 0.3MPa and 0.5MPa while the concertation of the C4F7N is 0%, 5%, 9% and 13%.

Results show that the surface flashover voltages of the pure CO2 will be promoted up to 2 times when adding 5% C4F7N to it. With the increase of the creepage distance, the dielectric strength of the mixture gas is going to decrease under the same pressure and C4F7N concentration. When gas pressure rises, the downward trend exacerbates with the increase of the creepage distance. What's more, Increasing the C4F7N concentration has no obvious effect on increasing the surface flashover voltage.

ELECTRIC FIELD ANALYSIS OF 35KV LINE ARRESTER UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

Mengzhen Li[1]
1. Xi'an Jiaotong University

With the rapid development and extension of power system, transmission line can go through mountainous area where the climate is more complex than plain. Therefore, line arresters, which are usually used in power system to protect devices from overvoltage, are exposed to fog and dust in the air and even to ice. In actual operations, the surface insulation strength of metal oxide line arrester can be thus decreased due to inevitably dirt and icing, and the flashover voltage can be significantly reduced, which threatens the operation safety of the entire transmission line. Operation experience shows that most accidents occurred on transmission lines are caused by switching and lightning overvoltage, which will make electric field and potential distribution of line arrester even worse under bad surface condition. Therefore, the internal and external electric field and potential distribution of a 35kV line arrester under power frequency voltage, switching and lightning overvoltage are studied quantificationally. ANSYS and COMSOL finite-element software was used to calculate the field and potential distribution of the arrester under clean, polluted and icing condition. Based on the analysis of the electric field distribution, the main influence factors of the electric field and potential distribution as well as the equivalent calculation method under different environmental conditions of the arrester are obtained, which can give help to the design and application of line arresters under different environmental conditions. Based on these calculation, artificial pollution test and icing test are carried out in laboratory, which give support to the result of quantificational calculation and analysis.

STUDY OF DISSOCIATION CHARACTERISTIC OF SF6-N2 MIXTURES UNDER CORONA DISCHARGE WITH PIN-TO-PLATE ELECTRODE

Jiayin Yan[1], Weidong Ding, Yanan Wang[1], Saikang Shen[1], Lanxi Li[1], Zheng Zhongbo[1]
1. Xi'an Jiaotong University

SF6/N2 gas mixtures has the huge potential. However, due to the inevitable insulation defects in high voltage apparatus, partial discharge is caused, and then the mixture is decomposed, which ultimately endangers the safe operation of the equipment. The study on the decomposition of SF6/N2 mixtures in corona discharge is of guiding significance to the timely detection of early failure of equipment and the insulation of diagnostic equipment.

In this paper, the defect model of electrode corona discharge was designed, and the experimental platform was set up. The variation of discharge during SF6/N2 mixtures decomposition was studied by using impulse current method. By changing the applied voltage, gas pressure, gap distance, water content, and mixing ratio respectively, the effects of these factors on the discharge energy, discharge quantity and decomposition products of SF6/N2 mixtures were studied. The experimental results show that the SF6/N2 mixtures decomposition produces include NF3, SOF2 and SO2F2 under the defect of the corona discharge of the pin-to-plate electrode. The production rate of NF3 is low while the output of SOF2 is more than SO2F2. The production of decomposition products also increases along with the discharge time increasing, the applied voltage increasing, the pin-to-plate electrode gap distance reducing, the SF6/N2 gas pressure and the proportion of SF6 reducing. The ratio and the total yield of SF6/N2 mixtures decomposition products can be used as the characteristic parameters to distinguish the spark discharge and corona discharge of the pin-to-plate electrode.

THE DISCHARGE CHARACTERISTICS OF C5 AND ITS MIXTURES IN UNIFORM FIELD UNDER AC VOLTAGE

Yue Li, Zhichuang Li[1], Jiayin Yan[1], Zheng Zhongbo[1], Yishu Liu, Yanan Wang[1], Alfred Suzan, Weidong Ding[1]
1. Xi'an Jiaotong University

SF6, an insulated gas with high dielectric strength, is widely used in the power system. However, SF6 is one of the six limited greenhouse gases specified with a GWP of 23500. Therefore, it is necessary to assess a candidate as alternatives to SF6 in electrical equipment.

In this paper, a new insulating media C5F10O with a GWP value of only 1 and a dielectric strength twice that of SF6 is studied. The discharge characteristics of C5F10O mixed with N2, CO2, and Air in different pressure, ratio are discussed in uniform field under AC voltage. An experimental platform for the discharge was designed, which consists of a 300 KV AC generator, divider, and a test chamber, where the Rogowski electrodes with the distance of 10mm are mounted. The breakdown experiments of 95%CO2/N2/Air mixed with 5% C5 at 0.1-0.5 MPa were carried out respectively. The experiments were repeated at least five times for each test condition. The results show that the insulation performance can be greatly improved by adding a small amount of C5 gas to CO2/N2/Air. Among them, C5 mixed with Air has the best insulation performance, followed by the mixture with N2 and CO2.The insulation strength of 5% C5 /95% Air at 0.5MPa can reach 78% of SF6 in the same experimental conditions. In addition, the breakdown voltage of 2%C5, 5%C5 and 8%C5 mixed with Air at 0.1-0.5 MPa were measured. The results reveal that the higher the mixing ratio of C5, the higher the discharge voltage of mixed gases is. At 0.5MPa, the insulation strength of 8%C5/92%Air is approximately 87% that of SF6.

Therefore, the mixtures of C5 and Air are expected to replace SF6 in terms of electrical strength. However, the liquefaction temperature of gases and the toxicity of products after decomposition need to be considered comprehensively.

C5F10O/N2 GAS MIXTURE TO SUBSTITUTE SF6 IN HIGH VOLTAGE APPLICATIONS

yue li, Zhichuang Li, Jiaqi Yan[1], Yishu Liu, Zheng Zhongbo[1], Yanan Wang[1], Alfred Suzan, Weidong Ding[1]
1. Xi'an Jiaotong University

In recent years, C5F10O has become one of the most promising alternatives to SF6.Not only because it fundamentally solves the issue of greenhouse effect of SF6 with the GWP of 1, but also, thanks to its high content of fluoride, the insulating strength of C5 is twice as good as SF6.However, the liquefaction temperature of C5 is 27°C under normal pressure, so the most crucial challenge for it is the liquefaction case for high voltage application.

In this paper, N2 is added to C5 to reduce its liquefaction temperature. Refer to the practical application, the scheme of C5 mixed gas instead of SF6 is explored combining with liquefaction temperature and the concentration of C5.Firstly, the saturated vapor pressure of C5/N2 gas mixture at different temperatures and molar concentrations was calculated by using Antoine equation and gas-liquid equilibrium law. The results reveal that 2%C5/98%N2, 5%C5/95%N2and 8%C5/92%N2 liquefied at 0.7MPa, 0.3MPa and 0.2MPa under the lowest operating temperature of GIS(-15°C)respectively. And then, the breakdown voltage of mixture with different concentration in critical conditions is measured under AC voltage. Furthermore, the LM algorithm is used to fit the function with gas pressure P and molar ratio K. It demonstrates that under the saturated vapor pressure, the insulation strength of 2%C5, 5% C5,8%C5 gas mixture can reach up to 78%, 56% and 43% of SF6 at 0.5MPa.Therefore, increasing the pressure is a more effective way to improve the insulation strength of C5 mixture than ratio.

In summary, the paper indicates the mixture of 2%C5/98%N2 at 0.7MPa is expected to replace SF6 at 0.5MPa in GIS, which provides an important reference for the substitution of C5 in high voltage application.

INVESTIGATION OF IMPULSIVE BREAKDOWN OF INTERFACES FORMED BY ESTER INSULATING LIQUIDS AND SOLID DIELECTRICS

Chris Williamson[1], Igor Timoshkin[1], Scott MacGregor[1], Mark Wilson[1], Martin Given[1]

1. Strathclyde University

As naphthenic mineral oils are classified as a Class 1 water hazard, both the power and pulsed power industries are actively investigating suitable replacement liquid insulation. Natural and synthetic ester liquids present a possible alternative to these naphthenic mineral oils, primarily due to their comparable dielectric properties. Furthermore, ester liquids offer a number of additional benefits over conventional naphthenic oils such as improved biodegradability, reduced toxicity, increased flash point and the ability to absorb large amounts of moisture, as a consequence of the higher saturation point of ester liquids. For these reasons, significant research efforts have focused on the suitability of esters in the replacement of naphthenic mineral oils. However, most published research has examined ester liquids as the insulating medium within bulk insulating systems, with little known of the performance of liquid-solid interfaces formed between esters and solid polymers used in practical high voltage power and pulsed power systems.

This paper will present and discuss the breakdown performance of liquid-solid interfaces formed by MIDEL 7131 synthetic ester, FR3 natural ester and different solid dielectric materials, Nylon 66, Perspex and PVDF. These interfaces will be stressed with standard lightning impulse voltages of both positive and negative polarity, following the IEC 60897 methodology. This standard uses a point sphere geometry generating a highly divergent field. Key breakdown characteristics, such as breakdown voltage and time to breakdown will be obtained and compared with those for liquid-solid interfaces formed between the same chosen solid dielectric materials and a naphthenic mineral oil. The results of the study will provide data for designers and operators of power and pulsed power systems, helping to determine whether naphthenic oils can be directly replaced with esters in existing high voltage designs, and informing the clearances in new designs.

RESEARCH ON THE SPECTRUM OF THE SURFACE FLASHOVER OF THE HIGH-GAIN GAAS PHOTOCONDUCTIVE SEMICONDUCTOR SWITCH

Shaoqiang Wang[1], Wei Shi[1], Cheng Ma[1], Hong Liu[1], Lei Hou[1]
1. Xi'an University of Technology

The GaAs photoconductive semiconductor switches (GaAs PCSS) have present huge development potential in many application fields, for example dielectric wall accelerator, terahertz source, ultra-wideband pulse source and high-power microwave weapons, etc. Compared to the pure electrical switch devices, the GaAs PCSS have many advantages, such as fast response speed, good stability, and simple structure. When the GaAs PCSS work in the high-gain mode, the high electric field is a necessary condition. And the high bias electric field is the most effective way to increase the output electric pulse amplitude. But in the strong electric field, the surface flashover seriously affects working voltage and the lifetimes of the GaAs PCSS. So the development of GaAs PCSS has been hampered by the surface flashover. Although the surface of GaAs is covered with organic silicon gel, surface flashover still occurs. Compared to the spectrum of the surface flashover of the GaAs PCSS in different conditions, the process of surface flashover is studied. In the spectrum of surface flashover with the laser excitation, the spectrum line of 890nm is presented. What is more, only under the laser excitation can the spectrum line appear. Based on the F-K effect and two-photon absorption principle, the phenomenon is reasonably explained. And the phenomenon eventually leads to fact that the current filament propagation velocity is much faster than the carrier saturation drift velocity in the high-gain GaAs PCSS.

* Corresponding author: Wei Shi, E-mail: swshi@mail.xaut.edu.cn.

MODES OF KHZ AC DISCHARGE IN LIQUID PHASE H2O

Xiaoliang Tang[1], Siyuan Dong, Zidian Liu, Gao Qiu
1. Plasma Physics & Application Lab., Department of Applied Physics, College of Science, Donghua University.

Liquid plasma is a new concept developed in recent decades and has been studied since the late 1960s. It can be divided into three types: DC discharge, pulsed discharge, RF (Radio Frequency) and microwave discharge. As the liquid phase discharge environment is complex, the mechanism of discharge is still largely unknown at present. The field ionization is a discharge mechanism proposed by Kuskova, which argues that the strong electric field causes electrons to accelerate collisions, the plasma is produced by liquid water ionization; Rogers used the field ionization mechanism, and they consider that the discharge process is the dissociation of water Dissipated state, modeled the discharge processes "dissociation"; the breakdown mechanism of bubbles is that the discharge occurred in water bubbles, the bubbles were generated by the ohmic heating water at the tip of the electrode, when the bubble is large enough to form a bridge, water bubbles are breakdown and produce discharge; some other scholars believe that electrical breakdown of liquid is a mixing process of heat and electricity, the regulation of heat and electricity in liquid phase discharge is particularly important.

In this paper, some experimental equipment has been set up for kHz frequency AC liquid phase discharge, and the temperature of the deionized water was regulated during discharge. The electrical characteristics and spectra of liquid phase H2O discharge have been investigated. Two discharge modes, high temperature and low temperature, were both found. The results show that there are two mechanisms in liquid phase discharge: the field ionization mechanism and the breakdown mechanism of bubbles, and these two mechanisms are always developed simultaneously; the temperature is the key factor determining the discharge type. At high temperature, the breakdown of bubbles is the main discharge mechanism, and the field ionization mechanism occurs mainly at low temperature.

INSULATOR TECHNOLOGIES TO ACHIEVE MAXIMUM ELECTRIC FIELD HOLDOFF

Cameron Harjes[1], Jon Cameron Pouncey[1], Jane Lehr [1]
1. UNM

In large machines, such as accelerators and high power microwave systems, it is common to implement pulsed power technology. Pulsed power attempts to deliver large amounts of power in a short amount of time. This is done by generating high voltage and delivering that energy to the desired load quickly through switches. To ensure that the energy is delivered to the desired load it is necessary to use insulators to separate high voltage from ground. The insulators function is crucial in the success or failure of the system and because of this, much research has been done in the materials, geometries, and sizes of insulators. A common mean of failure for these insulators is surface flashover. Surface flashover occurs when the electric field becomes strong enough to accelerate electrons along the surface of the insulator to a point where an arc is created between high voltage and ground. The machine is therefore limited to the amount of voltage it can holdoff and the amount of power it can deliver. By making modifications to the insulator, improvements in electric field holdoff has been documented. This paper attempts to analyze the different methods used to increase the electric field holdoff to improve the function of the system.

IMPACT ON ELECTRODES DURING PLASMA DECOMPOSITION OF CARBON DIOXIDE

Kamau Wright[1], Toby Poole[1], Chittaranjan Sahay[1]
1. University of Hartford

A reactor being developed and instrumented for plasma decomposition of carbon dioxide contains a pin-to-plane microdischarge, with a stainless steel pin and aluminum electrode. The degradation of the aluminum electrode over testing time is an unwanted effect of this particular system. A predictive model of degradation of the current electrode is being developed to relate the system parameters and treatment time with degradation of the electrode. Other aspects of the set-up are also being studied based on this phenomenon, including energy losses from the system, which can detract from the overall efficiency of the process of plasma decomposition of carbon dioxide. A test electrode of aluminum is arranged with a demarcated grid of test sections. Then, plasma discharges are applied at the centers of these grids within each area of approximately 2 mm x 2mm. Scans of these areas are taken using a three-dimensional optical profiler for non-contact measurement and characterization of micro- and nano-scale features of the aluminum surface. It should be noted that the instrumentation utilized provides up to 0.15 nm vertical precision. Hence, a predictive model can be developed with the purpose of determining how long the discharge gap length can remain within a reasonable range to sustain the plasma discharge across the electrodes. Toward the goal of engineering a plasma system which can be consistently deployed to decompose carbon dioxide, considerations on longevity of the electrodes and/or necessary maintenance can be a useful step in scaling these systems and preparing them for more widespread use. Results will include impact of the microdischarge on the electrodes during typical treatment times of plasma decomposition of carbon dioxide.

SUSTAINED FUSION REACTIONS FROM A SHEARED-FLOW-STABILIZED Z PINCH

Uri Shumlak[1]
1. University of Washington

The Z-pinch plasma configuration is one of the earliest magnetic confinement concepts. It has a simple cylindrical geometry and an equilibrium characterized by radial force balance in which plasma pressure is confined by an axial (Z) current. The force balance indicates that fusion conditions can be achieved through plasma compression simply by increasing the current; however, virulent pressure-driven instabilities quickly destroy the equilibrium and obfuscate the path to fusion for the traditional Z pinch. More recently, introducing a sheared axial flow to the plasma was theorized to stabilize the Z pinch. Closely coupled with computational studies, a series of Z-pinch experiments (ZaP and ZaP-HD) at the University of Washington were used to test the theory of sheared-flow stabilization. Diagnostic measurements of the plasma equilibrium and stability confirmed that in the presence of a sufficiently large flow-shear, gross Z-pinch instabilities were mitigated, and radial force balance was achieved. Z-pinch plasmas of 50, 100, and 126-cm lengths were held stable for durations much longer than predicted for a static plasma, i.e. thousands of growth times. Adiabatic scaling relations combined with single-fluid and two-fluid simulations facilitated the theoretical understanding of stabilization which enabled increasing plasma parameters. Flow-shear stabilization was demonstrated to be effective even when a 50-cm long plasma column was compressed to small radii (3 mm), producing increases in magnetic field (8.5 T), density (2e17 /cc), and electron temperature (1 keV) as predicted by adiabatic scaling relations. The collaborative FuZE (Fusion Z-pinch Experiment) project between UW and LLNL scaled the sheared-flow-stabilized Z pinch to fusion conditions, and showed that fusion neutrons are produced in a 50-cm long Z-pinch plasma generated with a deuterium and hydrogen gas mixture. A 30-cm long neutron production volume was temporally and spatially resolved. Sustained neutron production was observed for durations up to 8 microseconds during which the plasma was stable, and the current was sufficiently high to compress the plasma to fusion conditions. The neutron production was demonstrated to be consistent with a thermonuclear fusion process since it was not associated with MHD instabilities and beam-target effects were found to be negligible. Likewise, the neutron yield scaled with the square of the deuterium concentration and agreed with the thermonuclear yield calculated from the measured plasma parameters. Experimental observations generally agree with theoretical and computational predictions, indicating that sheared flows can indeed stabilize and sustain a Z-pinch equilibrium and offering a potential path to achieve even higher performing plasmas.

ROADMAP ON THE DEVELOPMENT OF KLYSTRON MODULATORS FOR ESS

Carlos Martins[1]
1. European Spallation Source

The European Spallation Source will require, by its completion, a pulsed Linac capable of delivering a proton beam with a peak power of 125MW and a pulse width of 2.86ms and a pulse repetition rate of 14Hz. The required klystrons are fed by 33 high power long pulse modulators, each rated for 115kV/100A;3.5ms/14Hz. Due to their high power levels, not only the quality of the pulses delivered is of great concern, but also the power quality on the AC grid is a challenge. Additional constraints like cost, footprint, efficiency, reliability/maintainability made it impossible procuring a solution already available in the market by the time of decision.

This contribution will focus on the modulator development roadmap for ESS. It will describe the obtained results and lessons learned from the first phase of the project, where two commercial solutions were procured and tested leading to unsatisfactory results.

Concurrent to the commercial approach, ESS decided to launch an internal R&D project aiming at developing a new class of modulators, particularly suited for long pulse and high power applications. The topology (Stacked Multi-Level) is modular and based on several HV modules connected in series using High Frequency Transformers, fed from a primary low voltage inverters. In order to cope with power quality requirements, Active Front Ends are used at the first stage of the capacitor chargers. A reduced scale prototype, capable of powering one klystron, was built and successfully validated on a dummy load and on the real load. The series production of the first batch of 12 full scale units was outsourced on a built-to-print basis. The first series unit, capable of feeding 4 klystrons in parallel, was recently tested at full power on a HV dummy load. Experimental results of both the prototype and first series unit will be presented and discussed.

OPTIMAL DESIGN OF A HIGH VOLTAGE HIGH FREQUENCY TRANSFORMER AND POWER DRIVE SYSTEM FOR LONG PULSE MODULATORS

Max Collins[1], Carlos Martins[2]
1. Lund University
2. European Spallation Source

The stacked multi-level (SML) klystron modulator topology has been suggested as an alternative to conventional pulse transformer based topologies in an attempt to improve output pulse performance and reduce system size for long pulse applications. In this topology, a power converter chain including a high frequency transformer generates the output pulse in a pulse modulation/demodulation scheme, effectively eliminating the direct size-pulse length dependency while allowing higher degree of freedom in design.

However, increased complexity necessitates careful consideration from a system perspective to ensure appropriate component selection and design. First, from the perspective of the semiconductor switches, the pulsed nature of the load must be taken into account. High modulator average and peak powers are combined into a power cycling problem where lifetime issues must be managed when selecting semiconductor technology and converter operating frequency. Simultaneously, these considerations are directly coupled to the design of the high voltage high frequency transformer, the largest component in the SML chain, key in reducing modulator footprint and volume. In addition, appropriate passive components must be chosen with respect to transformer leakage inductance, switching frequency and switch ratings to constrain voltage overshoot without deteriorating system efficiency.

In this paper, these integrated design considerations are combined with a catalog of IGBT switches available on the market to form an optimization algorithm set to minimize transformer volume, indicative of system oil tank volume, while ensuring high system efficiency and long semiconductor lifetime. The impact of required system lifetime as well as tradeoffs between system efficiency and volume are studied. Finally, the algorithm is used to outline the design procedure for a system rated for pulse amplitude 115 kV / 20 A, pulse length 3.5 ms, pulse repetition rate 14 Hz, efficiency>90%, lifetime>25 years. The derived design is validated in both circuit simulation and through finite element analysis.

SATURATING PULSE TRANSFORMER CIRCUITS USING ADVANCED MAGNETIC MATERIALS

Jon Pouncey[1], jane Lehr[2], Brad Maynard[2], J. Martin Taccetti[3]
1. University on New Mexico
2. University of New Mexico
3. Los Alamos National Lab

The APERIODIC research group at the University of New Mexico has been investigating novel triggering technologies for compact pulsed power. These technologies include the use of advanced magnetics and novel topologies to develop high performance compact solid state electrical trigger systems*. One of the technologies under investigation is the use of advanced magnetic materials as the basis of saturating pulse transformer (SPT) circuits.

High performance triggering of high voltage three-electrode gas switches places difficult demands on the trigger generator system. For optimum performance, the trigger system must be capable of driving the trigger electrode(s) to a potential of up to 100 kV with 10's of nanosecond risetimes. Achieving these performance specifications with a compact all-solid-state design using conventional topologies is impossible.

The use of an SPT in an L-C circuit topology, as described by Fan and Liu [1], provides a means to overcome the limitations of conventional topologies to achieve the desired performance in an all-solid-state compact trigger pulser. However, there is still a significant amount of research and development that needs to be done to fully exploit the potential of this technology. The work at UNM has focused on two areas. The first is the use of advanced magnetic materials for the core of the SPT. The second is the development of circuit simulations that incorporate realistic models of the magnetic behavior of the core. This is important because the SPT L-C circuit has several free parameters that are mutually interactive – making it a system that is well suited to optimization through simulation.

* This work supported by The Office of Naval Research under STTR N00014-15-P-1214

1. X. Fan and J. Liu, A compact, all solid-state LC high voltage generator, Review of Scientific Instruments 84, 064703 (2013); doi: 10.1063/1.4808314

INTEGRATED KLYSTRON TEST STAND

Rebecca Simpson[1], Michael Kempkes[1], Marcel Gaudreau[1], Luan Jashari[1]
1. Diversified Technologies, Inc.

Diversified Technologies, Inc. (DTI) recently delivered an Integrated Klystron Test Stand for klystrons under development at the Naval Research Laboratory (NRL) and Communication and Power Industries, Inc. (CPI). The test stand provides an HV beam and depressed collector power supplies, mod-anode modulator, controls, and circuit/klystron protection. The Integrated Klystron Test Stand simplifies and speeds the ability of the user to safely and efficiently test and exercise the klystron over the full range of its capabilities.

This test stand design draws directly on previous DTI solid-state systems and shares common design elements based on DTI's patented solid-state switching technology—which has a history of reliable operational performance across more than 600 high voltage systems around the world. A single capacitor and solid-state cathode switch provide the peak beam power while providing protection for the klystron in the event of an arc. The switch opens and removes cathode voltage within $\sim 1\ \mu$s after an arc is detected.

A control cabinet houses the main system controls and interface, including most of the power distribution and a Programmable Logic Controller (PLC) for system sequencing, parameter and fault monitoring. The PLC sequences are based on DTI's klystron transmitter systems, with the addition of the flexibility and programmable sequencing in voltage, pulsewidth, and frequency required for klystron conditioning and testing across a range of parameters, rather than just the full power operation. A standard DTI switching power supply delivers a 10 to 32 kV DC high voltage input to the modulator. This high stability/low noise supply uses an advanced PWM inverter which gives excellent voltage and current regulation over the full output range. Nominal output behavior is 0.1% ripple and +/- 0.2% voltage regulation, with fast response to transients.

DESIGN OF A WIDE BAND TEST SYSTEM WITH INTERCHANGEABLE ANTENNA MODULES

Jon Mayes[1], William Nunnally[1], Jeremy Byman[1], Matthew Lara[1], Chris Hatfield[1], David Kohlenberg[1]
1. Applied Physical Electronics L.C.

Applied Physical Electronics, L.C. (APELC) has built a suite of wide band antennas, using a fat dipole geometry with an integrated resonator. Each antenna uniquely radiates a damped sinusoid, resulting in several cycles of energy at the predetermined center frequency, and with a wide band of frequency content. The unique aspect to this technology is the capability of using a single pulsed power source to drive different antennas. This paper describes a system consisting of a single Marx generator sourcing five unique wide band antennas, with center frequencies of 60, 100, 250, 400 and 500 MHz. The system design and results are discussed.

MACROPARTICLE COMBINATION ALGORITHM FOR PLASMA PIC SIMULATION

Jarrod Leddy[1], John Cary[2], David Smithe[1]
1. Tech-X Corporation
2. University of Colorado

The efficient simulation of plasmas via the particle-in-cell (PIC) algorithm requires that the macroparticle density be isotropic, while the physical density can vary significantly in space and time. This isotropic macroparticle density ensures good statistics in reactions and charge deposition while maintaining ideal computational load balance. Especially in the case of cascade ionization, when the physical density of electrons locally grows exponentially in time, the macroparticle density must be managed so that it does not also increase. This is accomplished through macroparticle recombination, where multiple macroparticles are combined into fewer macroparticles. We present a novel algorithm for preserving the momentum, energy, flux, charge, and phase space distribution of the original particles during this recombination process. Conservation of these quantities is important when the distribution function of the particles is non-Maxwellian, and especially when it is multi-modal. This new algorithm will be discussed in detail, and plasma simulations benefitting from its unique conservation properties will be shown. These simulations will include a simple example of crossing beams, as well as a complex simulation of plasma generation in the C100 SRF cavity for in situ cleaning. In both of these cases, there are discrete populations of electrons with different temperatures and mean velocities that must be preserved to accurately model the system.

BENCHMARKING THE KINETIC GLOBAL MODEL FRAMEWORK (KGMF): EEDF EVALUATIONS IN LOW-TEMPERATURE ARGON PLASMAS*

Janez Krek[1], Yangyang Fu[2], John Verboncoeur[2]
1. Michigan State University, CMSE
2. Michigan State University

Global (volume-averaged) models present valuable tools in predicting macroscopic plasma behavior and giving the ability to evaluate the importance of individual reactions in plasmas, which further helps identify the key reactions for spatial-dependent simulations[1]. The Kinetic Global Model framework (KGMf) was extended and coupled with a Boltzmann equation solver, BOLOS[2] (using two-term spherical approximation) and MultiBolt[3] (multi-term spherical approximation), to self-consistently compute electron energy distribution function (EEDF). By capturing the temporal evolution of EEDF, the KGMf enables fidelity of the results even for dynamic systems at a cost of a higher computational complexity. Adaptive EEDF evaluations are imperative to preserve the advantage of the global model while maintaining the accuracy of the solutions. Using the low-temperature argon plasma chemistry at high pressure, we compared different methods of controlling the EEDF evaluation frequency depending on changes of plasma parameters, e.g. electron density or electron temperature. The impact of individual parameters on the temporal evolution of discharge parameters is presented in terms of selected parameter values and computational time. The results are also compared to the simulation results obtained by ZDPlasKin with BOLSIG+[4].

[1] G. M. Parsey, Ph.D. thesis, Michigan State University, (2017).

[2] A. Luque, https://pypi.python.org/pypi/bolos, (2004).

[3] J. Stephens, J. Phys. D: Appl. Phys. 51, 125203 (2018).

[4] G. J. M. Hagelaar and L. C. Pitchford, Plasma Sources Sci. Technol. 14, 722-733 (2005).

*This work supported by the DOE Plasma Science Center Grant No. DE-SC0001939.

ADVANCED IMPLICIT AND HYBRID TECHNIQUES FOR THE SIMULATION OF HIGH DENSITY VOLUMETRIC AND ELECTRODE PLASMAS

Dale Welch[1], David Rose[1], Carsten Thoma[1], Dustin Offermann[1], Chris Mostrom[1], Robert Clark[1], Thomas Genoni[1]
1. Voss Scientific

Recent advances in implicit and hybrid techniques have demonstrated that finite-difference-time-domain particle-in-cell (PIC) simulation codes can effectively model volumetric and electrode plasmas at high density. Energy-conserving implicit kinetic algorithms greatly relax the spatial Debye length and temporal plasma frequency constraints allowing for larger simulations volumes and times. A new implicit technique based on the Magnetic Implicit algorithm for strongly magnetized plasma permits more accurate orbit calculations even with for cyclotron frequency-time step product much greater than unity. PIC fluid techniques facilitate hybrid simulation and further accelerate the computational speed. These new capabilities allow for more accurate simulation of pulse-power accelerators, high power diodes, laser-plasma interactions, as well as magnetic and inertial confinement machines. In this paper, we explore PIC methodologies for kinetic and multi-fluid simulation. Hybrid techniques for blending the various PIC descriptions into a single integrated simulation will be discussed. Finally, we will present stressing practical examples using these techniques in the LSP simulation code.

A MULTI-TERM SPHERICAL HARMONIC EXPANSION OF THE BOLTZMANN EQUATION FOR MODELING LOW-TEMPERATURE COLLISIONAL PLASMAS

J.L. Giuliani[1], D.D. Hinshelwood[1], I.M. Rittersdorf[1], P.F. Ottinger[2], Tz.B. Petrova[1], A.S. Richardson[1], S.B. Swanekamp[1], P. Adamson[1], S.L. Jackson[1]
1. Naval Research Laboratory
2. Syntek Technologies, Arlington, VA 22203

The Boltzmann equation describes the evolution of the electron and ion distributions over time through a six-dimensional phase space and is at heart of the plasma kinetic theory. For highly-collisional plasmas, scattering collisions keep the distribution function nearly isotropic in velocity space with small perturbations created by the hydrodynamic and electromagnetic forces. These plasmas are very common and include surface plasmas generated in pulsed power devices, plasma-filled microwave devices, air-breakdown in high-power microwave propagation, the plasmas generated by intense electron or ion beams, plasma medicine, electron-beam pumped excimer lasers, and hypersonic flows. For these plasmas, a spherical-harmonic expansion of the velocity-space distribution function is an effective technique for solving the Boltzmann equation. This talk will examine each of the terms in the Boltzmann equation in detail to derive conditions where a spherical harmonic expansion is useful. Expressions for the matrix elements in the expansion terms, which represent the projection of the various operators in the Boltzmann equation onto the spherical harmonics basis set, will be presented. The resulting multiple-term spherical-harmonic expansion makes no assumptions about either the direction of the E and B fields or the magnitude of the spatial gradients. Therefore, this expansion is appropriate for coupling with a Maxwell equation solver. When only the two lowest-order terms are kept, it is shown that the resulting equations are very similar in form to the continuity and force-balance fluid equations. Additional kinetic terms appear in the continuity-like equation which are related to collisions and to energy gains in the electric field that leads to Ohmic heating. Kinetic terms also appear in the force-balance-like equation. One related to collisions and another that is proportional to the derivative with respect to energy of the energy density.

*This work is supported by the NRL base program.

THE RIGID-BEAM MODEL AS A TEST CASE FOR SIMULATIONS OF PLASMA GENERATED BY AN INTENSE ELECTRON BEAM

Steve Richardson[1], Stephen Swanekamp[1], Tzvetelina Petrova[1], John Giuliani[1], Paul Adamson[1], David Hinshelwood[1], Stuart Jackson[1], Joseph Schumer[1]
1. Naval Research Laboratory

There has recently been a renewed interest at the Naval Research Laboratory (NRL) in better understanding the physics of the breakdown of air by a high-current, fast, pulsed electron beam. In order to simulate the breakdown of air that occurs under these conditions, new computational tools are being developed which will be able to accurately model the breakdown in the relevant parameter regimes. The rapid breakdown of air by an intense electron beam is a complex plasma physics problem. There are three main parts to this problem: the electromagnetic fields governed by Maxwell's equations, the plasma and beam electron dynamics described by the Boltzmann equation, and the plasma-driven chemistry of the air modeled by coupled rate equations for all the chemical and ion species. In order to test various simplified models for the Boltzmann and plasma chemistry parts of the problem, we have developed a standardized approximation to Maxwell's equations and the beam dynamics equations. Here we describe the resulting rigid- beam model, and show an example of how the rigid-beam model can couple to a Boltzmann solver. This rigid-beam model will allow us to more quickly develop and benchmark new models, which can then be validated against new data collected at NRL.

* Supported by the Naval Research Laboratory Base Program

MEASUREMENT OF PHOTOIONIZATION RATES AND QUENCHING PRESSURES

Justin K. Smith, Lisa E. Fisher, Jane M. Lehr, Michael D. Abdalla, Michael Skipper

Many computational codes that involve transient plasmas, incorporate photoionization rates to describe the evolution of such phenomena as streamer development and propagation. At near atmospheric pressures, photoionization rates decrease significantly due to collisional quenching. The collisional quenching is the process where an excited molecule returns to the ground state non-radiatively at higher pressures. In air discharges, the nitrogen molecule is typically the excited molecule that is responsible for photoionizing oxygen, and oxygen is the quenching molecule. There are concerns that the currently widely-used photoionization models significantly overestimates the photoelectron production which is typically attributed to the quenching pressure of the radiative states. Progress on measurements of the photoionization rates and the onset of collisional quenching are reported along with progress in the model development suitable for inclusion in computational codes.

Acknowledgement

The authors gratefully acknowledge support through from the Navy's STTR program 14-16-C-1038

EXPERIMENT ON THE PROPAGATION OF RELATIVISTIC PULSED ELECTRON BEAM IN PLASMA

R. Maisonny[1], Fabien Dorchies[2], claude fourment[3], Thomas Lahens[4]
1. CEA, DAM, GRAMAT, F-46500 Gramat, France
2. Universite de Bordeaux-CNRS-CEA, CELIA, Talence F-33405 France
3. CEA
4. CEA-CESTA, Le Barp, F-33116 France

We present an experiment designed to investigate the propagation of a high-current relativistic pulsed electron beam (4MeV, 2kA, 60ns) in plasmas. This experiment takes place on an existing electron source at CEA-CESTA, and uses a plasma cell specially designed to this purpose.

It consists of a $\sim$1 meter long beam line section holding a glass tube in the path of the electron beam. We generate a DC glow discharge a few tens of cm long in the glass tube and we have estimated the electron density to be around $10^9 cm^{-3}$ with 3 different methods, namely electrostatic probes, microwave interferometry and an original diagnostic based on a capacitive coupling with the plasma. A coil for additional inductive heating of the plasma has also been developed to increase the plasma density.

The plasma cell features some critical aspects such as plasma/vacuum windows or return current system, which deserve special care. We have particularly tested the resistance of different plasma/vacuum foils against the energy flux of the electron beam, as well as the mechanical and thermal stress due to the plasma discharge. In addition, the influence of the foils on the beam emittance and focusing has been numerically evaluated by PIC simulations with the LSP (large scale plasma) code. Finally, the preliminary results of the beam propagation in the plasma cell will be presented.

PLUME MORPHOLOGIES AND THEIR FORMATION MECHANISM OF AN ATMOSPHERIC PRESSURE ARGON PLASMA JET EXCITED BY A BIASED VOLTAGE

Xuechen LI[1]
1. Hebei University

Plume morphologies and their formation mechanism of an atmospheric pressure argon plasma jet excited by a biased voltage

Xuechen Li , Xiaotong Lin, Kaiyue Wu, Rui Liu, and Pengying Jia

College of Physics Science & Technology, Hebei University, Baoding,071002

Several morphologies of plasma plume are observed through using an argon plasma jet, including solid cone, hollow cone, regularly swells, corona surrounding filament, and corona surrounding feather. Results indicate that, with increasing the bias value of a low-frequency sinusoidal voltage, conical plume transits from solid to hollow. Through fast photography, a plump guided bullet (negative streamer) is found to propagate in the solid plume, while positive streamer is involved in the hollow plume. It behaves as a thin guided bullet starting out from the driven electrode end, which subsequently evolves into branched streamers propagating in the stream periphery. The hollow morphology is attributed to the mutual effects of Penning ionization and the residual charges, which are confirmed by adding different contents of oxygen or nitrogen into the working gas. With decreasing driving frequency, the conical plume transits to a regularly-swelling one. Investigation shows that intense discharges near the nozzle provide the following swell positions with active species, which can remarkably enhance the discharges there and induce the swells. This is verified through investigating distance of two adjacent swells as a function of gas flow rate and driving frequency. With a fairly high frequency, the corona surrounding filament plume is observed. Fast photography indicates that the central filament corresponds to guided positive streamer, while the surrounding corona come from guided negative streamer. Both of the two streamers can enhance each other. With changing the applied voltage to biased square wave, a corona surrounding feather plume is formed. It is found that there are two current pulses at the rising voltage edge and one at the falling edge. Result indicates that the feather corresponds to propagation of two positive streamers at the rising voltage edge, while the corona is formed during the propagation of negative streamers at the falling edge.

PLASMA PROPAGATION SPEED MODEL FOR INVESTIGATION OF ELECTRON TEMPERATURE AND PLASMA DENSITY OF AR PLASMA IN ATMOSPHERIC PRESSURE MICRO-DBD

PRADOONG SUANPOOT[1], Jirapong SORNSAKDANUPHAP[1], Bhagirath GHIMIRE[2], Guangsup CHO[2], Eun Ha CHOI[2]
1. Maejo University Phrae Campus
2. Kwangwoon University

A model based on plasma propagation velocity has been recently developed to estimate the electron temperature (Te) of atmospheric pressure u-DBD plasma. In this work, we have extended this model to calculate Te for plasma generated with Ar gas. Plasma has been generated by input discharge voltage of 2.7 kV at a driving frequency of $\approx$ 45 kHz. A high-speed single-frame intensified charged coupled device (ICCD) has been used to observe the space and time-resolved discharge images and estimate the value of plasma propagation velocity (ug). The value of ug for Ar plasma has been obtained in the range of 6.2x10^3 m/s. The electron temperature has been calculated for this plasma. The average electron temperature has been found to be about 1.18 eV and the average plasma density has been found to be about 3.62×10^{14} cm^{-3} for Ar plasma. Our results obtained with the modified convective-wave packet model can be a new contribution to plasma medicine.

OVERVIEW AND CHALLENGES OF PARTIALLY MAGNETIZED PLASMA MODELING

Kentaro Hara[1]
1. Texas A&M University

The current status and challenges of the discharge plasma modeling capabilities in crossed field devices are reviewed. The plasma flows in such sources, e.g., Hall effect thrusters and magnetron discharge, are partially magnetized, i.e., electrons are magnetized while ions are not magnetized. The partially magnetized plasmas present unique and complex phenomena in that collisions with neutral atoms (a feature of low-temperature plasmas) and instabilities and turbulence (a feature of high-temperature plasmas) coexist. A discharge plasma model is constructed by choosing the numerical methods, e.g., fluid or kinetic, for individual plasma constituents, including neutral atoms, ions, and electrons. In this talk, various models are used to illustrate device-scale phenomena, including the breathing mode and azimuthally rotating spokes, as well as small-scale physics, such as the electron cyclotron drift instability. Additionally, the limitation of drift-diffusion approximation is discussed for magnetized electrons.

CHARACTERISTICS OF PULSED DISCHARGE PLASMA WITH POROUS ELECTRODE WITHOUT DIELECTRIC BARRIER AT ATMOSPHERIC PRESSURE

Jie Li[1], Xi Li[2], Pan Dong[1], zhen yang[2], Jidong Long[1], Linwen Zhang[1]
1. Institute of fluid physics
2. China Academy of Engineering Physics

Stable and uniform large-volume plasma generated at atmospheric pressure attracts much attentions in recent years in for the potentials of numerous applications. In this study, one of the parallel plate electrode is designed with barrier-free small apertures distributed uniformly, so the working gas could flow uniformly to the operating discharge gap, and the other electrode is also barrier-free. Diameter of the electrodes are about 130 mm. A repetitive unipolar sub-microsecond pulse power (0∼-100 kV, ∼1 kHz, pulse width 230 ns, rise time 120 ns) is used to drive the barrier-free gas gap. Uniform discharge plasma can be steadily sustained even the gap distance exceeds 20 mm in He at atmospheric pressure with a flow rate of 5 L/min. Characteristics of the discharge has been studied by experiments. Temperature of the electrode nearly remained unchanged after 30min'discharge with the frequency of 500 Hz. Tests of electrical parameters showed that plasma generation occurs in the voltage-falling phase. Experiments of high speed photography with exposure time of 5 ns proved the discharge worked at homogeneous mode. It is found that type of the working gas, proportion of mixture gases, waveform of the applied voltage (especially the rising and falling time of the pulse) are the key factors for the stability of the discharge. Also, emission spectrum of the discharge was tested in our research to study the plasma characteristics of the discharge (such as spectral line intensity of emission spectrum, electron temperature). The evolution of pulsed glow discharge at atmospheric pressure was recorded by high speed photography.Some recent results will be mentioned in the report.

RADIATIVE STABILIZATION OF THE SHOCK-DRIVEN INTERFACIAL INSTABILITIES IN DOUBLE-SHELL TARGETS

Jiwei Li[1], Zhensheng Dai[1], Shiyang Zou, Shaoping Zhu[1], Xiantu He[1]
1. Institute of Applied Physics and Computational Mathematics

Double-shell targets, as an additional design for demonstrating and exploring ignition, consist of two concentric shells, a low-Z outer-shell (ablator) surrounding a high-Z inner-shell (pusher) kept in place by a low-density foam. The hydrodynamic instabilities such as Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) are especially critical due to the existence of several interfaces, such as the pusher/foam interface with a high Atwood number. In the talk, we will discuss the hyrdodynamic stabilization of the pusher/foam and foam/ablator interfaces due to the radiative shock in the foam layer. When the ablatively-driven shock by the laser or radiation enters the low-density foam layer (tens of mg/cc) from the outer shell, the shock may become radiating as the radiative flux plays a role in the dynamics to stabilize the pusher/foam and foam/ablator interfaces. The preheat of the radiative shock promotes the outer and inner shells expanding towards the foam layer, and the move of the interface renders the effective reduction of the Atwood number at the interfaces, resulting in the hydrodynamic stabilization. 2D simulation by the radiation hydrodynamic codes is also performed to verify the stabilization due to the radiative shock for the double-shell targets.

NUMERICAL ANALYSIS OF DIRECT-DRIVE GOLDEN DOUBLE-SHELL IMPLOSION

Yan Xu

The volumetric ignition which can substantially reduces the radiation loss requires low threshold temperature and low implosion velocity. Golden double-shell design is one of the volumetric ignition designs. The design consists of two concentric golden shells with the inner shell enclosing a volume filled with DT fuel. The thick inner golden shell can re-radiate the escaped radiation back to DT fuel to reduce the radiation loss. The outer shell consists of two layers: an Au layer covered with a CH layer. The CH layer which can efficiently absorb the energy of the incident laser beams acts as the ablated material to drive the vicinal Au layer as payload mass to fly inward like a rocket to collide with the inner shell to get velocity and pressure multiplication. In this report we numerically re-examined the physical processes of double-shell implosion. Numerous 1D multi-groups hydrodynamic simulations show that the velocity multiplications due to shells collision locate in range about 1$\sim$1.3 for mass ratio of two Au shells in 2$\sim$10 . Although increment of mass ratio of two Au shells does not increase the velocity multiplication, it increases the areal density of DT fuel in the highest compressed moment, thence increases the burning efficiency of DT fuel. Usage of high mass ratio of two Au shells is a way to increase the areal density of DT. The lower amount of DT fuel filled the higher implosion velocity required to get ignited. To get DT fuel efficiently burned the state ρRT$>$2g/cm^2 keV must be reached. 2D simulations are used to illustrate the development of non-uniformity of lasers illumination in the processes of implosion.

THE PRELIMINARY EXPERIMENT OF DRIVEN PRESSURE ENHANCEMENT BY HYBRID DRIVE ON SHENGUANG LASER FACILITY

Ji Yan[1]
1. Research Center of Laser Fusion

For the purpose towards to ignition based on Laser inertial confinement fusion(ICF), the traditional indirect drive scheme proposed to create an extremely high hot-spot pressure up to ∼350Gbar at stagnation phase and makes it ignited. On the other hand, the high compression ratio implosion(Cr∼35) design was necessary while the driven pressure was just around 100Mbar and limited by ∼300eV radiation temperature or peak laser power (Phot- spot∼ Cr3*Pdriven). And then, hydrodynamic instability become serious and makes ignition difficult.

Hybrid drive that combined with indirect drive and direct drive was proposed few years ago[1]. The hybrid drive scheme can increasing driven pressure few times based on “snowplow” effect and make the implosion compression ratio decreased to 25 in numerical simulations and make the hybrid drive scheme become robust.

The experiment of driven pressure enhancement was performed on ShenGuang Laser facility. The target was a half-cylindrical hohlraum with 1500micro length and 2500micro diameter. 20 laser beams as indirect-drive beam with 15TW/3ns were inject into hohlraum and create 200eV radiation. 4 laser beams as direct-drive beam with 4TW/2ns and 2ns delay were interaction on the sample that mounted on the bottom of half-hohlruam. The sample was consisted with three layers: CH as an ablator, Al as an preheating barrier and Quartz as a window. The diagnostic using VISAR for shock velocity history measurement. The experimental result show that the indirect-drive shock velocity was 43.6km/s, hybrid-drive enhanced shock velocity was 83.8km/s, respectively. The experimental result compared with simulation well. The driven pressure of hybrid drive is up to 150Mbar and 3.6times than 200eV radiation driven only.

[1] X.T.He, et al. Phys.Plasmas 23,082706(2016)

EXPERIMENTAL STUDY OF FAST DEUTERONS AND ELECTRONS IN DPF FUSION PLASMA

Pavel Kubes, Marek Sadowski[1], Marian Paduch[2], Jakub Cikhardt[3], Daniel Klir[3], Jozef Kravarik[3], Karel Rezac[3], Balzhima Cikhardtova[3], Roch Kwiatkowski[1]

1. NCNR

2. IPPLM

3. CTU

The plasma with fusion parameters produced in tokamak, or at the interaction of powerful lasers with matter or z-pinch discharges deals with similar questions, mechanism of generation of high energy beams of charge particles similar to the plasma in solar flares1,2. The plasma generated in plasma focus discharges has some advantages in solving of this problem – convenient parameters for complementary interferometric, XUV, deuteron and neutron diagnostics with temporal, spatial and energy distribution. The presented experimental research of fusion DD reaction was provided on the dense plasma focus (DPF) device3 at the current above 1 MA and the total neutron yield at the level of 10E11. These diagnostics made possible to register the existence and evolution of organized structures and time and locality of acceleration of charge particles. The fast deuterons were recorded by pinhole camera and CR-39 detectors. They showed their origin in small regions in plasmoids and in rings with diameter above DPF dense column. We discuss also the distribution of internal magnetic fields, filamentary structure of the current, difference in acceleration of electrons and ions, and the possible model of the fast energy acceleration based on the magnetic reconnection, which can be inspiration as for tokamak and laser-fusion as for solar-flare communities.

STAGNATION PERFORMANCE SCALING OF MAGNETIZED LINER INERTIAL FUSION

Matthew Gomez, David Yager-Elorriaga[1], Clayton Myers[1], Stephen Slutz[1], Matthew Weis[1], Christopher Jennings[1], Derek Lamppa[1], Adam Harvey-Thompson[1], Matthias Geissel[1], Patrick Knapp[1], Eric Harding[1], Stephanie Hansen[1], Michael Mangan[1], Carlos Ruiz[1], Gordon Chandler[1], Tim Webb[1], Tommy Moore[1], George Laity[1], David Ampleford[1], Kyle Peterson[1], Greg Rochau[1], Daniel Sinars[1], Kelly Hahn[2]

1. Sandia National Laboratories

2. Lawrence Livermore National Laboratory

Magnetized Liner Inertial Fusion (MagLIF) is a magneto-inertial fusion concept that is presently being studied on Sandia's Z machine. The concept utilizes an axial magnetic field of order 10 T to reduce thermal conduction losses as a cm-scale beryllium can implodes and compresses fusion fuel, which was preheated to of order 100 eV with a few kJ from a TW-class laser. During the implosion, the magnetic field is amplified through magnetic flux compression to several thousand Tesla, and the fuel temperature increases to several keV.

Scaling studies indicate that >100 kJ deuterium-tritium fusion yields are possible on the Z machine; however, this level of performance can only be reached by simultaneously scaling up the initial applied B-field, the energy coupled to the fuel by the laser, and the current driving the system. Using the original MagLIF platform, the input parameters were limited to 10 T, approximately 1 kJ of laser energy coupled, and 16 MA. Experiments conducted with these parameters resulted in a primary deuterium-deuterium neutron yield around 3x10¹² and a burn-averaged ion temperature of 2.5 keV. Recent efforts focused on developing enhanced capabilities for the MagLIF platform have demonstrated peak load currents approaching 20 MA and initial applied B-fields exceeding 15 T. Combining these improvements with a change in laser preheat protocol led to a primary neutron yield exceeding 10¹³ and an ion temperature over 3 keV. Additional efforts to further increase the B-field to >20 T, the laser preheat to >2 kJ, and the current to >20 MA are underway.

GENERATING AN IMPLODING ROTATING PLASMA IN MAGLIF TARGETS

Pierre Gourdain[1], Klaus Weide[2], Petros Tzeferacos[2], Marissa Adams[1]
1. University of Rochester
2. University of Chicago

Axially rotating plasmas implode very differently than non-rotating ones since the kinetic energy delivered by the implosion is now shared between pressure and rotation, rather than pressure alone. We propose to study this approach numerically inside a MagLIF target using a cryo-DT fiber rather than a gas pre-fill. An external pulsed-power generator is used to turn the fiber into a plasma. When the plasma has filled completely the liner, it is imploded by a much larger driver, such as the Z-machine. The rotation is initiated via $J \times B$ forces when a vertical magnetic field is present. Analytically, one can illustrate that for a given uniform B_z, and $B_\phi(r, z)$, a nontrivial J_r and J_z will be retrieved via Ampere's law. As a result, the MHD equations in 2D cylindrical geometry yield a rotational velocity dependent on both B_z and $B_\phi(r, z)$. Starting from the analytical solution, we assess how much rotation is expected in a MagLIF-like target. Then we complete our analysis by using the FLASH, a fully explicit adaptive mesh refinement code, that studies the viability of this new approach to magnetized target fusion. FLASH was developed in part by the DOE NNSA ASC and DOE Office of Science ASCR-supported Flash Center at the University of Chicago.

GAS CONCENTRATION DISTRIBUTION NEAR SURFACE IN AN IMPINGEMENT OF ATMOSPHERIC PRESSURE PLASMA JET BY TWO-DIMENSIONAL FILTERED RAYLEIGH SCATTERING

Yuanfu Yue[1], Yedhu Krishna[2], Gaetano Magnotti[2]
1. University of Minnesota
2. King Abdullah University of Science and Technology

Due to potential applications in plasma medicine and surface modifications, atmospheric pressure plasma jets (APPJs) receives great attentions by scholars in the last decade. Recently, the plasma induced flow instability and ionization propagation along thin mixing layer have been proposed and studied experimentally and numerically [1,2]. In respect to plasma-surface interaction, the mixing near surface is even important while understanding discharge physics and chemistry. In this report, the two-dimension filtered Rayleigh scattering is adopted to study the mole concentration distribution of helium and air near dielectric surface.

The plasma jet impingement is obtained by flowing helium to dielectric surface. The laser sheet generated by high spectral purity system at 532 nm is aligned approaching to the dielectric surface. By applying the iodine cell in the observation pathway and fitting the laser wavelength to spectral absorption curve of iodine, an effective suppression of narrow-band stray light from surface is achieved, while allowing the doppler broadened Rayleigh signal through and captured by camera, which shows great advantage in plasma-surface interaction.

By applying the method described above, the two-dimension mole fraction of helium and air near the surface is obtained. The error coming from laser energy variation and wavelength jitter is evaluated as well as the effect of stray light is discussed. The experimental outcomes are further compared with numerical results showing great consistency. The discharge effect on instability of mole fraction of gas is also discussed.

1. A. Lietz, E. Johnsen and M. Kushner, “Plasma-induced flow instabilities in atmospheric pressure plasma jets” Appl. Phys. Lett., 111,114101 (2017).

2. E. Doremaele, V. Kondeti and P. Bruggeman, “Effect of plasma on gas flow and air concentration in the effluent of a pulsed cold atmospheric pressure helium plasma jet” Plasma Sources Sci. Technol. 27 095007 (2018).

ELECTRIC FIELD MEASUREMENT OF DISCHARGE DEVELOPMENT IN LONG SPARKS

Zhehao Pei[1], Xing Fan, Kai Bian, Qiaogen Zhang, Weijiang Chen, Shengxin Huang
1. Xian Jiaotong University

Properties of discharge developing in air gaps have been used to investigate insulation coordination of high voltage devices and to simulate physical characters of lightning. The measurement of electric field is important and instructive for studying mechanisms and properties in long air sparks. We present an optical electric field measurement with BGO here for use in atmospheric plasma discharges. The measurement system is based on electro-optical technology, which consists of laser system, electro-optical module and optic-electrical module. Firstly, the design and structure of the measurement system is introduced and 1-D size of the BGO crystal is as small as 5mm, which is small enough not to bring sensible electric field distortion. Secondly, the measurement system provides detecting range with amplitude from 200kV/m to 1.5MV/m and time response to 2ns, meeting the most streamer-evoked partial electric field of 1MV/m and the rise time of 10ns. The calibration results are also provided, performing a high linearity with correlation coefficient of 0.9999 and root mean square error of 0.5776mV. Thirdly, a high speed video camera and a delicate current measurement system are also used for discharge development analysis, operating together with the electric field system in 1m rod-plane with impulse voltage, providing implications for physical investigations.

ELECTRIC FIELD MEASUREMENTS IN A NANOSECOND PULSED ATMOSPHERIC PRESSURE PLASMA JET IN HELIUM

Mahsa Mirzaee[1], Marien Simeni Simeni[1], Peter Bruggeman[1]
1. Department of Mechanical Engineering, University of Minnesota

We report on the spatial and temporal distribution of electric field strength in a nanosecond atmospheric pressure helium plasma jet during the evolution of the discharge when impinging on an ITO glass substrate. We used a non-invasive optical spectroscopy technique based on polarization-dependent stark splitting and shifting of the He I at 492.19 nm ($*2p\ ^1P^0 - 4d\ ^1D*$) line and its forbidden ($*2p\ ^1P^0 - 4f\ ^1F*$) counterpart. The wavelength separation between allowed and forbidden lines is dependent on the electric field strength due to the Stark effect. For the He I at 492.19 nm, the separation between allowed and forbidden components can be written as a third order polynomial function of the electric field[1]. The electric field is deduced from the experimentally measured separation. For our experimental conditions, the peak electric field value was measured to be $\sim$ 15 kV/cm at the streamer head and it reduces to $\sim$ 9 kV/cm at the streamer tail.

The results show strong interference of N_2 second positive system emission (ν = 1-7) in the low E-field regions and also the presence of a field free component in the He I line in spite of the time resolved measurements on a time scale of 4 ns. The impact of these factors on the accuracy of the technique and the possibility to measure surface electric fields is also discussed.

Acknowledgement: This work is partly supported by a Department of Energy Early Career Research Award (DE-SC0016053).

1.M. M. Kuraica and N. Konjević, “Electric field measurement in the cathode fall region of a glow discharge in helium”, Applied Physics Letters, June 4, 1997, pp. 1521-1523.

A NEW COLLISIONAL RADIATIVE MODEL FOR NEON LOW TEMPERATURE PLASMA

Rajesh Srivastava[1], Reetesh Kumar Gangwar[2], Shubham Baghel[1], Shivam Gupta[1]
1. IIT Roorkee
2. IIT Tirupati

Most of the earlier plasma diagnostic studies have focused on Ar, Kr and Xe [1] but not much attention has been paid to study Ne plasma which is equally important. In the present work, we take up the diagnostics of low temperature Ne plasma through optical emission spectroscopy (OES) technique. In this method, the emission measurements are combined with suitable collisional radiative (CR) model to extract electron temperature, electron density and population of species. A large amount of reliable electron impact excitation (EIE) cross sections data are required for optical-based plasma diagnostic techniques and at present these are not available in accurate and adequate manner for Ne. We calculate the required fine-structure EIE cross sections of Ne using fully relativistic method and develop a reliable CR model for the neon plasma [2].

In the present CR model, we take into account 40 fine structure states of Ne corresponding to 2p53s, 2p53p, 2p54s, 2p54p and 2p53d configurations along with its ground and ionic state. We calculate the required electron impact excitation cross-sections from the ground and excited states to upper states using fully Relativistic Distorted Wave (RDW) theory [2]. Thereafter, these cross sections are incorporated in the CR model of Ne plasma following our earlier work on Kr and coupling our model with OES measurements of Navratil et al. [3] where they obtained the intensities of the lines from 2p53p- 2p53s transitions. We will present the theoretical details of the model along with obtained the plasma parameters for neon plasma.

References:

[1] Priti, R. K. Gangwar and R. Srivastava, PSST. 28, 025003 (2019).

[2] R. K. Gangwar, Dipti, R. Srivastava, and L. Stafford, PSST. 25, 35025 (2016).

[3] Z. Navrátil, L. Dosoudilová, J. Hnilica, and T. Bogdanov, J. Phys. D. Appl. Phys. 46, 295204 (2013).

ELECTRON PROPERTY MEASUREMENT OF A HIGH REPETITIVELY PULSED HELIUM PLASMA JET USING LASER THOMSON SCATTERING

James Hornef[1], Jared Miles[2], Steve Adams[3], Stephen Mammack[4], Campbell Carter[4], Chunqi Jiang[5]

1. Frank Reidy Research Center for Bioelectrics, Old Dominion University
2. Air Force Research Laboratory, Wright-Patterson Air Force Base
3. Air Force Research Laboratory
4. Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton
5. Old Dominion University

The increasing use of atmospheric-pressure nanosecond pulsed plasma jets (APNPJs) in biomedical and environmental applications has motivated fundamental studies of the APNPJs including measurements of plasma properties such as the electron density and temperature. Quantifying these properties helps us to understand the roles of electrons during the initiation and development of the discharge, as well as the electron impact-related chemical kinetics resulting in generations of reactive plasma species. This study applies the laser Thomson scattering technique to resolve the spatial distribution and temporal development of the electron density and temperature in an APNPJ. A 1-mm in-width helium plasma jet was generated using a tubular dielectric barrier discharge (DBD) electrode driven by 150 ns, 7 kV pulses at a repetition rate of 4 kHz. Ring-shaped profiles, with higher values on the outer edge and lower values in the center, were observed for the electron density as the plasma jet exits the nozzle and converges as it travels away. A peak electron density of $4 \times 10^{19} cm^{-3}$ was observed at an axial distance of 7-8 mm from the nozzle surface, after convergence of the ring. In addition, comparisons of these measurements with previous studies, including the one for a low repetition rate APNPJ [1], are discussed.

Acknowledgements: This work is supported by the Air Force Office of Scientific Research under Award FA9550-17-1-0257, and in part by the 2018 AFRL summer faculty fellowship.

INCOHERENT LASER THOMSON SCATTERING DIAGNOSTICS FOR STREAMER DISCHARGE IN HE GAS

Kyohei Eguchi[1], Ryo Fujita[1], Douyan Wang[2], Kentaro Tomita[3], Takao Namihira[2]
1. Graduate school of Science and Technology, Kumamoto University - Japan
2. Institute of Pulsed Power Science, Kumamoto University - Japan
3. Interdisciplonary Graduate School of Engineering Science, Kyushu University-Japan

Streamer discharge plasma, a type of non-thermal plasma, has received global attention as a source of reactive radicals, and is used for many applications such as ozone generation, decomposition of NOx and other gas pollutants, cleaning water, disinfection, deodorization, and medical applications. The tip of streamer discharge, known as the streamer head, in particular contributes to radical production. The peak electric field is located in the streamer head on the axis of symmetry of the discharge, likely resulting in many radical types. Very remarkable results in NO removal efficiency and superior ozone generation yield performed by streamer discharge have reported. Improving gas treatment methods requires understanding of physical characteristics of streamer discharge and streamer head, for example, electron temperature and electron density.

This study investigates characteristics of streamer discharge by observing the propagation process of streamer head in a needle to conic electrode with positive voltage using a high speed gated emICCD camera. Then, incoherent laser Thomson scattering (LTS) diagnostic for streamer discharge and streamer head with positive voltage was performed. LTS diagnostic is considered to be the most reliable technique measuring electron temperature and density in plasma simultaneously. In addition, LTS diagnostic has high resolution temporally and spatially, therefore, LTS diagnostic can measure location dependence of electron temperature and density in streamer discharge including streamer head. The measurement point was 1 mm and 2 mm from tip of the high voltage needle electrode, and Thomson scattering signals were measured at the point of initial phase of streamer head propagation. In the results, electron temperature of streamer discharge was 3 $\sim$8 eV, electron density of streamer discharge was 1020 m-3 $\sim$ 1021 m-3 order. This study has proven that LTS diagnostic can measure electron temperature and density in streamer discharge plasma.

ADVANCED STREAMER IMAGING TECHNIQUES

Siebe Dijcks[1], Sander Nijdam[2]
1. TU/e
2. Eindhoven University of Technology

Streamers are the precursors to sparks, which have undesired effects in many high voltage applications. An example of this is a circuit breaker where high voltages are switched by physically opening the electrical circuit, thereby creating an arc. This arc, which short circuits the separated electrodes is extinguished by flushing with an electronegative gas. After extinguishing, the circuit breaker needs to remain open for a successful switching operation. Therefore, new streamers which initiate at the high voltage electrodes and create electrically conducting paths, need to be prevented.

The electronegative gas of choice for the best performance in extinguishing arcs is SF6. However, due to its extreme potency as a greenhouse gas, alternative gasses are under investigation. This research focuses mainly on streamer discharge properties in CO2 in addition to air and N2.

Due to the complex nature of streamers and the simplified conditions used in numerical modeling of streamers, we attempt to simplify the streamer morphology in our experiments by reducing the applied voltage. These simplified streamers can then be imaged using stroboscopic and stereoscopic techniques. Using path tracking, grouping and triangulation algorithms, the 3-D morphology can be reconstructed. The reconstructed streamers can then be compared in detail to simulations.

When the streamer morphology becomes too complex and cluttered for these techniques, the cylindrical symmetry of the point to plane geometry can be used to perform an Abel inversion. Single shot streamer images are not cylindrically symmetric, but when numerous discharges are stacked, this symmetry appears.

Both methods operate in their respective streamer morphology complexity regime, where the full 3D reconstruction certainly extracts more detailed information compared to the stacked Abel inversions. The main challenge now lies in detailed diagnostics for the full regime.

DIRECT DETECTION OF MULTIPACTOR IN WAVEGUIDE STRUCTURES

Zachary Shaw[1], Luke R. Silvestre[1], Benedikt Esser[1], James Dickens[1], John Mankowski[1], Andreas Neuber[1]
1. Texas Tech University

An experimental setup was designed and implemented for the study of the multipactor effect in a rectangular WR 284 waveguide geometry under high vacuum. Operated at S-Band frequencies the multipactoring electrons are directly detected via an Electron Multiplier Tube (EMT). The custom fabricated test section consists of a copper coated steel structure transitioning to standard WR 284 waveguide dimensions via varying tapers. An RF transmitter with 2.8 kW peak power and a center frequency of 2.85 GHz is used to inject an RF signal into a traveling-wave resonator, to which the test section is integrated, pushing the traveling wave power to $>$ 20 kW.

Operating in the dominant TE_{10} mode allowed the height of the waveguide to be changed without affecting the cutoff frequency, which was facilitated with an exponentially tapered impedance transformer. Multiple tapers have been constructed from OFHC copper with gap sizes conducive to developing first and third order multipactor (at 2 mm and 5.5 mm, respectively). With the reduction of the inner waveguide height from $\sim$34 mm to 2 mm, an electric field greater than 2.7 kV/cm was achieved at 2.8 kW input power within the ring resonator. Simulations reveal a secondary electron yield of greater than one for copper for these conditions.

For detecting multipactoring electrons, the EMT is aligned with a 1 mm circular aperture in the broadside surface of the waveguide enabling electron multiplication through the tube dynodes. Initial electron seeding is accomplished via UV light below 280 nm injected into the waveguide structure. The onset of multipactor in graphene coated copper versus pure copper surfaces is discussed. Clearly observable is the early emergence of the direct electron signal over any visible light emission that could be detected with a photomultiplier tube.

TEMPORAL STUDY OF DUAL FREQUENCY MULTIPACTOR ON A DIELECTRIC

Asif Iqbal[1], John Verboncoeur[1], Peng Zhang[1]
1. Department of Electrical and Computer Engineering, Michigan State University, East Lansing, Michigan 48824-1226, USA

Multipactor [1] is a nonlinear phenomenon in which an electron avalanche driven by a high frequency rf field sustains itself by an exponential charge growth through secondary electron emission from surfaces. This work investigates the time dependent physics [2] of multipactor discharge on a single dielectric surface by a novel multiparticle Monte Carlo simulator [3] with adaptive time steps. This model is advantageous over previous models as it can estimate the particle flight durations exactly, offering better statistics than the single macroparticle model [4,5], yet less computationally costly than models with growing number of particles over time [2].

The study shows that the presence of a second carrier frequency [6] of the rf electric field changes the saturation level and temporal oscillation pattern of the normal surface field. It is found that in the parameter regime of our investigation, the instantaneous normal surface field and the multipactor electron population remains at a lower value for a longer duration within an rf period for dual tone operation than for single tone operation.

[1] P.T. Farnsworth, J. Frankl. Inst. 218, 411 (1934).

[2] H.C. Kim and J.P. Verboncoeur, Phys. Plasmas 12, 123504 (2005).

[3] A. Iqbal, J. Verboncoeur, and P. Zhang, Phys. Plasmas, 26, 024503 (2019).

[4] R.A. Kishek and Y.Y. Lau, Phys. Rev. Lett. 80, 193 (1998).

[5] P. Zhang, Y. Y. Lau, M. Franzi and R. M. Gilgenbach, Phys. Plasmas, 18, 053508 (2011).

[6] A. Iqbal, J. Verboncoeur, and P. Zhang, Phys. Plasmas 25, 043501 (2018).

Work supported by AFOSR MURI Grant No. FA9550-18-1-0062.

THE EFFECTS OF MULTIPACTOR ON THE QUALITY OF A SIGNAL IN A TRANSMISSION LINE

Patrick Wong[1], Yue Ying Lau[2], Peng Zhang[1], Nick Jordan[2], Ronald Gilgenbach[2], John Verboncoeur[1]
1. Michigan State University
2. University of Michigan

Multipactor is a much studied AC discharge [1,2] that is harmful to microwave components. There is substantial current interest on this topic because of its threat to satellite communications [3]. In this paper, we present an analytical transmission line model to assess the effects of multipactor, should it happen, on the distortion of a signal. Both planar and coaxial transmission lines will be studied and compared. Extensions to complex, multi-tone signals will also be investigated. The I-Q plots (normalized error vector) for all of the cases considered will be presented to show the effects of multipactor.

1. J. R. M. Vaughan, IEEE TED, Vol. 35, No. 7, 1988.

2. R. A. Kishek et al., Physics of Plasmas 5, 2120 (1998).

3. Special sessions on Multipactor, I and II, ICOPS, Denver, CO, June 2018.

This work was supported by AFOSR MURI Grant No. FA9550-18-1-0062, by AFOSR Grant No. FA9550-15-1-0097, and by L3 Technologies Electron Devices Division.

CST PARTICLE STUDIO SIMULATIONS OF COAXIAL MULTIPACTOR SUSCEPTIBILITY AND EVOLUTION

Stephen V. Langellotti[1], Nicholas M. Jordan[1], Y.Y. Lau[1], Ronald M. Gilgenbach[1]
1. University of Michigan

Multipactor breakdown is a cascade phenomenon that occurs in RF and microwave systems. It has been observed in microwave tubes, RF windows, coupling structures, transmission lines, and in accelerator structures. Multipactor can cause loading of microwave cavities, localized heating and detuning of signals. These effects can ultimately lead to inefficient operation and possible destruction of the device. Disruption of such devices, particularly of space-borne systems, must be avoided due to the extreme cost incurred by unexpected device failures. The large safety margins necessary to ensure that multipactor will never occur add excess bulk and cost to the device. These safety margins are based on susceptibility measurements from historical experiments, of which few have been conducted for coaxial geometry [1,2].

This work aims to investigate if simulations performed in CST Particle Studio can accurately predict the onset of multipactor in coaxial transmission lines. We use secondary electron emission data for copper with chemically cleaned surfaces [3]. Growth of multipactor has been explored by studying the evolution of the electron population after seeding with a few electrons. These simulations replicate the susceptibility data from Woo's experiments [1]. Ultimately, these simulations will be used to guide the design of a coaxial test bed that will be used to validate new theories and test the efficacy of mitigation schemes.

[1] R. Woo, “Multipacting Discharges between Coaxial Electrodes,” J. Appl. Phys., vol. 39, no. 3, pp. 1528–1533, Feb. 1968.

[2] T. Graves, ”Experimental Investigation of Electron Multipactor Discharges at Very High Frequencies”, Ph.D, Massachussetts Inistitute of Technology, 2006.

[3] I. Bojko, N. Hillert, Scheuerlein, ”Influence of air exposures and thermal treatments on the secondary electron yield of copper”, J. Vac. Sci. Technol. A Vac. Surf. Films, vol. 18, no. 3, pp. 972-979, May 2000.

----

* Work supported by AFOSR MURI #FA9550-18- 1-0062.

MULTIPACTOR DYNAMICS UNDER OBLIQUELY INCIDENT RF ELECTRIC FIELD

De-Qi Wen[1], Peng Zhang[1], Yangyang Fu[1], Janez Krek[1], John P Verboncoeur[1]
1. Michigan State University

It is well known that single-surface multipactor discharges have a negative effect the electromagnetic wave transmission in high power microwave devices. In this work, we examine the single surface-multipactor dynamics under obliquely incident rf electric field, such as occurs in TM waveguide modes, using particle-in-cell simulation. The results show that the oblique angle, θ, between the electric field and the dielectric surface has a strong effect on the multipactor discharge, and significantly reduced multipactor is found with increasing θ from 0 to 0.15π. In addition, in the base case $\theta = 0$, the time-dependent electron number has two identical oscillations over one rf period. However, one of these two oscillations decreases in magnitude at $\theta = 0.05\pi$ and disappears at $\theta = 0.15\pi$, because the perpendicular component of the rf electric field alternately reinforces and reduces the restoring field, increasing and decreasing the oscillation of the electron impact energy, respectively. In addition, the electrons are forced into a few branches in the phase space of velocity and position. Finally, we develop a simple dynamic model to investigate the multipactor suppression, and the susceptibility diagram shows the upper and lower boundaries get close, implying no multipactor develops at large oblique angles.

Acknowledgment: This work is supported by AFOSR MURI Grant NO.FA 9550-18-1-0062

SECONDARY ELECTRON YIELD MEASUREMENTS ON MATERIALS OF INTEREST TO HIGH VACUUM ELECTRONIC COMMUNICATION DEVICES

Talal Ahmed Malik, Sal Portillo[1], Joe Chen, Raul Gutierrez, Ryan Johnson, Edl Schamiloglu[2], M. Gilmore[2]

1. PI

2. University of New Mexico

Vacuum electronic communication devices, such as the traveling wave tube (TWT) and backward wave oscillator (BWO), can at times experience degraded performance up to complete failure due to the multipactor effect. This effect is tied to the production and acceleration of secondary electrons due to electron impact and coupling to the electromagnetic energy within the tube. As part of a Multidisciplinary University Research Initiative (MURI) led by Michigan State University, the University of New Mexico is carrying out a study of the SEY contribution from various materials used in high power vacuum electronic devices. This presentation describes SEY data from electron bombardment in the low energy regime, from 10 eV to 1 keV, on Cu (baseline), Monel, Kovar, Invar, Al of various tempers, Fe (Cu Plated) as well as silver- and gold-plated samples. Angular resolved measurement data will be presented. In addition, different surface cleaning treatment protocols employed in this study will be described. Experimental results are compared with available simulations and previous data published in the literature.

PREDICTING SECONDARY ELECTRON YIELD FROM FIRST PRICIPLES CALCULATIONS

Ryan Johnson[1], Raul Gutierrez, Salvador Portillo[1], Mark Gilmore[1], Edl Schamiloglu[1]
1. University of New Mexico

Currently, the total power, performance and lifetime of high-power RF devices, like vacuum electron devices, RF space systems, and accelerators, are severely limited by a phenomena known as multipactor. This occurs when the electromagnetic field is in resonance with secondary electron emission leading to a runaway avalanche of electrons in the device, resulting in degraded operation and potentially a corona discharge and the destruction of the device. An effective strategy for mitigating multipactor is to use in these devices materials that show a reduced secondary electron yield (SEY), however at present, ideal materials are not known and so currently there is much effort in identifying such low SEY materials. Here we present our efforts, as part of a Michigan State University led Multidisciplinary University Research Initiative (MURI) towards building a model by which the SEY of a material can be predicted based only on the atomic structure of the material, thereby allowing the *in silico* search for effective device materials. Details of this model, in which Density Functional Theory (DFT) is used to calculate the frequency dependent dielectric function of a copper metal surface, which is then used as input to Monte Carlo simulations for secondary electron emission, are presented and compared to experimental results.

This work was supported by AFOSR MURI Grant FA9550-18-1-0309 through a subaward from Michigan State University.

THE STORY OF THE LTD DEVELOPMENT

Alexander A. Kim[1]
1. Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences

In this presentation the LTD development story will be presented, which begins in the 1980's when the microsecond plasma opening switches (POS) were the focus of many pulse power scientists' research all over the world. The accompanying problems of this technology resulted in the development of the microsecond LTD to replace the long pulse Marx generator coupled to plasma opening switches. Boris Kovalchuk's design of the microsecond LTD cavity, in which the primary energy storage capacitors are directly integrated into the LTD structure, like the SPHINX accelerator of France, was the first crucial step towards the development of this new technology. This led to the invention of the fast (100 ns) LTDs, a natural step to follow which eliminated completely the need for pulse compression and power amplification. Most recently the LTD technology was further developed to generate output pulses of trapezoidal shape with very fast rise time ($<$ 10ns) and flat top, named "Square Pulse LTDs." This newest version of the technology, which replaces the sinusoidal pulse output of the standard LTD, is ideally suited for applications such as flash radiography, Z-pinch, high power microwaves, etc. In this presentation a number of different types of LTDs will be described and their operation analyzed. In addition, since an LTD cavity encloses many spark gap switches, the statistical regularity of these switches, important for the viability of LTD technology, will be discussed.

DIRECT OBSERVATION OF THE CURRENT EVOLUTION IN A SMALL-SCALE SELF-COMPRESSING PLASMA COLUMN

Christine Stollberg[1], Eyal Kroupp[1], Dmitry Mikitchuk[1], Marko Cvejic[1], Ramy Doron[1], Evgeny Stambulchik[1], Y. Maron[1], Amnon Fruchtman[2], Uri Shumlak[3], John Giuliani[4]

1. Weizmann Institute of Science
2. Holon Institute of Technology, Israel
3. University of Washington
4. Naval Research Laboratory

We report on the direct measurement of the evolution of the azimuthal magnetic field (B_θ) in a small-scale, self-compressing plasma column using spectroscopic methods. This measurement allows for calculating the radial distribution of the axial current density which is crucial for understanding the dynamics of the plasma compression, and for improving predictions of detailed MHD simulations. The direct measurement of the magnetic field in self-compressing plasma systems is challenging, since the plasma density rises to few 10^{19} cm^{-3}, resulting in strong spectral line broadening that fully obscures the Zeeman-split pattern.

In our experiment, a 27-kA current pulse with a rise time of 170 ns drives the implosion of an oxygen column with an initial radius of $\sim$3 mm. The main diagnostics is a high-resolution, polarization-based spectroscopic setup. Simultaneous measurement of the σ+ and σ- components of the Zeeman pattern enables the determination of the magnetic field from the separation of these two components. Additionally, we obtain the electron temperature and the electron density simultaneously with the magnetic field.

The detailed time and space resolved characterization of the magnetic field and plasma parameters results in a comprehensive picture of the plasma compression dynamics. During the compression stage, we observe that the entire discharge current is located in the imploding plasma. At stagnation, however, the current flowing in the stagnating plasma decreases significantly and the ‘missing’current resides at much higher radii.

The data presented here can be used to build a detailed model of the current evolution that includes the plasma resistivity and inductance. This may explain the mechanism of the current re-distribution, which is relevant for numerous similar experiments in the pulsed power community.

This work was supported in part by the Cornell Multi-University Center for High Energy-Density Science (USA), the US-Israel Binational Science Foundation, and the AFOSR (USA).

IDENTIFICATION OF THE CORONA POINT IN POINT-TO-PLANE GEOMETRIES IN ATMOSPHERIC AIR

Leonardo Rossetti[1], jane Lehr[1]
1. University of New Mexico

In highly non-uniform electric fields, corona appears when a geometry-dependent threshold voltage is reached. A further increase in voltage results in circuit-limited breakdown. As the electric field becomes more uniform, the difference between the corona-onset voltage and the breakdown voltage becomes smaller until finally breakdown commences directly. The gap distance and voltage where the corona onset curve meets the breakdown curve is known as the Corona Point.

The Corona Point is associated with the sustaining field – the minimum electric field which supports streamer propagation. This is of interest as it forms the basis for an additional requirement on streamer propagation to supplement the Meek-Raether avalanche-to-streamer criterion for electrical breakdown. The Corona Point is determined using a point-to-plane experimental setup that allows precise changes in electric field uniformity by moving the point closer to the plane. The potential on the electrode is ramped slowly to ensure that the threshold electric field for corona-onset is measured by triggering the digitizer with a photomultiplier sensitive in the 300-600nm range.

ON THREE DIFFERENT WAYS TO QUANTIFY THE DEGREE OF IONIZATION IN SPUTTERING MAGNETRONS

Alexandre Butler[1], Nils Brenning[2], Michael A. Raadu[2], Jon Tomas Gudmundsson[3], Tiberiu Minea[1], Daniel Lundin[1]

1. Université Paris-Sud

2. KTH Royal Institute of Technology

3. University of Iceland

High power impulse magnetron sputtering (HiPIMS) is an ionized physical vapor deposition (IPVD) technique that has received significant interest lately [1]. However, proper definitions of the various concepts of ionization are lacking while quantification and control of the fraction of ionization of the sputtered species are crucial in magnetron sputtering, and in particular in HiPIMS deposition. Here we distinguish between three approaches to describe the degree (or fraction) of ionization: the ionized flux fraction F_{flux}, the ionized density fraction F_{density}, and the fraction α of the sputtered metal atoms that become ionized in the discharge (sometimes referred to as probability of ionization). By studying a reference HiPIMS discharge with a Ti target, we show how to extract absolute values of these three parameters and how they vary with peak discharge current. Using a simple model, we also identify the physical mechanisms that determine F_{flux}, F_{density}, and α as well as how these three concepts of ionization are related. This analysis finally explains why a high ionization probability does not necessarily lead to an equally high ionized flux fraction or ionized density fraction.

[1] J. T. Gudmundsson, N. Brenning, D. Lundin and U. Helmersson, High power impulse magnetron sputtering discharge, Journal of Vacuum Science and Technology A, 30(3) (2012) 030801

[2] A. Butler, N. Brenning, M. A. Raadu, J. T. Gudmundsson, T. Minea and D. Lundin, On three different ways to quantify the degree of ionization in sputtering magnetrons, Plasma Sources Science and Technology, 27(10) (2018) 105005

NONLINEAR ELECTRON POWER ABSORPTION IN CAPACITIVELY COUPLED RADIO FREQUENCY DISCHARGES

Sebastian Wilczek[1], Jan Trieschmann[2], Ralf Peter Brinkmann[1], Julian Schulze[1], Zoltán Donkó[3], Thomas Mussenbrock[2]

1. Ruhr University Bochum

2. Brandenburg University of Technology Cottbus-Senftenberg

3. Wigner Research Centre for Physics

In low pressure capacitively coupled radio frequency (CCRF) discharges, the expansion of the plasma sheaths generate highly energetic electron beams traversing the discharge gap and supporting the plasma via ionization. The penetration of these electrons into the plasma bulk can lead to significant plasma oscillations and propagation of electrostatic waves. Consequently, the electron power absorption as well as the RF current indicate significant nonlinear dynamics in the low pressure regime. In this work, we investigate the nonlinear electron power absorption by means of 1d3v Particle-In-Cell / Monte Carlo Collisions (PIC/MCC) simulations in geometrically symmetric and asymmetric CCRF discharges. Pronounced electron power gain and loss dynamics are observed in the region between the plasma bulk and the plasma sheaths during the phase of sheath expansion. Oscillations observed in the RF current — which is a global parameter that can be easily measured by a current probe in an experiment — can be clearly attributed to these discharge dynamics.

OBSERVATION OF POSITIVE AND NEGATIVE NANOSECOND PULSED STREAMERS IN A COAXIAL ELECTRODE USING A QUADRUPLE EMICCD CAMERA SYSTEM

Hitoshi Yamaguchi, Terumasa Ryu[1], Douyan Wang[2], Takao Namihira[2]
1. kumamoto university
2. Institute of Pulsed Power Science, Kumamoto University

The environmental improvements by non-thermal plasma have been actively studied all over the world. Generally, a pulsed discharge having a time duration of 100s ns consists of two discharge phases including the primary streamer and secondary streamer discharges. It is also well known that the streamer heads always have the largest electric field during entire discharge process and meanwhile, the propagation behavior between electrodes is strongly influenced by the polarity of the applied voltage. In recent studies, the nanosecond (ns) pulse power generator with a short pulse duration of 5 ns achieved the higher energy efficiency for exhaust gas treatment and ozone generation than other discharge methods. However, the fundamental characteristics of ns pulsed discharge are still unclear. In our previous study, although several propagation processes of the discharge were revealed using a single high-speed gated emICCD camera, it could not clarify on the full details because the continuous propagation images were unable to obtain, therefore, a combination of different discharge shots were photographed by changing exposure onset time of the emICCD camera. In the present study, the newly developed high-speed imaging system combined with four emICCD cameras, which can observe the single ns pulsed discharge phenomenon at the same time or over time using delay generator built in each camera. The propagation of the positive and negative streamer heads was observed using this imaging system. In the experiment, ns pulsed discharge was generated in a coaxial electrode. The propagation behavior such as propagation velocity, thickness of streamer heads, were compared in more detail between streamer heads with different voltage polarities.

COMPARISON OF SHOCKWAVE CHARACTERISTICS INDUCED BY WIRE EXPLOSION AND WATER GAP DISCHARGE

Yi Liu[1], Yijia Ren[2], Siwei Liu[2], Fuchang Lin[1], Yang Liu[2]

1. 1. State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science &Technology, Wuhan, Hubei Province, China 2. Key Laboratory of Pulsed Power Technology (Huazhong University of Science and Technology), Ministry of Education, Wuhan, Hubei Province, China

2. State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science &Technology, Wuhan, Hubei Province, China

In order to study the effect of energy at different stages on the shockwave caused by wire explosion, the energy in different stages of copper, molybdenum wire explosion and water gap breakdown is calculated, and the shockwaves generated by the three different methods are compared. The results show that under the same breakdown voltage, due to the larger current value of the wire explosion at the moment of gap breakdown, the power injected into the plasma channel caused by the wire explosion is much higher than the power injected into the plasma channel caused by the water gap breakdown. Therefore, under the same breakdown voltage, the peak value of the shockwave generated by the wire explosion is much higher than the peak value of the shockwave generated by the water gap breakdown. Similarly, under the same initial energy conditions, the power injected into the plasma channel caused by different kinds of wire explosion is different, so the peak value of the generated shockwave is also different. From the discussion of the test results, the causes of different energy conversion efficiencies of copper, molybdenum wire explosion and water gap breakdown are obtained. Thus, a method for improving energy conversion efficiency of shockwaves generated by water discharge is obtained.

INFLUENCE OF CONDUCTIVITY ON STREAMER PROPAGATION AND SHOCKWAVE INTENSITY IN UNDERWATER PULSED DISCHARGE

YI LIU[1], Siwei Liu[1], Yijia Ren[1], Fuchang Lin[1], Yang Liu[2]
1. Huazhong University of Science and Technology
2. Huazhong University of Science & Technology

Impulse breakdown in water has been widely studied over decades, and the understanding of the discharge phenomena and breakdown mechanism is of great importance to its applications. This paper presents an experimental study on impulse discharges performed in pin-to-plane electrode configuration with the water conductivity form (30 mS/m to 150 mS/m). Different streamer modes regarding the voltage polarities, shape characteristics and propagation velocities are observed by the high-speed camera. For positive streamers, two regimes of streamer have different responses to the change in water conductivity. Increasing the water conductivity leads to higher inception voltage of slow bush-like streamers whereas the inception voltage of fast filamentary streamers decreases, which may indicate different mechanisms of the two regimes in positive streamers. For negative steamers, the moderate tree-like streamers need lower applied voltage in higher water conductivity. The influence of water conductivity on streamer propagation and shockwave intensity are discussed in detail. The water conductivity has a great influence on the streamer initiation and propagation via the formation of micro-bubbles near the electrode and the distribution of space charge. The results confirm that the water conductivity can directly decide the energy consumption in the pre-breakdown process and the discharge process, while the shockwave intensity is closely related to the latter process. However, water conductivity has little influence on the post-breakdown process. Taking two selected discharges in 32 mS/m and 142 mS/m as an example, the same breakdown voltage leads to the same shockwave intensity and similar dynamic behavior of the induced cavities.

LIMITS TO HIGH POWER AMPLIFICATION

John Luginsland[1], Jack Watrous[1], David Simon[2], Brad Hoff[2]
1. Confluent Sciences, LLC
2. Air Force Research Laboratory

JW Luginsland1*, JJ Watrous1, DH Simon2, and BW Hoff2

1 Confluent Sciences, LLC

2 Air Force Research Laboratory

There has been tremendous progress in the power levels of high-power electromagnetic sources, such as klystrons, magnetrons, and TWTs that produce power into the gigawatt (GW) range. The vast majority of these sources are oscillators, where there is not a controlled phase signal associated with the high-power signal. In general, this is not surprising – amplification typically denotes linearity with respect to some input signal, while high power inevitably implies non-linear processes that generate intense relativistic AC electron beams. The vacuum electronics community has performed significant analysis on the sources for oscillation, typically involving undesired electromagnetic feedback from reflections in the device. The limits of high-power amplification in the GW range could be caused by these kinds of reflections, but also from non-linear processes associated with the intense space-charge in high-power microwave devices. One device that has both amplifier and oscillator configuration is the relativistic klystron driven by intense relativistic annular electron beams. In fact, the oscillator configuration explicitly introduces engineered feedback to produce oscillation. Here we report on a new model that captures both amplification and oscillation in the relativistic klystron, building on previous oscillator models(1). We interrogate this model with analytic and numerical methods to develop insight into the limits of high-power amplification. This model is also compared with particle-in-cell simulation and experimental performance. Additional efforts to develop a similar model for a TWT(2) will be detailed.

1. Luginsland, Lau, Hendricks, Coleman "A model of injection-locked relativistic klystron oscillator." IEEE Trans. Plasma. Sci, 24, 935, 1996

2. Hoff, Simon, French, Lau, Wong "Study of a high power sine waveguide traveling wave tube amplifier centered at 8 GHz." Phys. Plasma, 23, 103102, 2016.

Work was supported by FA9550-19RDCOR025.

REP-RATED TESTING OF A COMPACT MAGNETRON WITH DIFFRACTION OUTPUT (MDO) AND PLANS FOR TESTING THE FULL MDO*

Dmitrii Andreev[1], Artem Kuskov[1], Daniel Reass[1], Andrew Sandoval[1], Edl Schamiloglu[1], Yeong-Jer Chen[2], Jack Kreger[2], Jordan Chaparro[2]
1. University of New Mexico
2. NSWC

The University of New Mexico (UNM) proposed a compact magnetron with diffraction output (MDO) that is consistent with a permanent magnet guide magnetic field [1,2]. This compact high power microwave (HPM) source was tested at UNM and the particle-in-cell simulations accurately predicted its experimental operation [3]. This compact MDO was then tested at NSWCDD using a rep-rated power modulator. The power modulator was developed in a manner to drive a variety of potential relativistic RF sources with varying impedance and voltage requirements, providing flexibility for potential changes in drive voltage, impedance, and pulse width/repetition rate. UNM's compact MDO with a permanent magnet was the first source to be tested. The initial pulse width and repetition rate settings ranged from 50 – 250 ns and up to 10 Hz, respectively, allowing the investigation of pulse shortening, efficiencies at high repetition rate conditions, and possible interactions between the two conditions. The experimental results of this testing will be presented. Finally, plans for testing UNM's full S-band MDO [4] with a superconducting magnet will also be described.

1. C. Leach, S. Prasad, M. Fuks, and E. Schamiloglu, "Compact Relativistic Magnetron with Gaussian Radiation Pattern," IEEE Trans. Plasma Sci., vol. 40, 3116-3120 (2012).

2. C. Leach, S. Prasad, M. Fuks, and E. Schamiloglu, "Compact A6 Magnetron with Permanent Magnet," Proc. 2012 IEEE International Vacuum Electronics Conference (Monterey, CA, 24-26 April 2012), p. 491-492.

3. A. Sandoval, "Experimental Verification of A6 Magnetron with Permanent Magnet" (M.S. Thesis, University of New Mexico, Albuquerque, NM, 2018).

4. M. Fuks and E. Schamiloglu, "70% Efficient Relativistic Magnetron with Axial Extraction of Radiation Through a Horn Antenna," IEEE Trans. Plasma Sci., vol. 38, 1302-1312 (2010).

*Research at UNM was supported by ONR Grants N00014-16-1-2352 and N00014-16-1-3101. Research at NSWCDD was supported by ONR 30, ONR 35, and JNLWD.

EXPERIMENTAL RESULTS OF A METAMATERIAL-ENHANCED RESISTIVE WALL AMPLIFIER PROTOTYPE*

Patrick Forbes[1], John Booske[1], Nader Behdad[1]
1. Electrical and Computer Engineering Department University of Wisconsin-Madison

Theory and simulation predict the Metamaterial-Enhanced Resistive Wall Amplifier (MERWA) could be developed into a high power amplifier with wide instantaneous bandwidth[1]. Similar to a Resistive Wall Amplifier and Easitron[2], the MERWA produces exponential slow space charge wave growth for a velocity modulated beam. In contrast to the Resistive Wall Amplifier and Easitron, our research suggests the MERWA's slow space charge wave gain occurs in the presence of a lossy metamaterial-circuit's backwards (anomalously dispersive) electromagnetic wave. Due to the backward wave interaction and associated risk of backward wave oscillation, an important tradeoff exists involving the amount of circuit loss and its effect on oscillation, bandwidth, and gain. Prototype metamaterial circuits made of meandered wires[3] have been constructed out of copper (low loss) and stainless steel (high loss) for the purpose of proof-of-concept experiments to verify existence of MERWA gain. This talk will summarize results of simulated models and experimental hot test measurements using the prototypes including effects of varying circuit loss or introducing severs to prevent oscillation.

1. T. Rowe, J. H. Booske, and N. Behdad, "Metamaterial-Enhanced Resistive Wall Amplifiers: Theory and Particle-InCell Simulations," IEEE Trans. Plasma Sci., vol. 43, no. 7, 2015, pp. 2123-2131.

2. C. K. Birdsall and J. R. Whinnery, "Waves in an electron stream with general admittance walls," Journal of Applied Physics, vol. 24, no. 3, pp. 314-323, 1953.

3. T. Rowe, N. Behdad, and J. H. Booske, "Metamaterial-Enhanced Resistive Wall Amplifiers Design Using Periodically Spaced Inductive Meandered Lines," IEEE Trans. Plasma Sci., vol. 44, no. 10, 2016, pp. 2476-2484.

*Work supported by the Air Force Office of Scientific Research under Award No. FA9550-16-1-0509 and by a graduate fellowship from the Directed Energy Professional Society.

HIGH POWER AMPLIFICATION EXPERIMENTS ON A RECIRCULATING PLANAR CROSSED-FIELD AMPLIFIER

Steven Exelby[1], Geoffrey Greening[1], Nicholas Jordan[1], Drew Packard[1], Yue Ying Lau[1], Ronald Gilgenbach[1], Brad Hoff[2], David Simon[2]
1. University of Michigan
2. Air Force Research Laboratory

The Recirculating Planar Crossed-Field Amplifier (RPCFA) is an S-band high-power microwave amplifier adapted from the Recirculating Planar Magnetron developed at the University of Michigan.1 The RPCFA has demonstrated amplification in excess of 16 dB for input signals up to 40 kW at frequencies ranging from 2.40 to 3.05 GHz. Pulsed power for the RPCFA is provided by the Michigan Electron Long Beam Accelerator with Ceramic insulator stack (MELBA-C), which generates pulses of -300 kV, 1 – 10 kA, for approximately 400 ns. The injected RF power is produced by various magnetrons ranging in both power (10-40 kW) and frequency (2.40-3.05 GHz), as well as a moderate power ($\sim$1 kW) generator with continuously variable frequency.

The RPCFA has been fabricated and tested experimentally, verifying the results of MAGIC particle-in-cell simulations.2 The RPCFA has demonstrated amplification over a continuous frequency band from 2.6 to 3.05 GHz. For injected powers up to 40 kW, the amplifier is unsaturated, producing output powers approximately proportional to the input. These amplified, output microwave power levels have high variance and measures have been taken to understand and improve reproducibility. Cathodes with carbon brazed emitters have been tested to improve electron emission and create a more reproducible beam. These cathodes have decreased the variation of emission current, which has decreased the variation of amplification. Current research is focused on delivering input powers on order of 1 MW. A pulse forming network has been built to drive a 2.5 MW-rated MG5193 magnetron. Two existing magnetrons have consistently generated up to 2 MW on a test-stand.3 Amplification at MW input drive would confirm the high-power capabilities of the design and may also reduce variations in gain due to the stronger fringing RF fields.

INTER-DIGITAL MAGNETRON AND RIPPLED-FIELD MAGNETRON: TWO REMARKABLE REINCARNATIONS OF A VOLTAGE-TUNABLE MAGNETRON*

Andrey Andreev[1], Dmitrii Andreev[1], Samuel Smith[1], Stacie Hernandez[1], Ahmed Elfrgani[1], Edl Schamiloglu[1]
1. University of New Mexico

Originally all magnetrons were nonrelativistic [1]. The inter-digital magnetron (IDM) [2] is, perhaps, the most peculiar magnetron variant, operating at anode voltages ≤ 5 kV. The rippled-field magnetron (RFM) [3], another variant, is relativistic, operating at voltages ≥ 1 MV. It came to our attention that the RFM [3] is the relativistic analog of the IDM [2].

The IDM consists of a cathode and two sets of interleaving anode fingers (teeth, vanes) joined alternately to opposite faces of a cylindrical cavity. When voltage is applied to the cathode, the electrons initially circle in crossed radial electric E_r and axial magnetic B_z fields, and are intercepted by the inter-digital anode. The resulting interleaving anode current flowing along each anode finger in opposite axial directions produces a B_r varying in the θ-direction, superimposed onto B_z.

One may replace both cathode and anode interleaving fingers of the IDM [2] with a corresponding set of interleaving anode and cathode permanent magnets, also oriented alternately in the z-direction in such a manner that results in B_r varying in the θ-direction, and superimposed onto B_z. Assuming that the set of interleaving cathode permanent magnets may be covered by an electron emitting smooth surface and, correspondently, the set of interleaving anode permanent magnets may be covered by the electron absorbing smooth surface with both covers facing the magnetron interaction space, one may effectively have a RFM [3].

Theoretical analyses and particle-in-cell simulations of both the IDM and RFM will be presented, which should provide for wide frequency tuning by varying the voltage.

1. G.B. Collins (Ed.), Microwave Magnetrons (Vol. 6) (McGraw-Hill, New York, 1948).

2. J.F. Hull and A.W. Randals, "High-Power Interdigital Magnetrons," Proc. IRE, vol. 36, 1357 (1948).

3. G. Bekefi, "Rippled-Field Magnetron," Appl. Phys. Lett., vol. 40, 578 (1982).

*Supported by DARPA Grant #N66001-16-1-4042

HIGH-POWER MICROWAVE GENERATION BY A DOUBLE-ANODE VIRTUAL CATHODE OSCILLATOR

Kazuki Nagao[1], Kazuya Sakurai[1], Wataru Takatsu[1], Van Thuan Pham[1], Taichi Sugai[1], Weihua Jiang[1]
1. Nagaoka University of Technology

The virtual cathode oscillator (vircator) is one of the promising devices oscillating high-power microwaves. Simplicity and high-power capability are advantages. However, the low efficiency and frequency stability are serious problems. To improve oscillation efficiency, strengthen the feedback of the electromagnetic wave to the electron beam is important. To strengthen feedback, double-anode is effective because it strengthens the modulation of beams. In this paper, we dealt double-anode to improve output power. Experiments were carried out on a repetitive pulsed power generator "ETIGO-IV" (maximum output: 400 kV, 13 kA, 120 ns, 1 Hz). The output microwaves are diagnosed for peak power and energy by using horn antennas. The microwave frequency is obtained by fast-Fourier analysis of the signal recorded by a high-speed digital oscilloscope. From the experimental result, the microwaves are obtained peak power of $\sim$100MW. These results are shown that the output of the virtual cathode oscillator can be progress by using the double-anode. In addition, particle-in-cell simulations were carried out by using a simulation code "MAGIC." Simulation results are compared with experimental results to examine the effect of the double-anode and possible ways of further improvement of microwave efficiency.

PROBLEMS OF DEVELOPMENT A COLD-CATHODE MAGNETRON IN PULSE MODE FOR APPLICATION IN AN ACCELERATOR

Sergiy Cherenshchykov, Sergiy Cherenshchykov

High efficiency and low construction costs of magnetron have a significant benefit for an accelerator RF feeding. Main disadvantage of magnetron is poor frequency stability. The disadvantage may overcome due to injection phase lock. This solution is ready for the pulsed mode operation of accelerator. Next step of a magnetron advantage development is application a secondary emission cold cathode. It allows next decrease construction costs and much increase lifetime. The last one allows decrease operation costs. Important problem is ignition of self-supported secondary emission from a cold cathode of a magnetron. Ignition of magnetron occurs on slop of the high voltage pulse applied to the cathode. After initiation the electron emission continues at the top of the following part of the pulse. Such an igniting method can contribute to the deterioration of frequency stability due to subsequent voltage fluctuations on the subsequent flat part of the pulse. Another way for good frequency stability is application magnetron type amplifier. That is an amplitron. Generally the amplitron have secondary emission cold cathode. The ampliton are ignited by input RF power. Main disadvantage of the amplitron is low gain. The gain is 13-20 db at high power. In compare injection phase lock scheme need input power to magnetron on 30 db and more low than magnetron power. That is means "amplification" more 30 db. Another amlitron disadvantage is more complicated design in compared with magnetron. Magnetron may be ignited by input RF power too. However, the optimal start frequency does not coincide with the generation frequency. So fast magnetron frequency tuning is need for development. Another approach is application stabilitron scheme of amlitron with ignition by slop of the high voltage pulse. It may allow achieving good frequency stability without seed RF power. Application of a coaxial magnetron is possible for similar goal.

NEW INSIGHTS IN PULSED POWER DRIVEN EXPLOSION OF UNDERWATER WIRES AND WIRE ARRAYS

Simon Bland[1], David Yanuka[1], Alexander Rososhek[2], Savva Theocharous[1], Sergey Efimov[2], Margie Olbinado[3], Alexander Rack[3], Ya.E. Krasik[2]
1. Imperial College London
2. Technion
3. European Synchrotron Radiation Facility

Pulsed power driven underwater wire explosions are accompanied by the efficient generation of strong shockwaves. In the case of cylindrical or quasi-spherical wire arrays, convergence of these shockwaves results in high energy density conditions with multi Mbar pressures being obtained on axis, even in compact 'table-top'experiments. However much of the physics underlying wire explosion and shockwave interactions remains undiagnosed – making modelling efforts difficult and prone to misinterpretation.

Recently, we have performed the worlds first high current pulsed power experiments coupled to a synchrotron. The resultant multiframe, phase contrast radiography images provide absolute density measurements at high resolution. On the ID19 beamline at ESRF we explored the explosion of aluminium, copper and tungsten wires, using a $\sim$30kA, 500ns current source. As the wires expanded and ionised unexpected striation instability growth was observed inside the dense wire material. In two wire experiments, interacting a shockwave launched into the water with the surface of the exploding wires produced a new test bed for Richmeyer Meshkov instability growth. With a cylindrical array of wires, multiple shock reflections were observed and the increase in density of the water at convergence of the shockwaves seen.

As part of the talk we will compare the quantitative data produced with leading hydrodynamic codes. We will show that underwater wire explosions can be used for the determination of phase transitions which are accompanied by a weak shock generation; as well as show direct evidence of Al wire combustion obtained through spectroscopy. Finally we will discuss how the techniques can be extended, exploring the use of underwater arrays for flyer acceleration, and the production of different hydrodynamic instabilities such as the Kelvin Helmholtz.

This work was sponsored by Sandia National Laboratories, First Light Fusion, EPSRC, NNSA under DOE Agreement Nos. DE-NA0003764 and DE-SC0018088 and the Israeli Science Foundation.

THOMSON SCATTERING ON LABORATORY PLASMA JETS TO STUDY CURRENT POLARITY EFFECTS

Jacob Banasek[1], Sophia Rocco[1], Tom Byvank[1], William Potter[1], Bruce Kusse[1], Dave Hammer[1]
1. Cornell University

Thomson scattering measurements have been performed on plasma jets created from a 15 μm thick radial Al foil load on COBRA, a 1 MA pulsed power machine. Two different spectrometers were used to collect both the ion acoustic wave (IAW) and the electron plasma wave (EPW) spectral features. The IAW feature gives a good measurement of the electron temperature, while the EPW feature measures the electron density. The laser used for Thomson scattering had an energy of 10 J at 526.5 nm and a 2.2 ns full width at half maximum duration. The IAW feature was recorded with a streak camera for time resolution of the scattering, while the EPW feature was integrated over the entire laser pulse but had spatial resolution. This Thomson scattering system was used to compare plasma conditions in the jets under different current polarities. Previous experiments and computer simulations showed that the direction of the current can significantly affect jet properties due to extended magnetohydrodynamic effects such as the Hall effect. Experiments show that around peak current, jets with current flowing radially outward (“reverse polarity”) through the foil were taller and denser than jets with current flowing radially inward (“standard polarity”). This caused reverse polarity jets to be heated from 20 to 40 eV from inverse bremsstrahlung by the probing laser, while standard polarity jets stayed relatively constant at 20 eV. The EPW feature measures densities outside of the jet to be around 5×10^{17} cm^{-3} while inside the jet the density was at least 2×10^{18} cm^{-3}. In addition, the widths of the Thomson scattering peaks will be discussed, as they can give either information on the temperature of the plasma or other plasma properties.

Work supported by the NNSA Stewardship Science Academic Program under DOE Cooperative Agreement - DE-NA0003764.

ALUMINUM DOUBLE PLANAR WIRE ARRAYS AND DOUBLE PLANAR FOIL LINERS ON THE UNR AND UM PULSED POWER DRIVERS

Christopher Butcher[1], Victor Kantsyrev[1], Alla Safronova[1], Ishor Shrestha[1], Jeffrey Rowland[1], Veronica Shlyaptseva[1], Austin Stafford[1], Paul Campbell[2], A. M. Steiner[3], Stephanie Miller[2], D. A. Yager-Elorriaga[3], Nick Jordan[2], Ryan McBride[2], Ronald Gilgenbach[2]

1. University of Nevada, Reno

2. University of Michigan

3. University of Michigan, Ann Arbor, MI 48109, USA

In previous studies at the UNR high-impedance Marx bank Zebra generator (1.9 Ω, 1.7 MA, 100 ns), Double Planar Wire Arrays (DPWAs) proved to be excellent radiators, and Double Planar Foil Liners (DPFLs) proved useful for future ICF applications. This presentation will showcase the results of joint UNR/UM experiments with Aluminum (Al) DPWAs and Al DPFLs at the UM low-impedance Linear Transformer Driver (LTD) MAIZE generator (0.1 Ω, 0.6 MA, and 100–250 ns). The DPWAs consisted of two wire planes of micron-scale sized Al wires, while the DPFLs consisted of two planes of micron-scale thickness. Comparisons of the radiative properties and implosion dynamics of Al DPWAs and DPFLs on the MAIZE LTD are discussed, as well as compared to previous results with Al on the Zebra generator. The current pulse of the low-impedance MAIZE LTD is heavily dependent upon the load inductance. Compared to the higher impedance Zebra generator, implosions on the MAIZE LTD are characterized by a longer risetime and lower than expected peak current. Diagnostics in both studies include an absolutely calibrated filtered PCD (>2.4 keV) and Si-diodes (>1.4 keV), x-ray pinhole cameras, spectrometers, and optical shadowgraphy systems. By comparing a simulated current trace to the measured current trace, the inductance over the time of the shot can be predicted, which is then used to calculate the effective radius over time of the current-carrying plasma. The research was supported by the NNSA under DOE grant DE-NA0003047.

PHOTONIC DOPPLER VELOCIMETRY (PDV) OF BARE AND DIELECTRIC-COATED ALUMINUM EXPLODED BY INTENSE CURRENT

Bruno Bauer[1], Trevor Hutchinson[1], Thomas Awe[2], Sheri Payne[2], Daniel Dolan[2], Brian Hutsel[2], Jamin Pillars[2], Bonnie Mckenzie[2], Sonal Patel[2], Kevin Yates[3], Vladimir Ivanov[1], Stephan Fuelling[1], Richard Siemon, Seth Kreher[1], Christopher Rousculp[3], Irvin Lindemuth[1], Edmund Yu[2]

1. University of Nevada, Reno
2. Sandia National Laboratories
3. Los Alamos National Laboratory

Understanding the evolution of ohmically heated conductors is a fascinating physics challenge with numerous applications. The expansion of aluminum-6061 rods pulsed with rapidly rising lineal current density ($3\times10^{15}\,\mathrm{A\,m^{-1}s^{-1}}$ for 80 ns, from the SNL-Mykonos linear transformer driver) has been measured with photonic Doppler velocimetry (PDV). The 400-μm rod radius was much larger than the electrical skin depth. Bare rods were compared with rods coated with 5, 17, and 41 μm-thick transparent Parylene-N [poly(p-xylylene) $(\mathrm{C_8H_8})_n$]. The results are compared with those from magnetohydrodynamic simulations and from previous shadowgraphy and streak imaging of aluminum exploded using the UNR-Zebra generator. PDV shows the aluminum surface starts expanding when the surface magnetic field reaches 85 ± 10 T, consistent with previous data. Interestingly, PDV observes a gradual, continuous, fairly constant acceleration, over tens of nanoseconds, in contrast to previous measurements, which were consistent with a nanosecond explosion to fairly constant vapor expansion speed. Coatings tamp the expansion, with thicker coatings slowing the expansion more than thinner ones. The expansion rate was not affected by varying the aluminum surface finish under the 41-μm-thick coatings. Later, if self-emission indicates plasma formation, the breakdown appears correlated with a rapid decrease in PDV signal.

*Work supported by SNL PO1742766 and DOE grant DE-NA0003870. SNL is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, a subsidiary of Honeywell International, for DOE-NNSA under contract DE-NA-0003525. LANL is operated by Triad National Security for DOE-NNSA under contract 89233218CNA000001.

SHOCK WAVES GENERATED BY UNDERWATER ELECTRICAL EXPLOSION OF A SINGLE WIRE

Sasha Rososhek[1], Sergey Efimov[1], Viktor Gurovich[1], A. Virozub[1], Somesh Tewari, Ya.E. Krasik[2]
1. Technion
2. 1 Physics Department, Technion, Israel Institute of Technology

The observation and analysis of shock waves generated by the underwater electrical explosion of a single aluminum and copper wires are reported. Experiments were carried out using microsecond timescale high-current generators delivering ∼180 kA pulse with 1.2 μs rise-time and ∼30 kA pulse with 1 μs rise-time. Shadow streak imaging was applied to study shock waves generated by the radially expanding wire while energy was deposited into the wire. The first two weak shock waves, generated prior to the wire explosion, are related to the solid-liquid and liquid-vapor phase transitions. The energy density deposition analysis and one-dimensional magneto-hydrodynamic simulation coupled with the equation of state and conductivity model revealed that these shock waves were not associated with melting or evaporation of the entire wire. The third strong shock wave is related to the beginning of the vapor-low ionized plasma phase transition when the main energy deposition occurs. One-dimensional hydrodynamic simulations coupled with the equation of states for a wire material and water showed that the wire expanded with sub-sonic velocity and the strong shock was generated by the compressed water layer formed in the vicinity of expanding wire. The dynamics of this shock was analyzed employing a simplified model, which assumes the uniform density of a compressed layer between the shock wave and expanding wire. The model results showed a satisfactory fit for both the shock wave trajectory and radial expansion of the wire's boundary obtained in the experiment.

IRRADIATION OF SILICON TARGETS BY OUTFLOWS EMITTED BY CONICAL WIRE ARRAY Z-PINCHES.

Felipe Veloso[1], Gonzalo Muñoz-Cordovez[1], Mario Favre, Donovan Diaz-Droguett[1], Vicente Valenzuela-Villaseca[1], Milenko Vescovi[1], Heman Bhuyan[2], Edmund Wyndham[3]

1. P Universidad Catolica de Chile

2. Pontificia Universidad Católica de Chile

3. Instituto de Física, Pontificia Universidad Católica de Chile

Energetic charged particles and plasma outflows are emitted by some transient high dense plasmas, particularly, different kinds of Z-pinches [1,2]. These emissions have been studied for producing surface modifications, implantation and/or deposition onto different substrates [2]. In this work, the axial outflows, composed of both keV-MeV ions and plasma jet, of a tungsten (W) conical wire array Z-pinch are used to modify the surface of a silicon (Si) target in a single shot basis. The experiments are performed in the Llampudken pulsed power driver (∼350kA in ∼350ns) [3]. To probe the plasma jet outflow, side-on UV/XUV pinhole imaging is performed, whereas ions outflows is studied using a set of Faraday cups. The substrates are analyzed using standard material science techniques including FE-SEM, EDX, XRD and AFM.

Figure 1 shows a Faraday cup signal collected 23cm above the conical array and a SEM imaging with spatially resolved EDS obtained from an irradiated Si target at similar position. The signal shows negative and positive excursions, corresponding to electrons and ions axially expelled from the array. Time-of-flight measurements indicated that characteristic W ions energy can reach up to a few MeV. Black dots on SEM/EDS image indicate tungsten presence over the target. Besides this, the irradiation of silicon reveals different kind of changes in surface morphology, such as micropores and stripes-like structures, according to their axial distance from the array. Both the characterization of tungsten plasma outflows and the effects of their interaction with silicon target will be shown and presented.

Acknowledgement: Funded by project FONDECYT 1171412. GMC and MV acknowledge CONICYT grants for graduate studies.

References:

[1] G Muñoz-Cordovez, et al, Phys Plasmas 25, 102101 (2018)

[2] H Bhuyan, et al, J Phys D: Appl Phys 40, 127 (2007)

[3] H Chuaqui, et al, Laser Part Beams 15, 241 (1997)

EFFECTIVE METHANE CONVERSION BY NEGATIVE NANOSECOND REPETITIVELY PULSED DISCHARGE

Cheng Zhang[1], Shuai Zhang[1], Hao Sun [1], Bangdou Huang[1], Yuan Gao[1], Tao Shao[1], Zehui Liu[1]

1. Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciences

Conversion of methane (CH4) to value-added chemicals and fuels by non-thermal plasmas is a solution for effective energy utilization in the 21st century. In this paper, CH4 conversion by a nanosecond repetitively pulsed (NRP) discharge is studied. Negative NRP discharge can realize various discharge regimes, namely corona discharge, filamentary discharge and spark discharge, in a needle-plate reactor1,2. In corona discharge, the plasma is quite diffusive, but the input energy is so low that only trace hydrogen is found in this regime. The main products of filamentary discharge are H2, and C2H6 with hydrogen selectivity of 40% and 12%, while the CH4 conversion rate is 13%, As for the spark discharge, the input energy is much more energetic that the main products become H2, C2H2 and amorphous soot. The CH4 conversion rate is 77%, and the selectivity of C2H2 is 6%. The ultrafast ICCD images and optical emission spectroscopy were recorded to study the discharge mechanism and plasma chemistry. It is found that short pulse width could inhibit the growth of bright spots around the electrodes, prevent the transition between filamentary discharge and spark discharge, and thusly control the input energy smoothly. The CH, C2, and Hα are the highest emission spectra profiles in these discharge regimes, respectively. The appearance of C+ in the spark discharge accounts for the dramatic increase of current and temperature. The gas temperature estimated by the rotational temperature of CH(A-X) and C2 swan band are 700 K, 1000 K and 1800 K, respectively, which suggests the thermal reactions play an important role in controlling the final products.

1. Y. Gao, S. Zhang, H. Sun, R. Wang, X. Tu, and T. Shao, "Highly efficient conversion of methane using microsecond and nanosecond pulsed spark discharges," Appl. Energy, vol. 226, pp. 534-545, 2018.

2. S. Zhang, Y. Gao, H. Sun, H. Bai, R. Wang, and T. Shao, "Time-resolved characteristics and chemical kinetics of non-oxidative methane conversion in repetitively pulsed dielectric barrier discharge plasmas," J. Phys. D: Appl. Phys., vol. 51, no. 27, p. 274005, 2018.

THE DYNAMICS OF THE MICROPLASMAS INSIDE A CAPILLARY

Shuqun Wu, Xueyuan Liu, Chang Liu, Yuxiu Chen, Chaohai Zhang

The dynamics of the microplasmas inside capillaries

Shuqun Wu, Xueyuan Liu, Chang Liu, Yuxiu Chen, Chaohai Zhang

1Center for More Electric Aircraft Power System, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China

*E-mail: wushuqun2010@hotmail.com

The miniature of the plasma jets is very much desired for root canal treatment, single-cell-precision cancer treatment, micro-patterning functionalized surface, and inner tube surface modification [1]. An effective and simple approach to realize microplasma jets is the reduction of the tube diameter. However, the plasma properties may be changed as the tube diameter decreases. As the tube diameter decreases to several μm, the dynamics of the microplasmas remains unclear.

In this work, with the assistant of an air DBD, the microplasma could be ignited inside capillaries with diameter of 4 μm and length of 2 cm. The electron density of the microplasma reaches as high as 1017 cm-3, while the gas temperature of the microplasma remains close to the room temperature. To obtain the propagation velocity of the microplasma plume, a photomultiplier tube (HAMAMATSU H10721-01) was used to detect the plasma light emission. An optical fiber having a hole with diameter of 0.2 mm was connected to the photomultiplier tube (PMT). By moving the PMT fiber along the microplasma plume, the light signals emitted from different positions of the microplasma plume were monitored. Therefore, with the knowledge of the time shifts between these light signals and the positions of the fiber, the propagation velocity of the microplasma plume can be determined by the position interval divided by the time shift. It is found that, with the applied voltage left unchanged, as the tube diameter decreases from 100 μm to 50 μm, the propagation velocity of the microplasma plume slightly increases. As the tube diameter decreases from 50 μm to 20 μm, the propagation velocity decreases significantly. Moreover, as the tube diameter decreases from 20 μm to 4 μm, the propagation velocity keeps almost unchanged. These results are largely different from these results in plasma jets. To further understand the propagation of the microplasmas with diameter of several micrometers, an intensified charge-couple device camera (ICCD) is used to capture the dynamics of the microdischarge.

[1] Ye D, Wu S, Yu Y, et al.. Applied Physics Letters, 2014,104(10310510).

PLASMA TREATMENT ON HEAVY OIL MODEL COMPOUNDS IN A NANOSECOND PULSED DBD REACTOR

Hao Sun[1], Shuai Zhang[1], Yuan Gao[1], Cheng Zhang[1], Tao Shao[1]
1. Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciences

Converting heavy oil into valuable chemical products is a novel application for non-thermal plasma1. The nanosecond pulsed DBD is known for its high reactivity at low temperature2, which has a potential for high oil conversion. However, the interaction between plasma and liquid is a complex and inefficient process, because the plasma merely can treat the liquid surface. In this paper, we used a sloping coaxial DBD reactor as a liquid film reactor to produce free falling liquid film, of which contact area was significantly improved. Heptane and 1-methylnaphthalene were used as the model compounds. The reactor was powered by nanosecond pulsed DBD to improve the uniformity and reactivity. Before the liquid was injected into the reactor, the discharge was diffusive. The plasma became filamentary at the present of the liquid film. Based on a circuit model, we found it is the vapor that increases the breakdown voltage of the primary discharge, and leads to the instability of the discharge. The model compounds were cracked into hydrogen, light gaseous hydrocarbons, various lighter or heavier liquid hydrocarbons. However, the conversion rate was quite low, namely 16% and less than 2%, respectively. CH, C2, and Hα were found in the OES, which confirms that the model compound was cracked into light hydrocarbon fractions. Complicated decomposition and recombination reactions take place in the DBD plasma, and thusly generate complex products.

1.K. Zhang, R. Wang, W. Han, S. Zhang, Q. Wang, and T. Shao, ”Progress of heavy oil processing by plasma technology,” Trans. China Electrotech. Soc, vol. 31, no. 24, pp. 1-15, 2016. (in Chinese)

2. Y. Gao, S. Zhang, H. Sun, R. Wang, X. Tu, and T. Shao, ”Highly efficient conversion of methane using microsecond and nanosecond pulsed spark discharges,” Appl. Energy, vol. 226, pp. 534-545, 2018.

DEVELOPMENT OF LOW FREQUENCY DIELECTRIC BARRIER DISCHARGE USING ROTATABLE ELECTRODES

Tatsuo Ishijima[1], Kentaro Morimoto[1], Naw Rutha Paw[1], Takuma Kimura[2], Mohammad Rasel Pervez[1], Eugen Stamate[3], Yasunori Tanaka[1], Yoshihiko Uesugi[1]

1. Kanazawa University

2. National Institute of Technology Ishikawa College

3. Technical University of Denmark

Various non-equilibrium atmospheric pressure plasma generation methods are used for industrial applications such as corona discharge and dielectric barrier discharge (DBD). A DBD is developed for surface treatment of particulate materials using a rotatable electrode at low frequency high-voltage power source. The rotatable electrode dielectric barrier discharge reactor (RE-DBDR) is consisted of a cylindrical dielectric chamber, two fixed cylindrical thin metal electrodes attached on the outside wall of the chamber, and a rotatable rectangular thin metal plate electrode supported by an axial rod located in the chamber center. DBD can be ignited owing to an electrostatic induction effect between the floating electrode and the outside electrodes. Since the rotatable electrode is electrically floating, proposed electrode configuration enables us to enlarge DBD volume by rotating the thin plate electrode at high rotational speed. DBD in flowing air is generated inside a cylindrical discharge device using a sinusoidal voltage pulse of Vpp = 30 kV with frequencies of 60 Hz, 80 Hz, 100 Hz and about 10 kHz with an amplitude modulation. Electrical discharge characteristics depend on ratio of a rotational frequency of the floating electrode fr with the frequency of an applied voltage pulse fp. The measured ozone concentration, which increased with rotational speed, is proportional to the discharge power consumption. At 60 Hz operating frequency and 3 slm air flow rate, the ozone concentration increased from 7.2 ppm at fr =0 to 108.4 ppm at fr =120 Hz.

We observed the emission spectrum and found strong N2 molecular band spectra of second positive system (C-B). N2(C-B) has a maximum fr =120 Hz when measured power consumption of DBD and ozone concentration has a maximum at fr =120 Hz. These results suggest that effective discharge area could be controlled by rotational speed of the floating electrode and applied high-voltage frequency.

PLASMA ASSISTED CHEMICAL LOOPING REACTIONS USING NANO-CATALYSTS FOR CO-PRODUCTION OF SYNGAS AND HYDROGEN

Rajagopalan Ranganathan[1], Zhongqi Liu[1], Steven Fondriest[1], Robert Dupont[2], Amelia Biase[3], Laura Holifield[1], Ruigang Wang[1], Mruthunjaya Uddi[4]

1. University of Alabama
2. Michigan Technological University
3. Smith College Picker Engineering Department, MA
4. Unviersity of Alabama

We present the results of non-equilibrium plasma enhanced Chemical Looping (CL) reduction/oxidation steps with water splitting oxidation step and CH4+CO2 reforming step, respectively. Syngas and C2 hydrocarbons are produced during the reduction step and hydrogen is yielded during the oxidation step. Combinations of nano-catalyst and Oxygen Carrier (OC) materials such as Ni-based perovskite with ceria and Ru-CeO2-NR (nano-rod) are used to improve the performance at lower temperatures along with the plasma. Experiments show production of hydrogen and syngas at low temperatures (150-400 °C) while no reactions are observed with catalyst alone for testing temperatures below 750 °C. Optical Emission Spectroscopy of the heterogeneous reactions will be presented. The experiments were conducted in the temperature range 150-400 °C under atmospheric pressure. Temporal optical emission of various species such as CO2, CH, CO, OH, and C2 based species are collected over the wavelength range of 300 to 600 nm and analyzed for understanding the heterogeneous reaction mechanisms.

TRANSIENT PLASMA-BASED REMEDIATION OF NANOSCALE PARTICULATE MATTER

Sisi Yang, Sriram Subramanian, Dan Singleton, Christi Schroeder, William Schroeder, Martin Gundersen, Stephen Cronin

Recent studies have shown ultrafine particulate matter (UFPM) produced by a variety of sources represents a serious health hazard and has been associated with various forms of cancer. In this study, we demonstrate a highly effective method for treating restaurant smoke emissions using a transient pulsed plasma reactor based on a nanosecond high voltage pulse generator and also explore the remediation effect of transient pulsed plasma together with an applied DC-bias. We measure the size and relative mass distribution of particulate matter produced in synthetic and actual commercial charbroiling processes (e.g., cooking of hamburger meat) both with and without the plasma treatment. With plasma treatment, we observe up to a 55-fold reduction in total particle mass and a significant reduction in the nanoparticle size distribution using this method for charbroiler emission. For synthetic emission with both polyaromatic olefin PAO-4 and soybean oil, we found that a more than three-order-of-magnitude reduction in particulates can be achieved by this plasma discharge with applied DC bias. The effectiveness of the UFPM remediation increases with both the pulse repetition rate and pulse voltage, demonstrating the scalability of this approach for treating higher flow rates and larger systems.

PATTERN DEPENDENT PROFILE DISTORTION IN PLASMA ETCHING OF HIGH ASPECT RATIO FEATURES

Shuo Huang[1], Seungbo Shim[2], Sang Ki Nam[2], Wonyup Ko[2], Mark Kushner[1]
1. University of Michigan
2. Samsung Electronics Co. Ltd.

In plasma processing for semiconductor fabrication, patterns are transferred from the overlying mask (typically photoresist, PR) to underlying features, ideally replicating the mask pattern. Feature distortion (e.g., twisting, tilting and edge roughness) during plasma etching can result from charging, polymer deposition and pattern dependencies. With feature sizes now less than tens of nm, there is randomness in the flux of particles into the feature. This randomness is enhanced at the etch front of high aspect ratio (HAR $>$ 50) features due to conduction limits and sidewall scattering. Stochastic charging on the walls of features by ions can produce interference between neighboring features through the resulting electrostatic fields. The intrinsic randomness and electrostatic interference can result in profile distortion and feature-to-feature variation.

In this paper, we report on results from a computational investigation of feature distortion during pattern transfer from PR to silicon-dioxide using tri-frequency capacitively coupled plasmas sustained in fluorocarbon gases. The reactor scale modeling was performed using the Hybrid Plasma Equipment Model (HPEM). The feature scale modeling was performed using the 3-dimensional Monte Carlo Feature Profile Model (MCFPM) which was updated to address patterns having different arrangements of vias (e.g., rectilinear, honeycomb).

Due to stochastic fluxes of different species into the features, non-circular profiles with contact edge roughness can occur. Charge deposition by ions on inner surfaces of features repels subsequent ions and deviates their trajectories, resulting in decreased etch rates and twisted profiles. With a periodic boundary condition when simulating a single via (circular HAR hole) little distortion is predicated. When simultaneously simulating multiple vias, pattern dependent distortion is predicted. The randomness of charging of surrounding vias produces stochastic electric fields which affects trajectories of ions in adjacent vias.

PULSED POWER TECHNOLOGY AND APPLICATION DEVELOPMENT AT NAGAOKA UNIVERSITY OF TECHNOLOGY

Weihua Jiang[1], Taichi Sugai[1], Akira Tokuchi[1]
1. Nagaoka University of Technology

This is a summary of pulsed-power related researches conducted at Nagaoka University of Technology. Compact, repetitive, and solid-state switched pulsed power sources have been developed for industrial applications. Various circuit topologies and switching devices have been studied in order to optimize the output and demonstrate the performance of different pulsed power generators. The circuit methods include Marx and LTD, as well as inductive-energy-storage using opening switch. The switching devices cover a wide range of power semiconductors including the latest type of SiC-MOSFET. These activities have been carried out in cooperation with and supported by our industrial partners who are exploring the possibilities of commercializing these systems for applications in environmental, biological, and material fields.

ADVANCED NANODIELECTRIC MATERIAL SCALING FOR FURTHER SIZE REDUCTION OF ULTRA-HIGH VOLTAGE, 500 KV CAPACITOR PROTOTYPES

Randy Curry[1], Luke Brown[2], Samuel Dickerson[1], Sarah Mounter[1], Aaron Maddy[2], Madison Schwinn[3]

1. University of Missouri

2. University of Missouri, Center for Physical and Power Electronics

3. University of Missouri, Center for Physical and Power Electroncis

The Center for Physical and Power Electronics has been developing compact capacitors for use in high voltage pulsed power, directed energy applications. Specifically for vehicle stopping. These 130 pf capacitors use a proprietary nanocomposite dielectric material named MU100 and were designed for 500 kV operation with 60% reversal. This material was initially developed to reduce the size of high frequency, high voltage dielectric loaded antennas, however, due to its unique material characteristics, and the nanocomposite has shown promise in development of very compact, high voltage capacitors that can operate over the temperature range of -40 C to 120 C. The material was successfully used to fabricate capacitor prototypes capable of repeatable performance at 500 kV with lifetimes greater than 104 shots. The capacitors used for this design had a diameter of 3.4 cm and an 8 cm height based on application requirements. This work covers the scaling of much more compact capacitors that have the same volume as the 3.4 cm diameter capacitors but a diameter of 6.35 cm. They are assembled in series for the 500 KV design. This new capacitor design allows for the further reduction of volumetric size of the final 130 pf capacitor assemblies. With a 6.35 cm diameter design, a volume reduction of over 2 times over that of commercial capacitors is achieved while maintaining the breakdown strength performance over a wide range of temperatures. The results of the scaling tests

will be reported and the implications discussed.

*Work supported by the JNLWD under contract number W15QKN-14-9-1001

FIRST IMPLEMENTATION OF A SOLID-STATE IMPEDANCE-MATCHED MARX GENERATOR

Tom Huiskamp[1], Jeroen van Oorschot[1]
1. Eindhoven University of Technology

In this contribution we present the first implementation of a solid-state impedance-matched Marx generator (IMG). Our application - transient plasma for environmental applications - requires fast (several ns rise time), high-voltage pulses with flexible pulse duration (10-100's of nanoseconds) and amplitude (up to several tens of kV). The IMG topology was introduced in 2017 by researchers from Sandia National Laboratories and is ideally suited to generate such pulses. Where the original IMG topology was conceived with modules ("bricks") of spark gaps and capacitors (just like in linear transformer drivers), we implemented the IMG topology with MOSFET switches, capacitors and PCB transmission lines into a first prototype of ten 1-kV stages. This first prototype is capable of generating fast pulses with 10-kV output voltage, adjustable pulse duration and <5 ns rise time. The impedance-matched structure consists of coaxial 1-kV stages comprising multiple parallel transmission lines, each energized by a fast MOSFET circuit. These stages are stacked in series and a coaxial transmission line placed at the center of the IMG structure ensures proper impedance matching. The solid-state IMG was designed with 3D transient EM simulations, circuit simulations and experimental verification of single stages and the full-stage prototype. In this contribution, we present the first results.

PORTABLE SHORT PULSE NEUTRON SOURCE FOR IDENTIFCATION AND LOCALIZATION OF CLANDESTINE NUCLEAR MATERIALS

Brady Gall[1], Michael Heika[2], Michael Blasco[2], Joseph Bellow[2], Bernard Meehan[3], Jessie Walker[4], Mark Gerling[5], Yuri Podpaly[6]

1. Mission Support and Test Services LLC

2. NNSS

3. NSTec

4. Los Alamos National Laboratory

5. Sandia

6. Lawrence Livermore National Laboratory

The reliable detection of special nuclear materials continues to be a primary goal of national security programs conducted by the NNSA Defense Nuclear Nonproliferation organization. While these programs are diverse, many share a core need for a small, robust pulsed neutron generator. This project addresses this need by deploying a recently developed portable dense plasma focus (DPF) neutron source to identify and localize special nuclear material objects. The portable DPF system was presented at ICOPS 2018; it weighs approximately 100 lbs and uses 750 W of utility electrical power. The DPF produces 30 nanosecond-wide neutron pulses with a total yield of 6E7 neutrons per pulse at the DD fusion energy of 2.45 MeV. The system has a repetition rate of 0.2 Hz., resulting in a time-average yield of approximately 1.2E7 neutrons per second. The portable DPF was deployed at the Device Assembly Facility (DAF), located at the Nevada National Security Site (NNSS), to measure the active interrogation response products of highly enriched uranium (HEU) objects. Two primary diagnostic systems were implemented to measure the response products of the HEU objects: 1. Sandia National Laboratories'(SNL) Mobile Imager of Neutrons for Emergency Responders (MINER) detector array to determine the spatial localization of the neutron-stimulated HEU object; and 2. Lawrence Livermore National Laboratory's (LLNL) recently developed short-pulse fast fission diagnostic to obtain signature fast-fission neutron spectra of the fissioning HEU object. These two compact diagnostics solutions, combined with the portable DPF system, provide safe, mobile, and effective integrated platform for sensing and locating clandestine nuclear materials.

LOW ENERGY LASER TRIGGERING AT 1535 NM

Jon Pouncey[1], jane Lehr[2], Josh Foster[3], Scott Hamlin[3]
1. University on New Mexico
2. University of New Mexico
3. MegaWatt Lasers Inc

The use of lasers to initiate the closure of high-power gas switches was initially explored soon after the development of suitable high power pulsed lasers in the 1960's. The low jitter, excellent triggering range, and galvanic isolation provided by laser triggering has been extensively exploited in the triggering of megavolt switches in large pulsed power machines. However, the lasers and optical systems used in these systems are very large, complex, and expensive. This has led to the perception that laser triggered gas switches are necessarily large, complex, and expensive – with the corresponding reluctance among the directed energy and compact pulsed power community to consider their use in compact pulsed power systems.

The APERIODIC research group at the University of New Mexico has been investigating novel triggering technologies for compact pulsed power. One of the technologies under investigation is a system we have named the micro integrated laser switch (MILS). This system holds the potential to overcome the limitations of traditional laser triggering of gas switches.

As part of the preliminary work on developing the MILS concept, UNM has collaborated with MegaWatt Lasers to conduct laser triggering experiments using a COTs erbium-doped glass passively Q-switched micro laser. This 28 mm by 9 mm laser produces 4 ns pulses at 1535 nm with an average energy of 250 μJ. One of the principle advantages of this laser is that, due to the wavelength and energy, it is eye-safe and can be operated without the stringent controls necessary for the lasers typically used for laser triggering.

MICROSECOND FAST, 100 KV MODULAR PULSE CHARGER

Tyler Klein[1], Andreas Neuber[1], James Dickens[1]
1. Texas Tech University

A pulse charger module was designed and tested for use in scaled experiments. Each pulse charger module is powered with a 12 V Lithium-ion battery and set to charge a 1 nF capacitor up to 100 kV in less than 10 μs. This is achieved by initially charging a 1.5 μF capacitor to 5 kV. Using a thyristor switch, this capacitor will then discharge into two transformers paralleled on the primary side. Each transformer yields a 50 kV output, however, ground referenced with opposing polarities. Thus, by placing the 1 nF capacitor between the resulting +50 kV and -50 kV terminals while grounding the other two output terminals, a differential voltage across the capacitor of up to $\sim$ 100 kV was obtained.

A PIC 18F26K80 8-bit microcontroller in each charger module will be used to control the module, communicate to other modules and to a computer, and monitor voltages. Each module is kept in a low power mode when not in use and fiber optic communications is used throughout such that electrical isolation between modules and the master computer is ensured. During use, each PIC will be able to automatically detect the number of modules, as well as its position, in the set. This is important to ensure proper timing of communications between PICs and for identifying modules independently. Voltage monitoring in each module is achieved using the 12-bit A/D converter on the PIC. If an error occurs, the PIC relays the error to the other PICs as well as to the computer. The outputs of each module will then be disabled, and the PICs will wait for further commands from the user. The computer will be able to see all errors that occur in the system as well as which module was error flagged.

NEW MARX BASED GENERATOR USING IGBTS FOR ADJUSTABLE QUASI-RECTANGULAR PULSES

Yahia ACHOUR[1], Jacek Starzyński[1], Andrzej Łasica[2]
1. Military University of technology
2. Warsaw University of Technology

The use of semiconductor switches in pulsed power field experienced big progress in the last decade. The offered intriguing characteristics, combining compactness, controllability and simplicity of control, help to build generators with controllability level which was not possible to achieve with classical switches.

This work is about a new architecture of solid-state modular Marx generator capable of creating rectangular pulses with fully controllable polarity, amplitude, pulse width, and repetition rate. The proposed structure uses half of the number of switches usually used in generators of such performance. The modular structure gives the possibility to add more stages to the generator without any additional changes.

Each generator module consists of a capacitor, two coils, inversely coupled with a shared core and two switches. Such a structure allows the parallel connection of capacitors in the charging phase. The oppositely directed magnetic fluxes subtract, thus reducing the inductance of the circuit.

During the discharge phase, the fluxes of inductors add to each other to create high inductance, considered as an open circuit. The discharge is controlled by two sets of IGBTs: the first is activated for positive pulses; and the second for negative polarity.

The proposed design can be adjusted to produce positive or negative unipolar pulses with controlled amplitude. The applied inductive charging increases the repetition rate, reduces the Joule losses improving the power efficiency and remove the necessity of charging through the load.

A SPICE simulation was applied to verify the developed model and to check the expected performance. Then the four stages prototype generator was built according to the proposed design using available on the market IGBTs with a maximum output voltage of 8 kilovolts for bipolar configuration and 16 kilovolts for the unipolar structure. All results were compared to check and confirm the validity of the proposed architecture.

INVESTIGATION OF LOW AMPLITUDE LIGHTING STRIKES ON LOW VOLTAGE ELECTRICAL SYSTEMS

David Barnett[1], Landon Collier[1], William Brooks[1], Andreas Neuber[1], John Mankowski[1], James Dickens[1], Anthony Harrison[2], W. A. Harrison[3], David Hattz[3]

1. Texas Tech University
2. CERN
3. CNS Pantex

This study serves to investigate the voltage and current development in commercial electrical systems and the impact of various protection schemes. Various tests are conducted on miniature mock electrical systems to determine breakdown thresholds and mechanisms. The area of interest includes low current amplitude lightning impulses in the range of 2 kA to 5 kA peak. The test setup is constructed from a 4 stage, 44 kJ Marx generator capable of 400 kV impulses. To further control the testing, a low inductance ground path is used along with a variable resistor, inductor circuit to control the impulse characteristics. The risetime is adjusted from 500 ns to 5 μs with peak current from 2 kA to 5 kA. Under test are small sections of conduit systems of 10 ft to 50 ft with various junctions and connections to mimic commercial electrical systems. These flaws or lack thereof are evaluated for breakdown threshold and current flow direction. Common wires under test are 10 and 12 AWG both stranded and solid core THHN along with different types of MOVs placed at various points in the system to mimic typical lightning protection schemes. Voltage and current measurements are taken at the entry and exit points in the conduit system under test. A photomultiplier tube (PMT) is used for diagnostic measurement of arc characteristics inside the conduit during lightning impulses. Resulting voltage and current waveforms are presented for different various risetime impulses and setups ups along with MOV effects.

MODELING OF PULSE TRANSFORMER BASED ON IMPEDANCE CHARACTERISTICS MEASUREMENT AND TWO-PORT NETWORK THEORY

Xin Liu[1], Cheng Zhang[1], Xian Liu[1]
1. Institute of Electronic Engineering, China Academy of Engineering Physics

This paper presents a new effective methodology for modeling of linear pulse transformer. The transformer is treated as a two-port network, and the impedance matrix is measured by a commercial impedance analyzer in a sweep frequency mode when primary and secondary are in some different conditions. When ignoring winding resistances, a linear transformer become a oscillation system with no attenuation, on this basis, the s domain analytical expression of the element in the impedance matrix is deduced. The result show that, after the resonance frequency and slope in low frequency on the amplitude-frequency curve are measured, the analytical expression formula of the impedance can be written directly. Furthermore, when considering winding resistances, for each extremum point on the amplitude-frequency curve, two correction factors are added in the analytical expression to reflect the effect of the resistances. The value of the correction factors are obtained by fitting of the amplitude-frequency curves through Matlab or Origin, the initial value of the factors are given to insure the convergence of the fitting. By this way, the s domain analytical expression formula of the measured impedance is obtained, and a T-type equivalent circuit model was synthesized based on it. Finally, the method is applied to a pulse transformer modeling, both the simulated and measured amplitude-frequency curves, phase-frequency curves, and time-domain waveforms meet well, which validated the accuracy of the modeling method.

CHARACTERIZATION OF SUSTAINED SERIES DC ARC DURATION FOR ADVANCED DETECTION SCHEMES

Bailey Hall[1], Dennis Grosjean[2], Dan Schweickart[3], Jin Wang[1]
1. The Ohio State University
2. Innovative Scientific Solutions, Inc.
3. Air Force Research Laboratory-WPAFB

Series arcs in dc power systems can occur if energized wires split, or load connections are physically interrupted. Compared to their parallel counterparts, series dc arcs decrease load current, making detection more challenging. Series dc arc models, along with accompanying detection methods have been studied in the past . However, few studies link load and source impedance to the timing of series dc arcs. In this paper, using a broad set of data taken at different RC loads with a fixed loop impedance, the minimum required time for a sustained series dc arc to occur was determined. Analytic models describing the transient behavior of series dc arcs are used to link the load and line impedance to this necessary timing condition. The findings in this paper can guide the design of future dc power systems, ensuring that detection and protection schemes operate within the minimum time window.

THREE-DIMENSIONAL MODEL OF THE SATURN ACCELERATOR WATER TRI-PLATE TRANSMISSION LINE CONNECTION TO THE VACUUM INSULATOR STACK

Ken Struve[1]
1. Sandia National Laboratories

Calculation of the power flow from the 36 pulse forming lines to the vacuum region of Saturn has always been complicated by the three-dimensional structure of the rod and bottle connections to the vacuum insulator stack. Recently we have completed a 3-D calculation of the bottle configuration and found a large error in previous impedance estimates. We have used this calculation to determine impedance and to construct a 2-D model of each of the 36 bottles of each level of the insulator using the Transmission Line Matrix (TLM) technique. These TLM models are then used in a 2-D model for each of the three levels of the insulator. Each model starts at a measured forward-going pulse in the water tri-plate, and ends at the Brehmstrahlung load at the center of the machine. Because of transmission line lengths, and because of the short pulse lengths, each can be considered independent of the others. Thus the combination of the three models represents a quasi-3-D model of the load region of the machine. The results of these calculations agree well with measurement and thereby provide confidence in simulation predictions for those areas where measurements are not possible. Details of the 3-D bottle calculation, the TLM model, and results of the load region simulations using this model will be given.

* Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

DENYING UNMANNED AERIAL VEHICLE INVASION USING HIGH POWER ELECTROMAGNETIC WAVES

Jing-Shyang Yen[1], Jwo-Shiun Sun[1], Xuan-De Huang[1], Chia-Wei Lin[1], Hua-Yi Hsu[1], Chii-Ruey Lin[2], Kaviya Aranganadin [3], Ming-Chieh Lin[3]
1. National Taipei University of Technology
2. Minghsin University of Science and Technology
3. Hanyang University

The United States, China, and Israel are widely recognized as industry leaders in unmanned aerial vehicle (UAV) technology. A UAV or simply a drone has no onboard human pilot. Equipments necessary for a human pilot (such as the cockpit, armor, ejection seat, flight controls, and environmental controls for pressure and oxygen) are not needed, as the operator runs the vehicle from a remote terminal, resulting in a lower weight and a smaller size than a manned aircraft. Several other countries have operational, domestic UAVs, and many more have imported drones or have development programs under way. In recent years, UAVs are well developed and made commercially available. Airport control or public security might be endangered by intended invasion or accidental activities. A UAV might be used to carry aircraft ordnance such as missiles and is used for drone strikes. These drones are usually under real-time human control, with varying levels of autonomy, speeds, and payloads. Thus, denying this type of invasion is not a trivial task. In this work, electromagnetic effects on a UAV are studied using a conformal finite-difference time-domain (CFDTD) simulation in order to find some solutions to mitigating a UAV invasion. A commercially available model is used as the test case and the corresponding 3-D model has been imported in the 3-D CFDTD simulation code VSim for investigation. Preliminary results obtained including electromagnetic effects on the UAV and the corresponding field distributions will be presented.

----

* Work supported by the National Taipei University of Technology, Minghsin University of Science and Technology in Taiwan, and Hanyang University in Korea.

SOLID STATE POWER EMULATOR TO EVALUATE H-BRIDGE MODULE TEMPERATURE COMPARISON

Richard Thomas[1], Lauren Boteler[1]
1. Army Research Laboratory

The next step beyond single device evaluation is the evaluation of multiple devices in a module. These modules enable operation of higher power motors, inverters and converters. The challenge with testing modules is the increased power supply and load capacity required for proper evaluation. To evaluate a MOSFET module using the H-bridge circuit configuration running at 600V, 100A at 10kHz under normal testing conditions this would require a ∼60kW power supply and a load to handle such power. To reduce the needed power supply to handle this evaluation a Solid State Power Emulator (SSPE) underwent an upgrade from testing a single device to testing an H-bridge circuit. Using this upgraded SSPE for the module evaluation it will allow the testing to be done with only a ∼10kW power supply which is approximately an 83% power savings. The goal of this research is to compare and evaluate current wire bonded packages with packages that utilize multi-functional components (MFC) for connection and cooling. In comparing these two different modules which contain the same MOSFETs we are looking at the performance of module packaging by way of MFC in a design known as the Power Tower (PT). The PT module goal is to achieve 40X improvement in power density through a 4X lower thermal resistance and 10X smaller package. The use of the SSPE will demonstrate efficiency in both laboratory testing and high power system development.

LUMPED CIRCUIT MODEL OF MULTI-PULSE LASER TRIGGERED GAS SWITCH WITH BRAGINSKII RESISTIVITY

Joe Chen[1], Salvador Portillo[1], Gregory Dale[2]
1. University of New Mexico
2. Los Alamos National Laboratory

L3 Applied Technologies is developing series pulsed forming water transmission lines for Los Alamos National Laboratory. The Series Pulse-Line Integrated Test Stand (SPLITS) consists of a set of four, 5.5 ohm coaxial water pulse forming lines in series. Each water line is capable of producing a -300 kV pulse when driving a matched resistive load.

The University of New Mexico (UNM) is performing SPICE circuit modeling to simulate the performance of SPLITS. Microcap 10 is used as the SPICE program to model the first two, 120ns pulse forming lines with laser triggered, gas filled switches at varying currents and separation distance. One of the challenges of this effort is to model a time-varying resistance of the gas-filled switch. A solution to this is to implement Braginskii's gas arc resistance equation, which is time-varying, within the model. To further improve on the Braginskii model, a time-varying conductivity element will added in. Future work to understand the conductivity of a gas arc as it changes temporally may include time-resolved interferometry can be used to measure radial growth rates and densities. From there a relation can be made to the spitzer conductivity. Ongoing work is seeking to gain further understanding of this model and derive time-varying conductivity from time-resolve radial position measurements.

----

* Work supported by LANL contract #522006

NOVEL HIGH VOLTAGE PULSING TO GENERATE UNIFORM GLOW DISCHARGE AIR PLASMA FOR ENVIRONMENT FRIENDLY INLINE TREATMENT OF TEXTILE

Vishal Jain[1], Kushagra Nigam[1], Nisha Tanwani[1], Adam Sanghariyat[1], Nimish Sanchania[1], Sudhir kumar Nema[1]
1. Institute for Plasma Research

The OAUGDP is widely explored by researchers for studying surface treatment of materials using helium and argon plasma. However, generation of OAUGDP especially in the air could have great potential in industries because air is freely available in nature. The challenge is to avoid localized high energy streamer formation in the air because of very high voltage rating of power supply in case of the air plasma generation. However, the high power filament generation persists because the controlling the plasma discharge in the glow discharge region in atmospheric pressure air is not yet possible through the feedback control. Therefore, the abrupt transition from dark discharge to abnormal glow filamentary discharge takes place which tends to breakdown the dielectric material and put constraints to use the plasma for inline treatment in the industries.

In this paper, the energy control to the DBD (Dielectric Barrier Discharge) air plasma is proposed which ensure the uniform glow discharge plasma in the air gap. This energy control requires a unique high voltage switching which generates bundles of RF (Radio Frequency) discharge of 0.5 MHz to 2.5 MHz at 6kV but damped oscillations in nature. This damping period ranges from 8us to 10us in repetitive mode. The repetition of switching is limited to maximum 100 kHz to avoid appending of energy in the air gap of DBD to prevent filament generation. The 6kVrms is a significantly lower voltage than the voltage ratings of conventional pulsed DC supply used in DBD plasma generation at atmospheric pressure in the research lab. Still, it provides plasma power density of 2W/cm2 which is substantially higher for fast treatment of textile materials such as cotton, polyethene, polypropylene etc. The functionality measurements results for various materials and the diagnostics of the air DBD plasma are also presented in the paper.

REACTIVE SPUTTERING OF ALUMINUM ACETYLACETONATE FOR DEPOSITION OF ALUMINA FILMS

Ricardo Blanco[1], Larissa de Almeida[2], Rafael Ribeiro[2], Luciana Rossino[3], Nilson Cruz[1], Elidiane Rangel[4]

1. São Paulo State University (UNESP)

2. São Paulo State University (UNESP), Institute of Science and Technology, Sorocaba, Av. Três de Março, 511, Sorocaba, São Paulo 18087-180, Brazil

3. Sorocaba Technological College – FATEC

4. Paulista State University

A brand new methodology for depositing alumina films in a faster, lower cost and ecologically friendly rout is proposed here: the reactive sputtering of the aluminum acetylacetonate, AAA using DC pulsed plasmas. Firstly, the AAA powder was spread on the center of the electrode of a capacitively coupled plasma system. Substrates were placed around it. Plasma was excited from argon and oxygen atmospheres by applying DC pulsed signal (-300 to -400 V, 20 kHz, 48-50 μs duty cycle) to the sample holder. Reactor walls were grounded. Deposition time was changed from 2 to 70 minutes in low (200 W) and high (500 W) power regimes. It was investigated the effect of the process time, t, and of the plasma power, P, on the deposition mechanisms, process temperature and properties of the films. Layer thickness and deposition rate were derived from profilometry analyses. Chemical composition, molecular structure and chemical states of the bonds were determined by associating energy dispersive spectroscopy, infrared spectroscopy and X-Ray photoelectron spectroscopy. Electron scanning and atomic force microscopies were used to evaluate the surface microstructure of the films whereas their crystalline structures were inspected by X-Ray diffraction experiments. Temperature of the electrode continuously increases with t and P reaching or overcoming that of sublimation of the AAA, process which affects the overall plasma activity and sputtering yield. As a consequence, thickness and deposition rate varied demonstrating the dependence of the deposition mechanisms on t and P. Further evidences of changes in the deposition kinetics were obtained by the evolution of the structure with t and P. In the regimes of low t and P, an organic structure containing Al very similar to the precursor was obtained. However, for higher P levels (500 W) an inorganic like Al_2O_3 structure was attained regardless t.

INVESTIGATION ON UTILIZING AUDIO SQUARE WAVE AND RADIO-FREQUENCY PLASMAS FOR CLEANING OF VACUUM DIODE ELECTRODES

Ricky Tang[1], Derek Lamppa[1]
1. Sandia National Laboratories

The Z machine is a high-current pulsed-power generator located at Sandia National Laboratories capable of delivering 100-ns, 30-MA current pulses to a variety of targets. Under certain conditions, however, a significant fraction of the current does not reach the load but is shunted across the inter-electrode vacuum gap that leads to the load. That undesirable current loss is believed to be due to neutral desorption from the heated electrodes that are then ionized, forming an electrode plasma that flows into the vacuum gap. Much past work on vacuum diodes have shown positive effects of various in-situ conditioning techniques in improving diode performance, including cryogenically-cooled electrodes, surface coatings, discharge cleaning, and electrode heating.

Due to the operation and scale of Z, an in-situ discharge cleaning approach was chosen as one approach for electrode conditioning. Implementation focuses on cleaning the convolute and final feed regions where majority of current loss is observed to occur. A novel approach of generating the cleaning plasma using a bipolar audio square wave (ASW) was developed and compares favorably with the conventional method of radio-frequency (RF) generation. Optical emission spectroscopy of the two plasmas reveals higher-intensity emission in the UV/visible range for the ASW plasma comparing to the RF plasma at comparable powers, suggesting that the electron energy is higher for the ASW plasma, which could lead to higher ionization, resulting in increased ion density and ion flux to surfaces. Both ASW and RF offer different sets of advantages and challenges for implementation on Z. Lab-scale investigation focuses on diagnosing the temporal and spatial evolution of both types of plasmas in the A-K gap via iCCD imaging to capture plasma emission. A residual gas analyzer (RGA) is used to study the efficacy of each plasma generation scheme by analyzing the inventory of desorbed gases from electrode surfaces.

SPECTROSCOPIC MEASUREMENT OF ACTIVE SPECIES GENERATED IN STREAMER DISCHARGE ON WATER SURFACE

Takuya Hayashi[1], Souhei Toyoda[1], Tomokazu Kanna[1], Takashi Sakugawa[1]
1. Kumamoto University

There are many reports reporting chemically active species using underwater discharge plasma. Another method is to bubble in water to produce chemically active species.

However, it is difficult to measure the active species by spectroscopy in the discharge in water.

We generated chemically active species utilizing streamer discharge generated on the water surface and measured spectroscopic measurements. A magnetic pulse compression circuit was used to generate streamer discharge. For spectroscopic measurement, a high sensitive spectroscopy capable of time resolved spectroscopy was used. Discharge on the water surface randomly propagations, so it is difficult to perform spectroscopic measurement at a fixed point. Therefore, we could develop a discharge chamber that can control the direction of progress of the streamer in one direction, and we were able to perform stable spectroscopic measurements. Particularly chemically active species are OH, Hα, Hβ. The generation characteristics of these chemically active species were examined when the ground electrode was installed in the medium chamber and when it was installed outside the chamber. As a result, strong emission of OH radicals was observed at the high-speed rise of the pulse voltage.

REILLUMINATION OF EXPIRING CORONA-LIKE PULSED DISCHARGES IN WATER

Raphael Rataj, Hans Höft[1], Juergen Kolb[2]
1. Leibniz Institute for Plasma Science and Technology (INP)
2. Leibniz Institute for Plasma Science and Technology

The reillumination of corona-like discharges in water was reported to start either during the high-voltage plateau or during the falling edge of applied high voltage pulses or not at all. For similar pulse durations and amplitudes, reillumination was then observed for a single filament or for all of the previously formed channels altogether. However, so far no general explanation for this characteristic has been presented.

A detailed study was conducted with single and reproducible high voltage pulses with adjustable fall times between 20 and 45 ns, amplitudes of 50 kV and durations of 100 ns that were applied to a point-to-plane geometry in deionized water. Voltages, currents and intensities of the emitted light were recorded for individual discharges. Plasma currents, discharge energies and channel lengths were derived. Additionally, consecutive images of the same individual discharge event were obtained using a framing camera. The different stages were then related with the electrical and optical measurements.

While no change in discharge development was found for the initial phase of the discharge instigated during the high-voltage plateau, the reillumination of discharge channels was observed only during the falling edge of the applied pulses. A transition from a reignition of single filaments to a reillumination of every channel with decreasing fall time was evident both in the framing camera images and the plasma currents.

PLASMA PROPERTIES IN A HIGH PRESSURE ALD REACTOR

Chenhui Qu[1], Pulkit Agarwal[2], Yukinori Sakiyama[2], Adrien LaVoie[2], Mark J. Kushner[3]
1. University of Michican
2. Lam Research Corp.
3. University of Michigan

The quality of a plasma enhanced atomic layer deposition (PEALD) film ultimately depends on controlling the flux of the reactive species onto the wafer. In a typical SiO_2 PEALD process, the first step is to treat the substrate with Si-containing precursor, usually without a plasma. Then the oxidation process is performed by exposing the substrate to an O_2-containing plasma. To achieve a high oxidizing radical flux to the substrate while limiting the ion energy to reduce damage on the film, a capacitively coupled plasma (CCP) operating in a few Torr is often used to. In these high pressures, a high radical flux can be produced while the ion energy onto the wafer is low due to the collisional nature of the sheath. The challenge to optimize this system includes improving plasma uniformity, minimizing ion energy and reducing UV/VUV damage.

In this work, results from a computational investigation of a high-pressure CCP reactor for PEALD of SiO_2 will be discussed. The goal is to provide insights on the tradeoffs in optimizing deposition conditions. The focus of this work will be the fluxes of radicals and ion into a feature with a moderate aspect ratio. The modeling platforms used in this study are the Hybrid Plasma Equipment Model (HPEM) and the Monte Carlo Feature Profile Model (MCFPM). The example system uses an Ar/O_2 mixture at 1-5 Torr with power deposition up to a few kW. The fundamental properties of the plasma (e.g. electron density, electron temperature, radical fluxes to the substrate) will be discussed. The ion energy and angular distributions (IEADs) are used for the feature scale modeling.

Work supported by Lam Research Corp. and the DOE Office of Fusion Energy Science.

ELECTRICAL DISCHARGE IN GAS-LIQUID MIXTURE: BREAKDOWN VOLTAGE AND ENERGY DEPOSITION DISTRIBUTION IN EACH PHASE

KUNPENG WANG[1], David Staack[1]
1. Texas A&M University

Pulsed electrical discharge was generated in a spark gap submerged in mineral oil with methane injected into the gap at ambient pressure. Spark gap was powered by a DC power supply (50 kV) with one resistor and one capacitor (30 pF). Breakdown occurs when the applied voltage reached the breakdown voltage of the mixture in the gap. Total breakdown voltage in the spark gap was predicted by studying breakdown in each phase and linearly combining them. Breakdown in gas phase with high pd values in the range of 200-1000 Torr-cm follows the Meek criterion. Liquid phase breakdown primarily depends on its dielectric strength close to 150 MV/m. One offset parameter f in the range of 0-1 was used to account for effects of impurities, electrode geometry and electrode surface area to estimate liquid breakdown voltage. Discharge energy deposition into two phases was also estimated based on predicted breakdown voltage. Breakdown voltages were studied experimentally as a function of gap distance and gas flow rate. Results showed that Meek criterion was able to accurately predict the breakdown voltage in gas phase as gap distance changes between 1-10 mm. Breakdown voltage in mixture at each flow rate increased when gap distance became larger. But breakdown voltage dependence on gas flow rate with constant gap distance showed more complex behavior: it dropped first with increasing gas flow rates, then increased as gas flow rates increased further. Discharge energy E was not evenly deposited into gas phase and liquid phase for all conditions. Changing gas flow rate and gap distance also changed the discharge energy distribution in each phase.

EVALUATION OF ELECTRIC FIELD AND CHARGE ON BIO-SUBSTRATES INDUCED BY NANOSECOND PULSED HELIUM PLASMA JET

xi li[1], shutong song[2], david alderman[3], Muhammad Arif Malik[4], Richard Heller[1], Chunqi Jiang[1]

1. Old Dominion University
2. Old Dominion Unviersity
3. ODU
4. Hampton University

Non-thermal atmospheric-pressure plasma jets are of interest to various biomedical applications including bacterial inactivation, surface modification and sterilization, wound healing and tumor apoptosis. The electric field and charge near the bio-substrates were considered important parameters influencing the plasma-induced biomedical effects due to the possible electroporation and chemical processes. This work investigated the electric field and charges above and in the bio-substrates with the plasma jet impinging on the substrate. Water, saline solution and pig skin were used as the substrate. The plasma jet was based on a dielectric barrier discharge (DBD) configuration, powered by 180 ns, 6 kV pulses at 1 kHz and with helium flow of 985 sccm. Decreasing the gap distance d between the electrode nozzle and the substrate surface increased the electric field in water or saline solution and the charges transferred to the substrate. The electric field in water is higher than that in saline solution under the same conditions. The charge transfer above the substrate surface as well as in the substrate were compared for different substrates by obtaining current flow at different locations of the system.

TWO TEMPERATURE SIMULATION OF SUBATMOSPHERIC ARC DISCHARGE*

Madhusudhan Kundrapu[1], Andrew Chap[2], Michel de Messieres[2], Carles Corbella[3], Michael Keidar[4]

1. Tech-X Corp.
2. Tech-X Corporation
3. The George Washington University
4. George washington University

Arc discharges that fall into low-temperature plasmas have several industrial applications including nanoparticle synthesis, plasma thrusters, and thin film deposition. The complexities associated with the simulation are dealing with large gradients of densities, temperatures, material evaporation, deposition, and species transport. Most widely used model for simulating the arc discharges is a single temperature fluid transport coupled to ionization equilibrium. The model could estimate the plasma properties to a satisfactory level in the arc column alone. Outside the arc, any charged species, that escape from the arc-core, will be chemically and thermally in a non-equilibrium state. These non-equilibria become more and more prominent with the decrease of the background pressure. At low background pressures ($<$100 Torr), due to fewer collisions between the electrons and heavy species, the electrons may not attain thermal equilibrium with the rest of the species. Thermal non-equilibrium influences the reactions in a significant way, particularly the electron impact ionization. In order to predict the species densities accurately, the reactions must take into account the differences in the species temperatures.

In the present work, we have attempted the two temperature simulations of arcs, used in the synthesis of nanoparticles. The simulations were performed in USim fluid-plasma software.[1] USim has a wide variety of fluid equation systems that could be customized for modeling the two temperature multi-species plasma system. The recently updated reaction solver in USim could be used for calculating the rate s of the species reactions, occurring at electron and heavy species temperatures.

1. Kundrapu, M., Loverich, J., Beckwith, K., Stoltz, P., Shashurin, A., and Keidar, M., "Modeling Radio Communication Blackout and Blackout Mitigation in Hypersonic Vehicles," Journal of Spacecraft and Rockets, Vol. 52, No. 3 (2015).

----

* Work supported by DOE SBIR Phase II Award No. DE-SC0015767. Dr. Curtis W. Bolton is the program manager.

GAS TEMPERATURE DETERMINATION OF NONTHERMAL PLASMA THROUGH BOLTZMANN PLOT METHOD

Marcus Ashford[1], James Allen[2], Jennifer Zirnheld[3], Kevin Burke[3]
1. Primary Contributor
2. Secondary Contributor
3. Faculty Supervisor

Nonthermal plasma (NTP) causes delayed melanoma cell death which is indicative of apoptosis. The NTP is produced by applying a high voltage signal to helium gas, causing ionization of a combination composing neutral gas molecules and ambient air. By exploring the plasma's physical temperature, the energy exchanged during the plasma-cell interaction can be further understood. The NTP discharge contains radical species including ions, electrons, and neutrals. The temperature of the electrons exceeds the temperature of the gas due to high energy collisions which suggest that the NTP is not in a state of Local Thermodynamic Equilibrium (LTE). The gas temperature can be understood as the physical temperature the test sample undergoes during the application of the plasma discharge. In order to determine the temperature of the gas, the Boltzmann Plot Method (BPM) has been instituted. This diagnostic has been proven to approximate the physical temperature of the gas using spectroscopic measurements of the OH radical present in the NTP discharge. For the application of the BPM, it is assumed the upper state of at least two spectral lines in the OH spectrum can be distinguished, the transition probabilities are accurately identified, and the plasma under study is in LTE. Even though the NTP is not in LTE, the temperature can still be resolved if the uncertainties of these assumptions are factored in to calculations. The comparison of spectral standards to experimentally measured spectra under high resolution provides a model of NTP temperature.

TEMPORAL GAS TEMPERATURE MEASUREMENT OF SINGLE FILAMENT IN ATMOSPHERIC PRESSURE PLASMA JET

Jiayin Li[1], Fan Wu, Xinpei Lu
1. Huazhong University of Science and Technology

The gas temperature is an important plasma parameter as it strongly influences the plasma chemistry which drives most plasma applications. The gas temperature in non-equilibrium plasmas is often obtained by fitting the synthetic spectrum to the experimental spectrum of the C3Πu-B3Πg ($\Delta v = -2$) band transition of nitrogen. However, the gas temperature obtained by this method is actually the average gas temperature of APPJ during the spectral acquisition, that is, the cumulative effect of temperature, and the error of the method is usually at ten degrees or even higher. For some plasma medical applications, ten degrees may exert different biological effect. As the discharge mode of APPJ is mostly like a pulse discharge and the minimum discharge duration is about ten nanoseconds, the gas temperature may decrease from a higher temperature after the discharge process. Therefore, the temperature perceived by the human body is likely to be different from the instantaneous gas temperature of APPJ. Whether relatively high temperature produced by APPJ has a biomedical effect on cells, tissues, etc. remains to be studied.

This work presented temporal gas temperature when DC air discharge was applied to the skin by a statistical way. The accuracy of the gas temperature and time resolution were on the order of K and μs, respectively. It was found that the gas temperature is highest at the peak value of discharge current. Then, the gas temperature rapidly decreased within 5 μs, and after 40 μs, the gas temperature returned to room temperature. When applied voltage was decreased, the peak value of gas temperature was not significantly changed, but the rate of change in gas temperature was become smaller. In other words, the gas temperature decreased more slowly and returned to room temperature later.

ONE-DIMENSIONAL NUMERICAL SIMULATION ON NANOSECOND PULSED DISCHARGE

Guofeng Lou[1], Fangtian Ma[1]
1. University of Science & Technology Beijing, China

A one dimensional model for nanosecond pulse non-equilibrium plasma discharge is developed. A numerical simulation has been done for nanosecond high voltage pulse DBD air discharge. The evolution and distribution of component parameters, electrical parameters for air discharge has been investigated. It is found that the sheath layer effects the electrical field distribution, the voltage and electron energy. The discharge parameters are non-uniform between electrodes.

CORONA DISCHARGE INDUCED SUBMICRON WATER DROPLET COALESCENCE AND GROWTH IN A SUBSATURATED CLOUD CHAMBER

Pengyu Wang[1], Jiawei Li[2], Chuan Li[3], Zhi Liu[2], Ming Zhang[3], Yong Yang[3], Kexun Yu[3]

1. State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical Engineering and Electronics, Huazhong University of Science and Technology

2. International Joint Research Laboratory of Magnetic Confinement Fusion and Plasma Physics, Huazhong University of Science and Technology

3. State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology

In natural, the condensation and coalescence and growth of water droplets play a significant role in the process of cloud formation, which is hard to occur under subsaturated environment. In this paper, the growth of water droplets is detected in a 0.24 m^3-subsaturated cloud chamber with unipolar corona discharge. The results show that the diameter of droplets can grow up from submicron to 31μm under -40 kV at relative humidity $\sim$ 80% and ambient temperature $\sim$ 10°C. The growth mechanism is further discussed combined with the calculation of electric field intensity distribution, and the measured negative ions density in the cloud chamber. What's more, a novel dynamic model of charged droplets motion is put forward to demonstrate the key role of electric field and charged particles in the evolution process of coalescence and growth of water droplets. The research results can provide a reference to the realization of atmospheric water resources utilization in arid regions.

ARGON COLD ATMOSPHERIC PRESSURE PLASMA JET ENHANCING SEED GERMINATION AND SEEDLINGS GROWTH OF FENUGREEK (TRIGONELLA FOENUM-GRAECUM)

Tahar Boutraa[1], Sahar Fadhlalmawla[1], Jamal Almarashi[1], Abdel-Aleam Mohamed[1]

1. Taibah University

Abstract

Atmospheric pressure cold plasma jet gained a great interest overall the world due to its wide band of application in medicine, industry and agriculture [Puač et al., 2018]. Therefore, in this work we investigated the impact of cold atmospheric pressure argon plasma jet on the germination and early seedling growth of fenugreek (Trigonella foenum-graecum L.). The plasma jet system is a two-electrode with and without additional grounded electrode which is called "accelerated electrode" (AE), and used with different exposure times: 0, 30-sec, 1-min, 10-min, 15-min and 20-min. The results showed that plasma jet had a significant effect on seed germination with 40%, 33%, 14%, 57% and 33% at 30-sec, 1-min, 5-min, 15-min and 20-min, respectively. The effect of plasma jet was not significant on root length, but in contrast to that the length of plumule significantly affected. The fresh weight of shoot significantly increased, and in particular at 10-min exposure time. The 1-min exposure time resulted in an increase of root and shoot dry weight, but the 15-min ground exposure time lead to a decrease of root and shoot dry weight. The root:shoot ratio of seedlings treated with plasma was lower compared to the control plants. The findings of this study suggested that cold plasma could stimulate the germination, taking in consideration that cold plasma is an economic and pollution-free method in plant productivity improvement. The results found that O-radicals emission spectrum was enhanced 5 times, because of the AE presence that enhance the electric field, and forming more streams. The effect of the three parameters; O-radicals, enhancement of the electric field and streamers, might be the cause of seed germination improvement by the plasma jet.

References

Puač N, Gherardi M, Shiratani M. Plasma agriculture: A rapidly emerging field. Plasma Process Polymers. 2018;15:e1700174. https://doi.org/10.1002/ppap.201700174

THE CHARACTERISTICS OF OZONE GENERATION IN THE ATMOSPHERIC DIELECTRIC BARRIER DISCHARGES

SICHAN KIM[1], Byung-Koo Son[1], Hyun Cho[1], Yun-Jung Kim[1], Bong-Joo Park[1], Guangsup Cho[1]
1. KWANGWOON UNIVERSITY / Department of Electrical and Biological Physics

The generation of ozone in dielectric barrier discharges (DBDs) is the important application of nonequilibrium discharges for plasma chemical synthesis. Historically, the DBD dates back to 1857, when Werner von Siemens showed that ozone can be produced in an oxygen flow passing through the annular discharge space between coaxial glass cylinders. Shortly after 1900 the first larger industrial ozone-generating systems for the treatment of drinking water were installed in Nice, France (1907) and St. Petersburg, Russia (1910). Today, more than 1500 drinking water plants throughout the world use ozone generators utilizing silent discharges

The generations of plasma and ozone in the atmospheric dielectric barrier discharges (DBDs) are investigated in the various structures of volume-DBDs, surface-DBDs, and hybrid-DBDs. According to the structures of DBD operating with AC-voltage of frequency of a several tens of kHz, the order of plasma density is almost the same order of (1017–1018) m-3 regardless of DBD-structures while the ozone generation density varies in the wide range of (1010-1021) m-3 according to the DBD-structures. And also the plasma density will not be affected by the environment temperature while the ozone concentration is strongly affected to be reduced as the temperature is increased.

In this report, the applications of ozone-generation are introduced with the small plasma DBD-panels in respect of (1) the ozone-water production system, (2) the pure-plasma sterilizer for the medical usages, and (3) the plasma laundry machine.

THIN-FILM DEPOSITION OF AL2O3-FILLED EPOXY RESIN USING PULSED PLASMA IN AR/O2/TEOS MIXTURE

TIngting Wang[1], Cheng Zhang[2], Fei Kong[2], Hao Sun[3], Haofan Lin[2], Tao Shao[2]
1. CSG Technology Research Center
2. Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciences
3. University of Chinese Academy of Sciences

Al2O3-filled epoxy resins (Al2O3-ERs) are commonly used as dielectric supports in the insulation system, which require surface deposition for improving surface insulation [1-2]. In this paper, pulsed plasma jet is used to deposit films on Al2O3-ER surface in mixture gases of argon (Ar), oxygen (O2) and tetraethyl orthosilicate(TEOS) mixture. The concentration of Ar/TEOS mixture gas is kept constant and the effect on the O2 concentration on the film deposition is investigated. The experimental results show that SiOx film with a thickness of 150 nm is formed on the ER surface after the plasma deposition. With the increase of O2 concentration, the absorbance peaks of C=C and C=O groups gradually decrease, and C element decreases first and then increases. The proportion of O element reaches a maximum value of 58.18% and the C element decreased to a 14.13% when O2 concentration is 25 sccm. The surface topography shows that the surface layer appears nano-particles on the ER surface without O2 additive. When O2 concentration increases to 25 sccm, the surface layer appears a flocculent structure. Furthermore, surface potential distribution test shows that the peak potential decreases by about 50% and the potential gradient significantly decliness when the O2 concentration is 25 sccm. Meanwhile average flashover voltages increase by more than 13%. The experimental results provided references for further optimization of film deposition conditions.

[1] T. Shao, F. Kong, H. Lin, Y. Ma, Q. Xie, C. Zhang. Correlation between Surface Charge and DC Surface Flashover of Plasma Treated Epoxy Resin [J]., IEEE Trans. Diel. Electr. Insul., 2018, 25(4): 1267∼1274

[2] C. Zhang, H. Lin, S. Zhang, Q. Xie, C. Ren, T. Shao. Plasma Surface Treatment to improve Surface Charge Accumulation and Dissipation of Epoxy Resin Exposed to DC and Nanosecond-pulse Voltages[J]. J. Phys. D: Appl. Phys., 2017.09.14, 50(40): 405203

INVESTIGATION ON SHOCK WAVE GENERATED BY UNDERWATER DISCHARGE DUE TO DIFFERENT PROGRESS OF PLASMA

Mitsuhiko Sato[1], Koki Takaura[1], Takashi Sakugawa[2], Hamid Hosano[2]
1. Kumamoto University
2. Institute of Pulsed Power Science

In the case of generating a shock wave by underwater discharge, there is a disadvantage that the electrode is consumed by a large current. When a thin electrode is used, dielectric breakdown tends to occur but consumption is accelerated. When a thick electrode is used, it is difficult to wear out but insulation breakdown hardly occurs and a large voltage is required. These effects are generally known for the influence on discharge by changing the electrode diameter. Progress of the plasma changes by changing the electrode diameter. We thought whether there is no influence on the shock wave generated by changing progress of changing. Pressure is the most important as application using shock waves. However, even if the rise time and energy of the shock wave change, the experimental result may be affected.

In this study, we investigate the influence on the shock wave when the electrode diameter is changed. We generated underwater discharge using pulse power generator, which is MPC (magnetic pulsed compression). The pressure of the shock wave generated by discharge depends greatly on the discharge energy. Spherical shock waves are generated from the opposing electrodes. We observe the bubble at that time. Also, reflecting spherical shock waves with parabolic reflector and outputting parallel shock wave. As a result, stronger shock waves can be generated, and measurement is facilitated. We measure pressure, rise time, and shock wave energy of shock waves at different electrode diameters. The shock wave was measured using FOPH (fiber optical probe hydrophone) and the discharge was observed by Schlieren method.

CALCULATION OF ARC CONDUCTANCE AFFECTED BY FLOW FIELD FOR IMPROVEMENT OF CURRENT INTERRUPTION PERFORMANCE

Yuya Ishikawa[1], Yuji Komai, Yoshifumi Maeda[1], Toru Iwao[1]
1. Tokyo City University

Numerical analysis was conducted in order to elucidate the flow field in post arc with applying transient recovery voltage. The objective of this simulation is to elucidate the arc phenomenon inside Gas Circuit Breaker (GCB) in post arc. GCB is an electric power equipment that quenches the arc using the compressed SF_6 gas. It has been reported that the decrement of the arc temperature at current zero point contributes to prevent the re-ignition with applying transient recovery voltage. Thus, it is necessary to elucidate the flow field in GCB for improvement of current interruption performance. Especially, the study of focusing on the flow field has been progressed using numerical analysis in order to elucidate the physical phenomenon in GCB. However, few reports have been studied the focusing on the flow field from center between electrodes to outlet of nozzle. In this paper, the calculation of arc conductance affected by flow field for improvement of current interruption performance is investigated in order to elucidate the behavior of gas flow. The parameter of this simulation is gas blaster angle and nozzle throat length. As a result, the re-ignition occurred with applying transient recovery voltage when the stagnant of SF_6 gas occurs near the outlet of nozzle. Moreover, it was elucidated that the decrement of arc conductance is not always to contribute to arc extinction. On the other hand, the reverse flow to inlet in center between electrodes occurred when the current interruption was successful. For these results, it is suggested that the re-increment of radial flow velocity to axial center near the cathode contributes to the arc extinction. In addition, the reverse flow near the center of arc column promotes the diffusion of heat. Therefore, the flow field plays an important role for improvement of current interruption.

SPECTROSCOPIC CHARACTERISTICS OF PULSED ARC DISCHARGE IN SUPERCRITICAL NITROGEN

Tomohiro Furusato[1], Tsuyoshi Kiyan[2], Daishi Suzuki[2]
1. Nagasaki University
2. Kindai University

Observation of stable electric discharge plasma and measurement of a plasma profile are difficult in research of the electric discharge plasma in a supercritical fluid. It clear that from the viewpoints of the shortness of the mean free path of the particles in a high pressurized phase, the instability by the both of the statistics delay and the formation delay in electric discharges, and the density fluctuation of a supercritical fluid, clustering, etc. However, a diagnosis of the electric discharge plasma under a supercritical fluid is a one of the subject of paramount work for the efficient reaction and material invention by fusion of a supercritical fluid and electric discharge plasma.

In this research, magnetic pulse compression method was adopted as the pulse power generator, and carrying out high repetition control of the pulse power supply generated stable pulse arc discharge plasma (locally thermal plasma) under the supercritical fluid. The pressure dependability of plasma temperature and electron density in the pulse arc discharge plasma in supercritical nitrogen is investigated by synchronizing a pulse power supply and a spectrum measurement system by using a delay generator.

From the continuous-spectrum data based on the arc discharge plasma measured with the instrument of emission spectrometer, plasma temperature was presumed using the equation of Planck's black-body-radiation. Moreover, from the characteristic excitation state of the bright-line spectrum covered by luminescence with arc discharge plasma, the influence of the Doppler spread or the Stark spread was separated, which was presumed as an electron density of pulse arc discharge plasma. Especially, the pressure dependability of the electron density of pulse arc discharge plasma have investigated from the result of having analyzed the line spectrum of the raw data picture observed by the simple spectrum system made by ourselves.

RESEARCH ON NANOPARTICLE PRODUCTION BY TIG PULSED ARC DISCHARGE

Daishi Suzuki[1], Tsuyoshi Kiyan[1]
1. Kindai University

Nanoparticles are fine particles expected to be applied not only to new materials also to various fields such as medical care, environment, and electronics. It are proceeding that various researches of nanoparticles production such as a method of physically preparing and a method of chemically preparing them. On the other hand, researches on production of nanoparticles by discharge plasma have also been conducted. In studies of nanoparticle production by discharge plasma, many researcher have been conducting using DC power supply or microwave power supply for discharges a primary method, In contrast there are very few research using pulse power supply. In the conventional method is used, huge energy has used for increasing efficiency of particle productions, it can be expected that if use pulse power for improvement of efficiency in nanoparticle production.

In this study, we used a needle electrode of tungsten as a negative electrode and a material electrode which makes into nanoparticles as a plane electrode anode. We are verifying a nanoparticle production volume of efficiency and conversion ratio by using TIG (Tungsten Inert Gas) arc discharge which performs negative discharge while injecting inert gas as pilot gas. TIG arc discharge is performed by a high repetition pulse power supply with a magnetic pulse compression circuit. Arc heating is performed by arc discharge with a high repetitive pulse power supply in reactor, heat generated used to convert the metal to nanoparticles, in which produced nanoparticles by rapidly cooled with the pilot gas. In the experimental study, we carried out verify of more proper condition of nanoparticle production by changing parameter of repetition rate and pulse width in pulsed discharge.

DEVELOPMENT OF 3D ELECTROMAGNETIC THERMAL FLUID SIMULATION FOR ELUCIDATION OF GAS CONTAMINATION PROCESS OF CIRCUIT BREAKER

Shoya Nishizawa[1], Yoshifumi Maeda[1], Toru Iwao[1]
1. Tokyo City University

The objective of this simulation is to elucidate the arc phenomenon in the circuit breaker at opening process. Ablation is one of the quenching methods. It has been reported that the occurrence of ablation contributes to decrease the arc temperature, because the energy loss increases with increasing the ablation and convection loss affected by ablation gas. Moreover, the physical properties of the gas change with the ablation gas. Therefore, it is important to analyze temporal transition of the energy loss and the temperature distribution under consideration of the process of ablation gas mixing. However, few reports have researched the focusing on the contamination process of ablation gas. The circuit breaker has a nozzle clogging phenomenon. The nozzle clogging occurs by closing the outlet with an electrode and an arc during the opening process. This prevents the arc quenching and extinguish, and the pressure in the circuit breaker rises. The high pressure derived from high temperature increases the flow velocity of arc, while the discharge flow rate decreases. Thus, the balance between pressure rises and heat flow exhausts is important. From the above, the current interruption can be improved by elucidation of temporal transition of arc temperature distribution with changing the open timing. In this paper, the gas contamination process under consideration of the ablation contamination during the opening process of circuit breaker is elucidated using the development of 3D electromagnetic thermal fluid simulation. As a result, the mixing process of the ablation gas plays an important role for quenching and extinguish the arc, because the nozzle clogging occurs with increasing the pressure rise and heat flow velocity of arc, and the energy loss increases with increasing the ablation and convection loss affected by ablation gas in the case of each contamination and opening timing.

PERFORMANCE OF A PULSED ELECTROMAGNETIC MICROPROPULSION SYSTEM WITH LOW ENERGY SURFACE FLASHOVER IGNITER

Adam Patel[1], Yunping Zhang[1], Alexey Shashurin[1]
1. Purdue University

The rapid development and application of nanosatellite technology has vastly accelerated mission complexity – sparking interest in robust, low power, and high specific impulse micropropulsion systems. Pulsed plasma thrusters (PPTs) have been extensively explored and employed to fill this role. However, the technology's longevity has been historically plagued by the durability of an igniter subsystem. In this work, a pulsed plasma accelerator (PPA) design with a novel low energy surface flashover (LESF) igniter is presented – enabling upwards of 1.5 million flashover events. A 3μF / 2kV flyback-supplied capacitor bank, offering shot energies of $\sim$6J, supported current pulse durations of $\sim$4μs with observed peaks ranging from several kA to tens of kA. Intensified charge coupled device (ICCD) photography was leveraged to visualize the propagation of plasma. Parametric studies on capacitance, propellant, and mass flow rate were conducted to minimize current reversal and maximize performance. Several gaseous and liquid propellants were assessed, with additional testing on the LESF igniter location and dielectric material.

HIGH DENSITY PLASMA THRUSTER

Dejan Nikic[1], James Grossnickle[1]
1. The Boeing Company

Utilizing a flow-stabilized plasma we have demonstrated a high thrust and high specific impulse thruster capable of producing 10 N to 1000 N of thrust while maintaining high specific impulse >5,000 s. The scaling relationship of the device suggests that it is possible to build a 10 N thruster with a thrust to power ratio of 95 mN/kW. Thrust of the device is achieved by increasing the plasma pressure and expanding it out of the nozzle of the thruster. Operating in this regime we are able to directly couple the magnetic pressure generated to the thrust of the device. Therefore the thrust is directly proportional to the current applied to the plasma during the current pulse. The present prototype is a pulsed device capable of producing thrust for up to 1 ms. Increasing the energy available to the device would allow for longer thrust duration. Active areas of research involve optimization of device length, pulse duration and input energy level. In addition multiple fuels are being studied.

STUDY ON STABILITY OF AN INNOVATIVE IGNITION TECHNOLOGY FOR MICRO-CATHODE ARC THRUSTER

Chongjian Ge[1], Yanan Wang[1], Le Cheng[1], Tianbo Zhang[1], Weidong Ding[1], Jinyue Geng[1]

1. State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University

Micro-Cathode Vacuum Arc Thrusters (μCAT) have the obvious advantages of simple structure, low average power consumption, high specific impulse, high working efficiency and wide output range, which gain a better application prospect in the field of micro-Nano satellite propulsion system, such as the system of the telephone satellites[1]. However, the traditional trigger ignition technique trough mental film is unstable and limits the life of the thruster, which remains to be explored and optimized for better engineering application[2,3].

In this paper, an innovative trigger ignition technology at low voltage with the use of SiC material is proposed. The structure and assembly of the thruster and triggering material are masterly designed. Ignition stability of the SiC material is verified by discharge experiments with the special attention paid to the change in material surface resistance during the working process. Experiment on discharge characteristics of the thruster with SiC material has been also carried out to study how external circuit parameters influence ignition stability. The results show that trigger signal of SiC material is more stable than that of metal film. The reason is that SiC material can overcome the imbalance effect of under-deposition or over-deposition on the surface of metal film during discharge by the original ignition technology, thereby increasing the stability of the trigger stability of the thruster. Future work will be focused on the mechanism of SiC material triggering process and the approach to optimize and improve the thruster's performance.

PULSED POWER SUPPLY DESIGN FOR VACUUM ARC THRUSTERS APPLICATION

Marvin Kuehn[1], Jochen Schein[1]
1. Bundeswehr University Munich (BUM)

A vacuum arc thruster is a compact solid propellant propulsion system, which is capable to produce thrust in uN range. It is particularly interesting for very small satellites with a limited space and mass budget.

For a space ready vacuum arc thruster system among other issues which need to be addressed the development of a suitable power supply is necessary. It should allow a stable and long term operation of the thruster under conditions which prevail on a solar cell powered satellite. Since a limited energy budget is available in this case, the thruster has to be operated in a pulsed mode.

In this work we present a pulsed forming network based power supply, which was adapted to suit the needs of the vacuum arc thruster applications under space condition. It features a design suitable for operation over many millions of pulses as well as an adjustable pulse length which allows to operate the thruster in different modes. Moreover, this design is compared to other power supplies suggested for the vacuum arc thruster.

STUDY OF CONDUCTIVITY ON HYDROGEN PEROXIDE CONCENTRATION BY HIGH REPETITIVE UNDERWATER DISCHARGE

Daiki Sugawara[1], Shunsei Kawamura[1], Hisanori Sone[1], Masahiro Akiyama[2]
1. iwate university
2. Iwate Univercity

Underwater discharges generate shock waves, active species such as OH radicals, high electric fields and so on. Underwater discharges have been studied for algae treatment and ballast water treatment. The conductivity of water treated by underwater discharge is different. Therefore, it is necessary that investigation about the influence of underwater discharge on the change of conductivity. OH radicals have a very strong oxidizing power, however their lifetime is very short. Hydrogen peroxide is a by-product of OH radicals, it is possible to investigate the amount of OH radicals generated by measuring the amount of hydrogen peroxide. Our research is study of conductivity on hydrogen peroxide concentration by high repetitive underwater discharges.

Experimental environments are as follows: pulse discharge by MPC (magnetic pulsed compression) method with maximum output 1 J/pulse and repetition frequency of 250 pps (pulses per second), liquid conductivity 110 to 45000 μS/cm, number of shots 2000 to 100000, pack test for hydrogen peroxide (WAK-H2O2, Kyoritsu Chemical-Check Lab. Corp.), visible spectrophotometer, a high voltage prove, a current monitor, a high speed camera for plasma movies.

Result, the residual amount of hydrogen peroxide decreased as the conductivity increased, and the increasing rate of the residual amount of hydrogen peroxide slowed as the number of shots increased. After 40000 shots, the increasing rate of the residual amount of hydrogen peroxide was almost constant.

STERILIZATION OF E. COLI IN SEAWATER USING DISCHARGE IN WATER AND DIELECTRIC BARRIER DISCHARGE

Hisanori Sone[1], Shunsei Kawamura[1], Koichi Takaki[1], Katsuyuki Takahashi[1], Masahiro Akiyama[2]
1. Iwate University
2. Iwate Univercity

Ballast water is seawater that is loaded as a ”weight” to maintain restoring force when a large cargo ship is not loading luggage. In order to balance the sailing at a shipping route where there is generally no load or less luggage, pump up seawater at the port of the departure place and pump out it with loading at the port of the arrival place. Since ballast water also contains inherent microorganisms and bacteria in area that collecting water, problems that the ecosystem around the port of the arrival place is seriously damaged due to such as alien species have occurred. This study is sterilization of E.coli using discharge in water and dielectric barrier discharge (DBD). The conductivity of water was 44500 μS/cm (seawater). In this experiment, the power supply voltage was applied 30 kV, the size of the reactor was 10 cm $\times$ 10 cm $\times$ 10 cm, and the electrode were a copper (diameter was 0.8 mm) and tungsten(diameter was 1.0 mm). The conductivity was adjusted by placing potassium nitrate in purified water. The amount of water was 500 ml. and the initial number of E.coli was adjusted absorbance was 0.15 at a wavelength of 600 nm. The frequency were 50 and 250 pps. the applied pulse number was 0, 1000, 5000, 10000, 25000, 50000, 75000 and 100000, Samples were taken and bacteria were enumerated. As a result, in the case of discharge in water, the number of bacteria was hardly changed until 10,000 pulses, however, it decreased from the 10000 pulse onward, and throughout, the number of bacteria decreased with increasing pulse number. In the case of DBD, the number of colonies decreased significantly compared with discharge in water. It is considered to be due to the difference in discharge range.

FLEXIBLE CONTROL OF PULSED POWER GENERATOR FOR RESEARCH APPLICATIONS WITH SENSORS

Masahiro Akiyama[1], Shunsei Kawamura[2]
1. Iwate Univercity
2. Iwate University

Pulsed power generators have been required high-reliability usability and portability by research applications such as bioelectrics, ozonizers, sterilization and water treatment. However, those pulsed power generators are difficult to develop a conventional pulsed power generator using only electric circuits.

The present work aims to develop a high-performance pulsed power generator using field programmable gate array (FPGA), Microcomputer, a Windows PC and sensors. The design specifications are as follows: a peak output voltage of 1.5 kV without a pressure transformer; universal serial bus (USB) connection; oscilloscope, high voltage probe and current monitor for measurement of output; sensors on temperature, pressure, humidity and luminous intensity; flexible control of pulse interval, pulse width, shot number and output voltage. The software, running on the Windows PC, is made from Visual C# with Visual studio 2017. It has a graphical user interface (GUI) and several functions such as selection of using PC or using controller. The complex control of pulsed power which this software and sensors enables is particularly applicable to industrial fields.

PLASMA SOURCE FOR GENERATING ULTRASONIC AND ULTRAVIOLET RADIATION IN WATER

Joseph Groele[1], John Foster[1]
1. University of Michigan

Ultrasonic and ultraviolet (UV) radiation in water leads to the production of hydroxyl radicals, and are thus considered advanced oxidation processes capable of removing organic contaminants from waters and wastewaters. Ultrasound in combination with UV irradiation increases the production rates of hydroxyl radicals, and traditionally involves both high-power ultrasonic transducers and UV lamps. This study investigates a plasma source for generating ultrasound and UV light simultaneously in water. Ultrasound transmitted to water is measured using a hydrophone, while the UV intensity is assessed using a radiometer and by chemical actinometry. Relationships between plasma parameters and produced ultrasonic and UV radiation in water are considered.

PRODUCTION OF CRUSHED SAND USING UNDERWATER PULSED DISCHARGE

Naoki Matsumoto[1], Masaaki Yano[2], Takao Namihira[3], Douyan Wang[4], Mitsuhiro Shigeishi[5]

1. graduate school of science and technology in Kumamoto University
2. graduate school of science and technology ,Kumamoto University in Japan
3. Institute of Pulsed Power Science , Kumamoto University in Japan
4. Institute od Pulsed Power Science , Kumamoto University in Japan
5. Graduate School of Science and Technology,Kumamoto University in Japan

Concrete consists of coarse aggregates, fine aggregates, and cement pastes. The coarse aggregates can be supplied from either crushed stone from mountains or recycled coarse aggregates from waste concrete. Recently, the fine aggregates can be supplied either from crushed sand which made from crushed stone or recycled fine aggregates from waste concrete. In previous days, the fine aggregate could be collected from river, but now become difficult due to regulations. Therefore, the demand for regenerated fine aggregate and crushed sand is expected to increase. Therefore, a new recycling and crushing technique is required, and it is considered that crushing technology using pulsed power can be used as one of them.

In this study, the coarse aggregate was crushed by underwater pulsed discharge to produce crushed sand, and the voltage condition with good treatment efficiency was optimized. Oven - dry density and water absorption ration of crushed sand were measured and evaluated as to whether it meets the industrial standards. Also, the particle size distribution and generation amount of fine particles were compared between underwater pulsed discharge method and the conventional jaw crusher method.

AGGREGATION INHIBITION OF NANOPARTICLE DISPERSION BY NONTHERMAL PLASMA IRRADIATION

Katsushi Suenaga[1], Ayumu Hyodo[1], Yuta Kawamura[1], Douyan Wang[2], Takao Namihira[2]

1. Graduate School of Science and Technology, Kumamoto University, Japan

2. Institute of Pulsed Power Science, Kumamoto University, Japan

The nonthermal equilibrium plasma has a high chemical reactivity and a characteristic that the temperature of the ion and the neutral particle is relatively low. Utilizing these features, many applications have been studied in the environmental field such as electrostatic precipitator, ozone generation, exhaust gas treatment, removal of volatile organic components, etc. In recent years, researches directed toward application to medical fields such as sterilization, dental treatment, and wound healing are actively conducted.

Nanoparticles have received much attention in recent years due to its remarkable properties, which offer important economic benefits and has been used in diverse applications. However, their property gradually decays because of aggregation, which means that adhesion between nanoparticles. To maintain high performance of nanoparticles in liquid requires a technique which maintains dispersion. Examples of conventional dispersion techniques include a bead mill, an ultrasonic homogenizer, a dispersant, and so on. Thus, numbers of equipment are required. Due to the disadvantages of conventional dispersion technologies, research on new dispersion technology has been conducted to solve these problems.

In this study, ZrO2 and ZnO were used for the target nanoparticles. ZrO2 is positively charged in solution. Conversely, ZnO is negatively charged in solution. The experimental results show that aggregation of ZrO2 nanoparticle dispersion was suppressed by irradiating non-thermal equilibrium plasma. The dispersion lifetime of ZrO2 could be extend its lifetime, but not in case of ZnO. The plasma irradiation increased the H2O2 concentration in the liquid. These results suggest that OH radicals may affect the surface hydroxyl group of ZrO2 to change the charged state.

EXPERIMENTAL RESEARCH ON SOLAR PANELS FRAGMENTATION BY ELECTRO-HYDRAULIC EFFECT WITH APPLICATION OF PULSED POWER

Mengyao Zhang[1], Baipeng Song[1], Ling Jiang[2], Jun Kang[2], Zhanlin Li[2], Yao Chen[2], Guanjun Zhang[1]
1. Xi'an Jiaotong University
2. Electric Power Research Institute of State Grid Qinghai Electric Power Company

Discharging in liquid can generate shock waves between electrodes as the result of transient pulsed power, which is defined as the electro-hydraulic effect. The high pressure stimulated by compressed shocks is widely used for mechanical application, such as medicine industry, machinery processing, geological exploration. With the rapid development of photovoltaic industry, the sustainable recycling problem of solar panels is becoming increasingly prominent. At present, the existing technologies of waste solar panels fragmentation, such as chemical corrosion or mechanical disruption method, are relatively primitive and not environmentally-friendly. On the basis of electro-hydraulic effect in water, this paper is focused on generation and characteristics of compressed shock waves induced by plasma explosion, and its application in solar panels fragment. A pulsed power platform with its amplitude of 100kV and width of 500ns is set up for experimental investigation. Combined with electrical and optical diagnostic method, the basic development process and accompanied physical phenomena of discharging is discussed, including the initiation of streamer, plasma channel formation and shock waves explosion. The results demonstrate that the maximum pressure of the shock wave is up to GPa, and especially fragment and seperation is started from interfaces of solar panels, because of their different mechanical properties. Meanwhile, the particle size and morphology of the broken panels parts are measured to evaluate the fragment efficiency and optimize the power parameters. Application of Electro-Hydraulic effect provides an efficient way to increase the value of solar panels extracted or recycled.

CALCULATION AND ANALYSIS OF SELF-RESISTANCE OF GROUNDING MATERIAL

Jiayin Yan[1], Zhu Yinan[1], Lanxi Li[1]
1. Xi'an Jiaotong University

The correct estimation of the self resistance of grounding conductor (due to the grounding resistance caused by the self resistance of grounding conductor) is of great significance for improving the design and construction level of grounding grids and the reasonable selection of the specifications of grounding conductors. However, there is no scientific calculation method for its accurate value, so it can not be considered accurately in actual engineering design. Therefore, the self resistance of grounding body is calculated and analyzed by means of a kind of grounding body self resistance calculation and analysis. The results show that the line resistance, soil resistance and contact resistance of earth and soil are the main factors affecting the size of the self resistance of grounding body. In order to facilitate the calculation and analysis of the self resistance of grounding conductor, the self resistance curve of grounding body in different soil environment is drawn. Finally, the method of reducing the self resistance of grounding body in practical engineering is put forward, which provides reference for the grounding design and construction.

GROWTH OF PHOTOCATALYTICALLY ACTIVE COATINGS ON ALUMINUM BY PLASMA ELECTROLYTIC OXIDATION

Lívia Sottovia[1], Elidiane C Rangel[2], Nilson C Cruz[3]
1. Laboratory of Technological Plasmas - Unesp, Sorocaba, Brazil
2. Laboratory of Technological Plasmas, Paulista State University
3. Sao Paulo State University

In many situations the performance of a given material is determined primarily by the properties of its surface. That is the case of photocatalytic degradation systems, where organic compounds are mineralized through chemical reactions stimulated by the light illuminating certain materials. Such effect can be enhanced by using treatment techniques able to adjust the surface characteristics, preferentially, without affecting bulk properties. In this context, plasma electrolytic oxidation (PEO) is very convenient because it enables the production of highly porous surfaces with tailored morphology and composition. In this work, photocatalytic active coatings have been grown on aluminum substrates by PEO using TiO2-containing electrolytes. The samples have been characterized by scanning electron microscopy with x-ray energy dispersive spectroscopy, x-ray diffraction and surface area measurements. The photocatalytic activity has been quantified evaluating the degradation rate of metformin. It has been observed that the coatings are mostly constituted by a mixture of rutile and anatase phases. Under certain conditions, 100% of metformin has been degraded after irradiation with UV-light for 90 minutes.

RE-ORIENTATION OF BN NANOSHEET INDUCED BY PULSED ELECTRIC FIELD AND ITS EFFECT ON THERMAL PROPERTIES OF EPOXY RESIN-BASED NANOCOMPOSITES

Yan Mi[1], Lulu Liu[1], Lu Gui[1], Xin Ge[1]
1. Chongqing University

In this study, low level of boron nitride (BN) nanosheets filler loading (5wt.%, 10wt.%) were incorporated in epoxy resin matrix to improve thermal conductivity of the nanocomposites by performing the alignment of BN nanosheets. The orientation of BN nanosheets in epoxy resin matrix are controlled by applying pulsed electric field during the curing process of epoxy resin/BN nanocomposites. The pulsed electric field has a pulse width of 1 μs, a field strength of 30 kV/mm, and a repetition frequency of 50 Hz to 50 kHz. Under the application of the pulsed electric field, the BN nanosheets are polarized and are subjected to electric field induced force, thermal motion and viscous drag. Scanning electron microscopy (SEM) and x-ray diffraction (XRD) show that the BN nanosheets are oriented parallel to the direction of the electric field. When the BN content is 5wt.%, the thermal conductivity of the nanocomposite with the application of the pulsed electric field is several times that without the pulsed electric field (0.215 W/mK). The results also show that the repetition frequency affects the thermal conductivity of the nanocomposites. The higher the repetition frequency, the higher the thermal conductivity of the nanocomposites. This paper provides guidance for the preparation of epoxy resin-based nanocomposites with high thermal conductivity at low BN loadings.

ELECTRIC BREAKDOWN IN GRANITE AS A FUNCTION OF PRESSURE AND TEMPERATURE CONDITIONS

Tony IMBERT[1], Thierry REESS[2], Antoine de Ferron[3], Laurent PECASTAING[2], Gauthier Demol[1], Baptiste Guegan[1]

1. ITHPP

2. UNIV PAU & ADOUR, Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique, IPRA, EA4581, 64000, Pau, France

3. Pau University

It is widely accepted that the breakdown field in fluid (water) is affected by the duration of the applied voltage. Consequently, when a solid (rock) is submersed into a fluid and placed between electrodes, a breakdown occurs in the solid dielectric rather than in the insulating liquid depending on the voltage-time characteristics and on the values of the electric field: there is competition between the dielectric strength of the two mediums.

Many experiments have been performed to determine the behavior of voltage-time characteristics of the discharge in fluids and solids at room temperature and atmospheric pressure. In these conditions, to be sure to generate the breakdown in the rock, the voltage pulse must be shorter than one microsecond and the applied electric field must reach at least 100 kV / cm.

This paper presents the dielectric strength test results of a 3mm point-to-point marble gap submersed in tap water at varying temperatures (from 20°C to 100°C) and static pressures (from 1 bar to 200 bar). In order to minimize the volume of the energy bank, the switching energy is limited to 50J.

Typical records of the current discharge and the applied voltage will be analyzed. The required energy consumption to initiate the breakdown in the rock will also be exposed. Those results will be associated to electric field simulations: the breakdown field distribution into the rock will be studied as a function of thermodynamic conditions.

EXCESS ION ENERGY BEING ESSENTIAL FOR ULTRA-SHALLOW IMPLANTATION

Noriyuki Sakudo[1], Noriaki Ikenaga[1]
1. Kanazawa Institute of Technology

Ion-implant energy for cutting-edge semiconductor device is decreasing since the junction depth becomes shallower along with the shrinkage of device size. The lowest energy level for practical use has been around several 100eV and will become lower in a near future [1]. For realizing such low-energy beams, ions are decelerated before implantation. We reported in the past that the exact energy value of such low-energy ion beam was determined not only by the potential difference between the ionization chamber and the target, but by the summation of the potential difference and the excess energy coming from the plasma potential in the chamber [2]. For the case of low ion energy of several 100 eV the excess energy has a considerable part of the total energy..

Up to now the plasma potential has been given under the assumption that the plasma was in a stationary condition in which both the ion and electron fluxes going out from the plasma were equal in absolute value and balanced at every point of the plasma boundary, i.e., there was no electric current intersecting the boundary. However, at the ion-exit slit of the practical ionization chamber only ions go out and electrons are retarded backwards. Thus, there exists directional electric current intersecting the plasma boundary at the exit slit. In this study we deduce a new formula by taking into account the ion electric current at the slit. Resultantly it is found the plasma potential is changed not only by the electron temperature as usual but also by the chamber structure.

[1] N. Suetsugu, M. Tsukihara, M. Kabasawa, F. Sato and T. Yagita, Proc. of 20th International Conference on Ion Implantation Technology, (2014) 157-160.

[2] N. Sakudo, K. Hayashi, Rev. Sci. Instr. 67 (1996) 1218-1220.

INVESTIGATION OF ENERGY CONTROL IN COAXIAL REACTOR FOR OZONE PRODUCTION BY USING NANOSECOND PULSED POWERS

Yoshifumi Sanuki[1], Yuki Utsumi[1], Kenji Teranishi[1], Naoyuki Shimomura[1]
1. Tokushima University

Ozone has been used an oxidation agent in various fields, and production of ozone with high efficiency and high concentration is required. In this study, ozone is produced in coaxial reactors using nanosecond pulsed power discharges. The ozone production with pulsed power discharges is efficient but relatively low-concentrated. In our previous studies, the ozone concentration increased with decrease of the diameter of the coaxial reactor. However, ozone concentration decreased in reversal by further decrease of the diameter of reactor. The surplus energy of applied pulse on the reactor is not consumed and can cause long and large wave tail of applied voltage pulse. The wave tail can develop spark discharges which are inefficient for discharge-chemical reaction. We investigated a control of the voltage pulse tail with adjusting the surplus energy in the reactor and its influence on the ozone concentration. A winding resistor was connected to the reactor to consume the surplus energy and to remove the voltage pulse tail. Ozone concentration of 14-mm reactor became higher in reversal than that of 17-mm reactor when the winding resistor was installed. This would be because potential of thinner reactor became available. Since the ozone concentrations were, however, lower than when the winding resistor was not installed, the applied pulse might not match the reactor basically. A coil-type coaxial reactor, having winding inner electrode, was additionally considered instead of the winding resistor. The reactor should be optimized for the applied voltage pulse not to result the surplus energy.

IMPROVEMENT OF OZONE GENERATION CHARACTERISTICS WITH SHORTER RISE TIME OF NANOSECOND PULSE VOLTAGE

Hideaki Fukuoka[1], Shuhei Iida[2], Douyan Wang[3], Takao Namihira[3]
1. Graduate School of Science and Technology
2. Graduate School of Science and Technology, Kumamoto University – Japan
3. Institute of Pulsed Power Science, Kumamoto University – Japan

Ozone has strong oxidation power and no-residual toxicity, therefore it is expected one of the next-generation oxidants. There are various applications using ozone such as clarification of drinking water, industrial wastewater treatment, and so on. At present, dielectric barrier discharge is the main method used for commercial ozonizers. However, as most of the input energy is lost as heat, its low energy efficiency into plasma phase has been a problem. In recent years, it is demonstrated that the pulsed discharge produced by 7 ns duration pulsed power gave us the high energy efficient ozone generation. However, there is still problems that the maximum ozone concentration using the nanosecond pulsed discharge has been saturated at approximately 40 g/m3. Therefore, in this study, the experimental results of high concentration ozone generation using nanosecond pulsed discharge was performed.

In this study, the purpose of improving pulse rise time, nanosecond pulse forming line using peaking switch was developed. The fast rise time pulse was formed by a peaking switch, and the rise time of pulse is shorten into 2 ns on the discharge reactor. Additionally, we investigated the effect of pulse rise time on ozone generation. As the result, in case of the experiment of faster rise time pulse, the efficiency of ozone generation is higher than the previous one which has 7 ns pulse which and 3 ns pulse rise time.

SHORT TERM ATMOSPHERIC PRESSURE COLD PLASMA TREATMENT: A NOVEL STRATEGY FOR ENHANCING THE SUBSTRATE UTILIZATION IN A THERMOPHILE, GEOBACILLUS SP. STRAIN WSUCF1

Magesh Rajan[1], Navanietha Rathinam[1], Rajesh Sani[1]
1. South Dakota School of Mines and Technology

There is a growing demand for developing a facile strategy to increase the yield of microbial processes. We report a novel strategy to disrupt the cell wall of microorganisms for enhancing the mass transfer of solutes/metabolites by treating the cells with cold plasma for an optimized time interval. Geobacillus sp. strain WSUCF1, a thermophile capable of producing cellulolytic enzymes with higher activity was used for this investigation. WSUCF1 treated with atmospheric pressure cold plasma for different time intervals of 2, 3, and 4 minutes was used as inoculum and its substrate utilization rates and biofilm formation were analyzed. Treatment with atmospheric pressure cold plasma for 4 minutes increased the rates of glucose utilization by 74% and increased the yield of biomass by 60% when compared with the control. WSUCF1 treated with plasma also displayed enhanced biofilm formation. This study for the first time, reports the use of cold plasma for enhancing the rates of mass transfer for enhanced substrate utilization and biomass yield in a thermophile.

PLASMA KINETICS STUDY OF A REPETITIVE 10-NS PULSED PLASMA IGNITION FOR COMBUSTION

David Alderman[1], Christopher Tremble[1], Shutong Song[2], Jason Sanders[3], Dan Singleton, Chunqi Jiang[1]
1. Old Dominion University
2. Old Dominion Unviersity
3. Transient Plasma Systems, Inc.

Combustion efficiency and rate of ignition were shown to be improved when fuel-air ignition was initiated with highly non-equilibrium plasmas generated by high-voltage, nanosecond pulses, also known as transient plasma ignition (TPI). In order to optimize the pulse power parameters for plasma ignition for combustion, detailed experimental investigations of the effect of rise time and pulse repetition frequency (PRF) were conducted for atmospheric pressure static methane/air ignitions. Plasmas driven by 10 ns, 12 kV pulses at a range of PRF from 1 kHz to 10 kHz were generated for combustion ignition with a pin-to-plate electrode configuration. Experiments revealed that a different mode in the plasma was initiated when the fuel/air mixture was ignited. At constant pulse duration and PRF, this plasma mode change occurred earlier for the faster rise time (e.g. 4 ns) compared to (e.g. 8 ns) [1]. In addition, faster PRF favored the earlier plasma mode change or earlier ignition. In this study, the kinetics of reactive plasma species that generated during the transient plasma ignition and combustion were investigated using optical emission spectroscopy (OES). Gated and filtered imaging in combination with electrical diagnostic techniques are to help understand the plasma chemistry related to combustion that is initiated with different pulse rise times and PRFs at a constant pulse width of 10 ns. Gas temperature of the PRF plasma ignition for combustion is discussed by measuring the rotational temperature of the second positive systems of nitrogen N2 (C-B).

*The work was supported in part by the Department of Energy (Phase I STTR, DE-SC001788) and the Air Force Office of Scientific Research (Award No. FA9550-17-1-0257).

[1] D. Alderman, C. Tremble, J. Sanders, D. Singleton, and C. Jiang, ”Initial Evaluation of Pulse Risetime on Transient Plasma Ignition for Combustion,” in IEEE International Power Modulator and High Voltage Conference, 2018.

TEMPERATURE EFFECT ON THE SURFACE FLASHOVER PLASMA OF THE GIS INSULATOR

Shijie LU[1], Liangen ZHANG[1], Hongtao ZHONG[2], Guo-ming MA[1], Cheng-rong LI[1], Yu YIN[3], Boyuan CUI[3], yuyi WU[3]

1. North China Electric Power University

2. Princeton University

3. China Electric Power Research Institute

Flashover plasma across an epoxy sulfur hexafluoride interface in gas insulated switchgear (GIS) may induce blockage of power cut. However, characteristics of flashover plasma across an epoxy sulfur hexafluoride interface under the operation temperature of GIS (80 Celsius degree) were less discussed previously. In this work, a high voltage experiment setup was built to investigate the temperature effect on the surface flashover plasma. The voltage, current, acoustic and ultra-high frequency signals were obtained with different kind of sensors. The experiments indicate that the flashover voltage reduced 11.74% when temperature increased from 20 Celsius degree to 80 Celsius degree. The distributions of electric field, temperature and the gas density were also simulated. A particle-in-cell model including field electron emission and temperature was developed to discuss the temperature effect. From the simulation results, it can be concluded that at higher temperature, it has more tendency to develop flashover across an epoxy sulfur hexafluoride interface initiated by field electron emission. This work will give a reference for evaluation and design of epoxy sulfur hexafluoride interface for high-voltage GIS applications.

EROSION CHARACTERISTICS FOR DIFFERENT GEOMETRIC ELECTRODES IN AN AC ROTATING ARC REACTOR

Kwan-Tae Kim[1], Hongjae Kang[1], Chan Mi Jung[1], Sungkwon Jo[1], Dae Hoon Lee[1], Young-Hoon Song[1]

1. Korea Institute of Machinery and Materials

In a gliding arc reactor, the arc string moves two dimensionally. On the other hand, in a rotating arc reactor the arc string moves three dimensionally by using a swirl motion of arc gas. The performance of most plasma generators using electric arcs is determined by the design of electrodes. Especially, the design of high voltage electrode is a dominant factor in determining the limitations in reactor operating current and power level as well as lifetime between maintenance (1). Design approach for the development of plasma reactor with long lifetime by less erosion of electrode has been carried out. Plasma reactor is based on the "rotating arc" design and different geometries of high voltage electrodes in an AC arc reactor, 3 types, were compared. Experiments were carried out with varying applied power at the same flow rate of discharge gas and arc length. Temporal change in voltage-current values is monitored, and electrode weight loss and erosion shape are compared after operation. In addition, a 3D scanning method is utilized to quantitatively evaluate the erosion rate of the electrodes depending on their shapes.

1. JOACHIM HESERLEIN, 1999, "Electrode Phenomena in Plasma Torches", ANNALS of THE NEW YORK ACCADEMY OF SCIENCES: Heat and mass transfer under plasma conditions, Vol. 891, pp. 14-27.

----

* This work was supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIP) (No. CRC-14-1-KRICT)

STATISTICAL EXAMINATION OF SPOKE EVOLUTION IN HIPIMS

Peter Klein[1], James W. Bradley[2], Jaroslav Hnilica [1], Petr Vašina[1]
1. Masaryk University
2. University of Liverpool

Plasma in high-power impulse magnetron sputtering (HiPIMS) discharge, similarly to other discharges utilizing ExB field (Hall thrusters, homopolar devices), undergoes self-organization into the ionization zones rotating in the ExB direction, called spokes. In different experimental conditions the appearance, number and rotational velocity of spokes change. Additionally, the spokes were observed to split and merge over time even when discharge parameters were kept constant.

A study is presented where a novel diagnostic method of strip probes together with well-established fast camera screening were utilized in order to track spokes during the whole stable high-current phase of the HiPIMS pulse. Strip probes embedded to the target locally capture the current flow over the whole pulse, while the fast camera captures a plasma emission from the whole target at a given time. Such combination allows observing events such as spoke merging and splitting in more detail.

It was found that spoke merging and splitting events effect neighboring spokes. Additionally, when spokes split or merged overall charge supplied through the spokes was conserved. Statistical examination of measured data revealed two distinct tendencies of the spoke configuration. At the low pressure, spokes merged and split over time seemingly in a random fashion around a stable configuration, while in higher pressure spoke splitting was strongly favored over the merging process. Therefore, at higher pressure number of spokes was observed to increase in time despite the discharge current and cathode voltage were kept constant. Based on experimental results, a phenomenological model based on the metal resputtering was created in order to explain merging and splitting events.

LORENTZ FORCE EDDY CURRENTS FOR NONDESTRUCTIVE TESTING

Agni Dhanabal[1], Trevor Drouillard[1], Robert Kile[1], Paul Melnik[2], Kenneth Miller[2], James Prager[2], Timothy Ziemba[2], Allen Garner[1]
1. Purdue University
2. Eagle Harbor Technologies

Nondestructive testing (NDT) is a growing need to test the integrity of industrial materials since small defects can lead to catastrophic failure during operation in areas ranging from aviation to nuclear pressure vessels. Lorentz force eddy currents provide higher testing speed and greater penetration depth of conductive nonferrous metals than other methods. This presentation assesses the effectiveness of using a 2D finite element model (FEM) of a permanent magnet with a copper coil probe using Ansys Maxwell to assess the feasibility of this approach. The FEM model enables the analysis of defects that are difficult to replicate physically and the translation of probe data into a computer simulated visualization of real defects. It also allows for testing various materials and external environments, such as vacuum or air under different conditions. We report the validation and verification of the 2D FEM model to analytic results and experimental data of known defects. Extensions to 3D FEM and more complicated defects will be discussed.

PULSED HIGH VOLTAGE ASSISTED LASER SELF-INDUCED PLASMA SHUTTER FOR HIGH SPATIAL RESOLUTION LASER REMOTE SENSING

Taieb Gasmi Cherifi[1]
1. Saint Louis University-Madrid Campus

Laser pulse clipping system using pulsed high voltage induced gas breakdown techniques is presented. The device is most indicated for high spatial resolution monitoring which is directly dependent on the transmitted laser pulse duration. The fast rise time high voltage pulse acts as gas pre-ionizer which improves the characteristics of the laser clipped pulse with regards to energy stability and pulse profile repeatability.

DESIGN OF OPTIMAL PULSE SOLENOID STRUCTURE FOR INDUSTRIAL APPLICATION Y.LIVSHITZ , FORMER CTO PULSAR ,YAVNE, ISRAEL

Yuri Livshitz[1]
1. engineer

ABSTRACT

There is a number of pulse magnetic field industrial applications where solenoids of long life time are required . It is a very problem to create such system (pulse current generator, working coil, high energy electric connection) that can perform unchangingly for millions, or at least 100 000s of pulses, with no down time. 5 pulse per/min repetition and B about 25T is also a must for most of industrial application, such as swaging, forming, impact bonding and pulse magnetic welding.

Coil design must therefore address to major problem of how to minimize stress to below or near the fatigue strength of coil's material. The task of providing to the MA –level currents involved is also very important

The simulation, calculation and experimental results are shown . The results confirmed the principal possibilities to produce said system with minimum losses for inductive connection between two parts of coil. Magnetic field distribution as well as equation between primary and secondary currents are in good accordance with simulation and calculation

The one turn and multi-turn system as well one –turn system with pulse transformer have been designed, produced and tested.

The practical result of use the system are reported too.

ATMOSPHERIC PLASMA FOR TREATMENT OF PERFLUOROALKYYL SUBSTANCES (PFAS) IN WATER: REACTOR DESIGN AND PERFORMANCE EVALUATION

Mubbshir Saleem[1], Mirko Magarotto[1], Omar Biondo[1], Pavarin Daniele[1], tampieri francesco[1], Cristina Paradisi[1], ester marotta[1], Marco Manente
1. University of Padova

Perfluoroalkyl substances (PFASs) are organic compounds of high thermal and chemical stability, used extensively to produce many commercial household products (non-stick products and fire-fighting foams etc.). They extremely persistent organic pollutants, which is of high concern due to their ability to bioaccumulate in living organisms. Traditional methods for wastewater treatment are not able to remove these compounds and, owing to the presence of highly stable carbon−fluorine bonds, also advanced oxidation processes (AOPs), employing hydroxyl radical (·OH) as the main oxidant species, showed limited or null mineralization of these compounds.1 In this perspective, application of atmospheric plasma for removing this class of recalcitrant organics has gained much attention in the last years.2 Among the advantages offered by the use of atmospheric plasma for water treatment, are flexibility, in situ generation of reactive species (OH, O, H, O3, H2O2, aqueous electrons) and no requirements of chemicals, advantages that envision atmospheric plasma as a green technology.3

The present study was carried out with AC and DC driven plasma reactors using perfluorooctanoic acid (PFOA) as model compound. PFOA is one of the main PFAS still used in some industries despite being phased out. Different reactor configurations were used, allowing generating plasma in gas bubbles produced inside the liquid, plasma streamers over the liquid surface with gas bubbling and streamers over a thin film of the solution. For each configuration plasma was produced in different gases (air or argon) and characterized by the measurement of discharge current and voltage. The decomposition rate of PFOA and the energy efficiency of the process were evaluated by measuring the residual PFOA and the mineralization yield achieved. Furthermore, degradation products and the reactive species possibly responsible for PFOA degradation were monitored and studied. The results obtained with different reactor configurations and power supplies will be compared and discussed.

CELL GEOMETRY-INVARIANT CALCULATION OF PLASMA MEMBRANE POTENTIAL DUE TO ELECTRIC PULSES USING VARIATIONAL CALCULUS

Adam Darr[1], Allen Garner[2]
1. Purdue University West Lafayette
2. Purdue University

The plasma membrane potential of non-spherical cells has been solved for the spheroidal case analytically [1,2] and approximated in other cases[3] These solutions become cumbersome for more complex shapes, such as spheroidal cells with protrusions or rod-like cells. In particular, many microorganisms are rod shaped and a direct method for determining membrane potential for these cells is valuable for quantifying electroporation for sterilization. In this presentation, we investigate a geometry-invariant calculation of the plasma membrane potential using variational calculus and the minimum energy principle. Comparisons to theories for ellipsoid and cylindrical geometries will be presented. The implications of these solutions for electroporation theory will be discussed.

1. Q. Hu and R. P. Joshi, “Transmembrane voltage analyses in spheroidal cells in response to an intense ultrashort electrical pulse,” Phys. Rev. E, vol. 79, 2009, Art. no. 011901.

2. J. Gisma and D. Wachner, “On the analytical description of transmembrane voltage induced on spheroidal cells with zero membrane conductance,” Eur. Biophys. J., vol. 30, pp. 463-466, 2001.

3. G. Pucihar, T. Kotnik, B. Valic and D. Miklavic, “Numerical determination of transmembrane voltage induced on irregularly shaped cells,” Ann. of Biomed. Eng., vol. 34, pp. 642-652, 2006.

Work supported by a Purdue Doctoral Fellowship.

MODIFICATION OF THE HODGKIN-HUXLEY WAVE BEHAVIOR BY ELECTROPORATION

Amanda Loveless[1], Martin Lopez de Bertodano[1], Allen Garner[1]
1. Purdue University

The Hodgkin-Huxley equations [1] have long been used to assess membrane current and its impact on conduction and excitation in nerves for action potential initiation and propagation by modeling the ion channels as parallel combinations of voltage and voltage-dependent conductance that yield a set of nonlinear differential equations. Applying sufficiently intense electric pulses (EPs) create membrane pores that form an additional, parallel, cell membrane potential-dependent shunt conductance that can arrest the action potential [2]. While a self-consistent theory provides the most thorough means of relating the applied EP conditions, cell membrane potential, and resulting cell membrane pore formation [2], it is not readily amenable to assessing the EP induced changes in the wave behavior. This study provides an initial assessment of a simpler approach to specifically examine the EP-induced wave behavior by using a semi-empirical approach to assess EP-induced cell membrane conductivity due to pore formation [3]. We report the impact of various EP conditions on the wave and chaos behavior of the Hodgkin-Huxley equations and potential implications on therapy and nonlethal defense.

1. A. L. Hodgkin and A. F. Huxley, “A quantitative description of membrane current and its application to conduction and excitation in nerve,” J. Physiol. vol. 117, pp. 500-544, 1952.

2. R. P. Joshi, A. Mishra, Q. Hu, K. H. Schoenbach, and A. Pakhomov, “Self-consistent analyses for potential conduction block in nerves by an ultrashort high-intensity electric pulse,” Phys. Rev. E, vol. 75, 2017, Art. no. 061906.

3. B. Mercadal, P. T. Vernier, and A. Ivorra, “Dependence of electroporation detection threshold on call radius: an explanation to observations non compatible with Schwan’s equation model,” J. Membr. Biol., vol. 249, pp. 663-676, 2016.

MODELING PLASMA SPECIES FORMATION FOR HIGH VOLTAGE ATMSOPHERIC COLD PLASMAS

Nancy Isner[1], Allen Garner[1]
1. Purdue University

Atmospheric cold plasmas (ACPs) can effectively inactivate microorganisms in liquids and foods. Many ACP delivery mechanisms exist, including plasma jets and dielectric barrier discharges, with pulsed or AC applied voltages. Of note, are recent experiments considering the impact of high voltage ACPs (HVACPs), which apply tens of kilovolts across a several centimeter parallel plate gap, to improve food quality in liquid and solid foods [1]. Because reactive species formation plays a critical role in this phenomenon, previous studies have assessed HVACP species formation, particularly the influence of the boxes and bags used to contain the plasma during treatment [2].

This study attempts to provide a first step toward developing a predictive model for plasma species formation for HVACPs. Specifically, we consider a one-dimensional AC dielectric barrier discharge for a parallel plate geometry and couple it to BOLSIG+ to improve plasma species characterization [3]. The implication of HVACP conditions on species generation in gas, the potential influence of different food conditions (e.g. solid, liquid, or semi-solid), and long timescale plasma chemistry will be discussed.

1. S. K. Pankaj, Z. Wan, and K. M. Keener, “Effects of cold plasma on food quality,” Foods, vol. 7, 2018, Art. no. 4.

2. R. S. Brayfield II, A. Jassem, M. V. Lauria, A. J. Fairbanks, K. M. Keener, and A. L. Garner, “Characterization of high voltage cold atmospheric plasma generation in sealed packages as a function of container material and fill gas,” Plasma Chem. Plasma. Process., vol. 38, pp. 379-395, 2018.

3. G. J. M. Hagelaar and L. C. Pitchford, “Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models,” Plasma Sources Sci. Technol., vol. 14, no. 4, pp. 722–733, 2005.

MAGNETIC FIELD EFFECTS ON EFFICIENCY OF NON-VIRAL GENE DELIVERY USING MAGNETIC NANOPARTICLES

Vasile Neculaes[1], Brian Bales[2], Allen Garner[3], Evelina Loghin[2], JB Mathieu[2]
1. GE
2. GE Global Research
3. Purdue University

While several non-viral gene delivery methods (e.g., electroporation and optoporation) have been developed with various degrees of success, no uniform solution with low cost, high transfection efficiency, low toxicity, simplified workflow and ease of use has been achieved. One approach to deliver genetic material into eukaryotic cells uses magnetic nanoparticles and magnetic fields [1]. While the mechanism of action is incompletely understood, it is hypothesized that the magnetic force brings the magnetic nanoparticle/DNA complexes in the cell growth medium sufficiently close to the cell membrane so that the genetic material will be rapidly taken into the cell by endocytosis [2].

The relationship between magnetic field intensity/magnetic force on cell transfection has not been characterized. This work examines the effect of magnetic field on transfection efficiency for various cell lines using commercially available magnetic particles and magnetic particles synthesized in-house. A commercial permanent magnet and an in-house electromagnet with varying magnetic field capabilities were utilized in experiments. For various cell lines, combining the magnetic field with magnetic particles did not improve siRNA transfection efficiency. For others, magnetic fields improved transfection 5 to 10-fold; however, increasing the magnetic field did not reproducibly increase transfection efficiency. This suggests that the mechanism is more complicated than previously thought, and requires research to determine the impact of particle size, charge, magnetic properties, aggregation and magnetic forces on gene delivery.

1. C. Plank, U. Schillinger, F. Scherer, C. Bergemann, J. S. Rémy, F. Krötz, M. Anton, J. Lausier, and J. Rosenecker, J., “The magnetofection method: using magnetic force to enhance gene delivery,” Biol. Chem., vol. 384, no. 5, pp.737-747, 2003.

2. Q. A. Pankhurst, N. T. K. Thanh, S. K. Jones, and J. Dobson, ”Progress in applications of magnetic nanoparticles in biomedicine,” J. Phys. D: Appl. Phys., vol. 42, no. 22, 2009, Art. no. 224001.

EFFECTS OF NANOSECOND PULSED ELECTRIC FIELDS APPLICATION AND COMBINATION OF ANTICANCER DRUG ON CANCER CELL

Soichiro Enomoto[1], Yasuo Yamamoto[1], Daisuke Konishi[1], Mana Futawaka[1], Yuki Kusuhashi[1], Kenji Teranishi[1], Yoshihiro Uto[1], Naoyuki Shimomura[1]
1. Tokushima University

In recently years, malignant neoplasm (cancer) occupies the extremely high percentage of cause of death; the percentage is ranked the first place in Japan and the second place in the United States. Currently, three major cancer therapy are radiation therapy, chemotherapy, and surgical therapy and these therapies have several disadvantages as large invasiveness and critical side effects. It has been reported that nanosecond pulsed electric fields (nsPEFs) application induced apoptosis on cancer cells; many studies apply it to a cancer therapy have been started.

In this study, we considered the effect of nsPEFs application on tumor cells and combinational effect of anticancer drug administration by experiment. 14ns- and 2ns-PEFs were applied to mouse melanoma cells: B16-F10 in the cuvette, and the cell surviving ratio was measured by crystal violet assay. The 2ns-PEFs application did not affect the cell surviving ratio of B16-F10. The 14ns-PEFs application decreased the cell surviving ratio of B16-F10 and the ratio reduced with increase in number of pulses. More apoptotic cells with pulse application were observed than cells in control sample with apoptosis–necrosis test using flow cytometry. In combinational treatment, the surviving ratio of cells of the combinational treatment of nsPEFs application and anticancer drug (Adriamycin) administration was significantly smaller than unilateral treatment. The surviving ratio of cells administered just after pulse application was significantly smaller than cells administered at 24 hours before nsPEFs application. It is thought that administration of Adriamycin has larger effect for affected cells by nsPEFs application.

COLD ATMOSPHERIC PLASMA FOR CANCER IMMUNOTHERAPY

Zhitong Chen[1], Richard Wirz[1]
1. University of California, Los Angeles

Cancer and cancer related diseases are responsible for about 13% of human deaths. For the great majority of patients, cancers are incurable because the intrinsic genomic instability renders many cytotoxic or targeted therapies ineffectual. Recent breakthroughs in understanding tumor immunobiology and a new generation of cancer immunotherapy has opened a new chapter in the fight against cancer [1]. Meanwhile, cold atmospheric plasma (CAP) entered the field of medicine to deliver reactive species (such as nitric oxide, superoxide, hydroxyl radical, atomic oxygen, singlet oxygen or ozone) and other agents for cancer therapy [2, 3]. CAP is unique in delivering a mixture of reactive species directly from the gas phase to cells and tissues. CAP operating parameters allow control of reactive species output, which enables tailoring of cancer therapy [4, 5]. In our research, we have developed a new CAP device for cancer immunotherapy by 3D printing a device that delivers favorable plasma conditions. The device design was developed using several plasma diagnostic techniques to evaluate CAP physics, including high-speed video, in-situ long-distance surface microscopy, and optical emission spectroscopy (OES). We also developed a CAP cancer immunotherapy strategy via in-situ reactive species delivery generated by CAP at a tumor site. Results show that CAP can promote effective antigen presentation and initiate T cell mediated immune responses that control tumor growth. On the other hand, we employ CAP to cancer recurrence after surgical resection because it remains a significant cause of treatment failure. We will characterize the plasma conditions that minimize both local tumor recurrence after surgery and development of distant tumor. Finally, we intend to identify the new immune-checkpoint molecules serving as potential drug targets for developing next-generation cancer immunotherapy.

VARIATION OF PHYSICAL PARAMETERS IN PLASMA WOUND HEALING

Jimo Lee[1], Won Seok Kim[2], Ki Beom Bae[3], Jae Koo Lee[2], Gunsu Yun[2]
1. POSTECH
2. Pohang University of Science and Technology
3. Pohang Techno Park

The plasma healing of acute wound is examined by controlling several external physical parameters such as driving frequency and power, duration and interval of plasma treatment, fraction of air mixture, and gap distance between plasma and wound. The variation of these physical parameters results in different amount of Reactive Oxygen and Nitrogen Species (RONS) reaching the wound, which stimulate the process of wound healing inside tissue on the physiological time scale as revealed by several important bio indicators. While focusing on the wound size and its rate of change as important physical indicators, which well correlate with the observation of optical emission spectra, the most promising results were obtained by Dual-frequency Microwave Plasma (DP) [1] with 2% air mixture to argon, showing much improved speed of wound healing compared with the previous experiments.

[1] Lee J, Nam W J, Lee S T, Lee J K and Yun G S 2018 Sheath and bulk expansion induced by RF field in atmospheric pressure microwave plasma Plasma Sources Sci. Technol. 27 075008

THE CURRENT TECHNOLOGY OF PLASMA SKINCARE AESTHETIC DEVICES

Guangsup Cho[1], Byung-Koo Son[1], Sichan Kim[1], Chanwoo Moon[1], Hyun Cho[1], Yun Jung Kim[1], Bong Joo Park[1]

1. KWANGWOON UNIVERSITY / Department of Electrical and Biological Physics

Since the floating-electrode dielectric barrier discharge (FE-DBD)[1] has been reported, which had the virtual ground electrode of human skin touching on the dielectric layer covering a high voltage electrode, a portable FE-DBD skincare device has been launched in Korean market. The operation voltage of low as 1-2 kV enabled a miniaturized power supply and a high-level of safety precautions. Portable plasma skincare device has made its debut in Korea. For the last years of 2016-2018 since the initial launch of skincare device, a hand-piece of hundred-thousand pieces was sold with an instant hit for consumers who were becoming increasingly concerned about facial beauty. The aesthetic technology of plasma skincare system is newly expanding to the hand-piece for hair-skincare and to the plasma soap for hands and bodies in using the plasma effect of sterilization and organic resolution.

Wearable plasma aesthetic devices are fabricated as hybrid type of dielectric barrier discharge (DBD) plasma treatment system, whereby the restrictions on treatment time and size of the treated area are eliminated. A patch-type plasma device is developed with the facial mask-pack combining to the facial aesthetics. A plasma bandage is also described as a wearable plasma system involving the portable power system.

[1] G. Fridman et al, "Applied plasma medicine", Plasma Process. Polym., vol. 27, 2008, pp. 503-533.

THE INFLUENCE OF APPLYING HIGH ELECTRICAL FIELD PULSES ON UNFOLDED PROTEIN RESPONSE OF CELLS

Akira Izutani[1], Yuji Furumoto[1], Yoshimasa Hamada[1], Masato Miyake[1], Kenji Teranishi[1], Naoyuki Shimomura[1], Seiichi Oyadomari[1]
1. Tokushima University

The application of pulsed power technology is spreading to biotechnology and medical fields. Pulse electric fields yield various influences on cells. Endoplasmic reticulum (ER) stress which is due to accumulation of unfolded proteins has been considered as one of pathogenies such as diabetes and Alzheimer. Unfolded protein response (UPR) is a built-in avoiding function of ER stress and conduct reactions as promotion and pausing of folding. The activation of UPR by application of nsPEFs on cells was studied. Here, proper conditions to activate UPR were explored in experiments. Eukaryotic translation initiation factor 2 subunit α (eIF2α) is phosphorylated and translation of protein is inhibited when cells are stressed. Transportations of protein before folding to ER was accordingly inhibited and that process is UPR. In this experiment, phosphorylated eIF2α (P-eIF2α) was observed to check the induction of UPR. Electric fields pulses of 14ns in pulse width were applied on MEF and HeLa cells and expression of P-eIF2α was evaluated by western blotting. Relatively high electric fields pulses: over 100kV/cm were applied in this experiment. Thapsigargin was used for positive control. The P-eIF2α expression of high electric field pulse applied samples was significantly smaller than low electric field samples. Nevertheless, a tendency was seen that P-eIF2α expression increased with number of pulses. The detailed results will be presented on the conference.

INACTIVATION PROCESS OBSERVATION OF HELA CELLS INDUCED BY ATMOSPHERIC-PRESSURE PULSED PLASMA JET

Tomohiro Ueji[1], Ken Watanabe[1], Yudai Suzuki[1], Takao Namihira[1], Douyan Wang[1]
1. Kumamoto University

Atmospheric-pressure pulsed plasma jet has recently received significant attention due to their unique capabilities. Among the biomedical field, atmospheric-pressure plasma jet has been utilized to inactivate human cell for the development of new cancer treatment. In the literatures, it has been reported that H2O2 produced by plasma is one of the main factors for inactivation of HeLa cell viability. In this study, H2O2 concentration in cell culture medium after plasma irradiation was measured by titanyl sulfate method. In addition, to compare the effects of H2O2 on HeLa cells in the cases of plasma irradiation and direct addition to the cell culture medium, two experiments were carried out. One is the measurement of cell survival ratio of both cases. The other is the observation of the cell death process by fluorescence microscopy and three-dimensional holographic/tomographic laser microscopy. The results of this work clearly demonstrated that H2O2 generated by atmospheric-pressure pulsed plasma jet is the main factor of HeLa cell death.

OPTIMIZATION OF GFP INTRODUCTION INTO HL-60 CELLS WITH A COMBINATION OF TWO DIFFERENT RECTANGULAR PULSES

Susumu Kono[1], Nobuaki Tominaga[1]
1. National Institute of Technology, Ariake College

Electroporation is a method to introduce genes into cells. In electroporation, voltage pulses are used to create pores on cell membrane, and then genes are expected to be introduced into cells through the pores. A condition of voltage pulse is very important factor to achieve high efficiency of introduction.

In this study, two different rectangular voltage pulses were applied in a short time to HL-60 (human promyelocytic leukemia cells) to introduce a GFP (green fluorescent protein). A nano-second high voltage pulse (15 - 200 ns, 500 - 5 kV) was applied first, and a second pulse was applied after 100 ms. The condition of second pulse (i.e. pulse duration and amplitude of voltage) was selected from 10 microsecond to 1 second and from 4 V to 400 V, respectively.

The conditions of HL-60 after pulsing were roughly divided into three types: 1st - no effect (no electrical damage, no introduction), 2nd - too much damage by voltage pulses, and 3rd - good introduction, and were plotted in a graph with an electric field on the vertical axis and an input energy on the horizontal axis. The graph showed that there was an area suitable for introduction. The best conditions of two pulses were easily found by the graph.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number JP17K06332.

NON-THERMAL PLASMA TREATMENT OF ARABIDOPSIS THALIANA WITH EFFECT ON EARLY DEVELOPMENT AND THE ACCUMULATION OF HORMONES GERMINATED SEEDLINGS

Dongjie Cui[1], Zhen Jiao[1], Ruonan Ma[1]
1. Zhengzhou University

Plant hormones such as abscisic acid (ABA), gibberellins (GA), auxin (IAA), cytokinins can enhance seedling growth through regulating various physiological and biochemical processes in plants. Recently, non-thermal plasma has been reported as a new approach to stimulate seed germination and growth enhancement by producing reactive oxygen nitrogen species (RONS), which could not only directly change enzyme activity and the redox state but also alter the accumulation of auxin in seedlings. The same effection suggest that there is a similar mechanisms of plant hormones and non-thermal plasma in improve seed germination and root length. Thus, the effect of the treatment by non-thermal plasma on the accumulation of auxin in germianted Arabidopsis seedlings were investigated in this study. After treatment, the hypocotyl length of seedlings were analyzed. The alteration of redox homeostasis in seedlings was evaluated by measuring the activity of important antioxidant enzyme (catalase (CAT), peroxidase (POD) and superoxide dismutase (SOD)) as well as the level of malondialdehyde (MDA), H2O2 and proline. Moreover, HPLC method for evaluation of the accumulation of auxin in seedlings. Furthermore, the expression of key genes related to anti-oxidative metabolism were analyzed by real-time RT-PCR to reveal the molecular mechanism for regulation of the growth enhancement and accumulation of auxin in seedlings.

It was established that pre-treatment with non-thermal plasma can effectively change homeostasis in Arabidopsis seedlings by disturbing H2O2 and MDA content, meanwhile influencing the activity of antioxidant enzyme (CAT, POD and SOD), consequently alleviating the non-thermal plasma-induced oxidative stress, as well as adjusting proline level. All these results will reveal the mechanism for plasma treatment markedly affects early development and the accumulation of auxin in Arabidopsis seedlings.

IMPROVED ELECTRODE CONFIGURATION FOR THE PRODUCTION OF PLASMA ACTIVATED WATER

Yun Sik Jin[1], Chuhyun Cho[1], HaChang-seung Ha, Chaehwa Shon, Daejong Kim, Seong-Tae Han

1. Korea Electrotechnology Research Institute

Recently plasma activated water (PAW) has drawn huge attention because of its potential applications, such as disinfectant and natural fertilizer. In this paper, we report on the efficient fabrication methods of PAW by a non-thermal plasma. As a non-thermal plasma source, we used the dielectric barrier discharge (DBD). The properties of the produced PAW were analyzed in terms of pH, conductivity and NO3 ion concentration.

In order to improve production efficiency (= production volume of PAW/kWh) and uniformity of discharge plasma, the optimum configuration of electrodes in the DBD was investigated. PAW production rate of 120 L/h and production efficiency of 40 L/kWh has been achieved through the optimized configuration of electrodes in the cylindrical DBD geometry.

GAS-PHASE ACTIVE PARTICLES MEASUREMENT OF THREE TYPICAL ATMOSPHERIC PRESSURE PLASMA JETS

Lanlan Nie, Fan Wu, Jiayin Li, Xinpei Lu

The atmospheric pressure plasma jets (APPJs) have found widely application in medicine application for abundant reactive oxygen and nitrogen species (RONS). Here, the five kinds of RONS (OH, O, NO, NO2, and O3) generated by the AC and pulsed DC excited DBD jets as well as the microwave plasma jets have been studied.

For the DBD jets, the range of NO2 is from 0.39$\times$ 10^{15} cm^{-3} to 44$\times$ 10^{15} cm $^{-3}$, NO concentration would change with air percentage varying from zero to 13 $\times$ 10^{13} cm $^{-3}$, the ozone concentration changes from 0.39$\times$ 10^{15} cm $^{-3}$ to 53$\times$ 10^{15} cm $^{-3}$, the absolute density of O atom is from 0.92 $\times$ 10^{15} cm $^{-3}$ to 2.20$\times$ 10^{15} cm $^{-3}$ and the OH density changed from 5$\times$ 10^{13} cm $^{-3}$ to 17$\times$ 10^{13} cm $^{-3}$. Comparing the AC power and pulsed DC have found that the AC power generated the most NO2. However, the pulsed DC discharge exerts more impact on the NO and O3 concentration. Considering the energy efficiency, the power consumption of 10 kHz AC is about 3 times of 8 kHz pulsed DC for the same O production.

For the microwave jets, OH concentration is 0.4$\times$ 10^{14} cm $^{-3}$ to 5.54$\times$ 10^{14} cm $^{-3}$. O density can be modulated by the O2 percentage in Ar and 1% percentage is the optimal value. And the O density changes from 3.1$\times$ 10^{14} cm $^{-3}$ to 62.6$\times$ 10^{14} cm $^{-3}$. O3 is proportional to O2 percentage and 2% O2 mixture achieves maximum O3 density of 6.9$\times$ 10^{16} cm $^{-3}$. NO is from 2$\times$ 10^{13} cm $^{-3}$ to 5.4$\times$ 10^{14} cm $^{-3}$ while NO2 is in the range of 5.5$\times$ 10^{14} cm $^{-3}$ to 5$\times$ 10^{15} cm $^{-3}$. The skin humidity has positive effect on OH, O3 and NO while negative effect on the O and NO2 concentration. For the normal skin with 40% humidity, the concentrations of the long life time species like O3 and NO2 is almost 101$\sim$2 times of the other reactive species.

TIME-RESOLVED ATR-FTIR TO REVEAL INACTIVATION KINETICS OF E. COLI BY ATMOSPHERIC DBD PLASMA

Liyang Zhang[1], Hao Wang[1], Haiyun Luo[1], Xinxin Wang[1]
1. Tsinghua University

A highly effective bactericidal dielectric barrier discharge (DBD) system with pulse power supply is established to inactivate Escherichia coli (E. coli) in solution. A time-resolved, pseudo - in situ method based on attenuated total reflectance Fourier transform infrared (ATR-FTIR) is developed to determine the molecular changes occurring in E. coli during the plasma treatment under different applied voltages. Results show that the germicidal effect is strongly correlated to the reduction and structural changes of macromolecules in bacteria including lipids, proteins and DNA. Damage to bacterial cell membrane and cell wall is observed. Morphology alteration revealed by Transmission Electron Microscopy (TEM) suggests leakage of cellar inclusion, consistent with the FTIR results. This work is supported by the National Key Research and Development Program under contract 2017YFC1200404

SURFACE DISCHARGE PLASMA INHIBITED THE BIOSYNTHESIS OF STAPHYLOXANTHIN IN STAPHYLOCOCCUS AUREUS

Yupan Zhu[1], Hangbo Xu[1]
1. Plasma biomedicine

In the recent years, atmospheric pressure surface discharge plasma as newly developed plasma source, becomes an ideal approach for the ROS/RNS generation and biomedical sample processing. Surface discharge plasma has exhibited excellent antibacterial activity against aggressive human pathogen Staphylococcus aureus (S. aureus), which could cause a wide spectrum of clinically significant hospital- and community-acquired infections in human. However, the mechanism of plasma sterilization against S. aureus is still not well understood. Staphyloxanthin, a yellowish-orange carotenoid pigment, is one of the most important virulence factors of S. aureus, which could not only act as an antioxidant to protect S. aureus from oxidative stress, but also enhance bacterial survival in harsh environments. Therefore, the effect of surface discharge plasma on the staphyloxanthin biosynthesis in S. aureus was investigated to further reveal the plasma sterilization mechanisms.

In this study, we used helium as the working gas, the cell suspension of S. aureus was treated by surface discharge plasma for different time. The bacterial cell viability after plasma exposure was evaluated by counting the colony forming units (CFU) assay, and further verified by LIVE/DEAD staining. Besides, the intracellular ROS level and the membrane potential were detected by fluorescent microscopy using 2',7'-dichlorofluorescein diacetate (DCFH-DA) and carbocyanine dye 3,3'-diethyloxacarbocyanine iodide (DiOC2), respectively. Meanwhile, the integrity of the cell membrane was indicated by release of intracellular components, like DNA/RNA and protein, and further verified by SEM-EDX. Moreover, the yields of staphyloxanthin in S. aureus and the amount of singlet oxygen in solution were measured by high performance liquid chromatography (HPLC) method. In addition, the oxidation reduction potential (ORP) and pH of plasma-treated bacterial cell suspension were monitored by a multimeter pH & Redox.

PLASMA SOURCE FOR KILLING BACTERIA AND BIOFILMS ON SURFACES

Jim Browning[1], Kate Benfield[1], Tiffany Berntsen[1], Daniel Moyer[1], Spencer Goering[1], Mariah Provost[1], Zeke Kennedy[1], Amanda White[1], Adam Croteau[1], Ryan Harper[1], Ken Cornell[1], Julia Oxford[1], Don Plumlee[1]
1. Boise State University

Cold atmospheric pressure plasma (CAP) has been shown to kill or destroy bacteria and biofilm through reactive etch and sputter. Plasma can be used to debride wounds or to remove bacteria from food processing surfaces. Our parallel plate source operates at 20 kHz and 2-5 kV using Ar and O2 working gasses. The device is fabricated from a Low Temperature Co-Fired Ceramic (LTCC) with a discharge gap of 0.5 mm, discharge widths from 2 mm to 5 cm, and metal AC electrodes embedded 35 μm below the LTCC surface. A HV probe and current transformer are used to measure the operating voltage and discharge current, respectively. The source has been used to kill a variety of bacteria (Staph. aureus, E. coli, Salmonella, Listeria) residing in 2-day biofilms grown on glass, stainless steel, rubber, and plastic solid supports. Analysis of surviving Colony Forming Units (CFU) show that the device reduces cell survival by 50 % in <10 s, with a 3-log reduction in viable cells following 40-150 s exposure. The current device creates a single discharge line, so samples must be rotated during exposure. Stacked arrays containing 8 or more devices and embedded ballast resistors (100 kΩ) are being developed to allow full exposure of a large area with discharge uniformity. Finally, work is progressing on an optical imaging technique to identify stained biofilms for selective CAP treatment. These results will be presented.

----

* This research is supported by the U.S. Department of Agriculture under the NIFA grant # 2018-67018-27881, by the National Institutes of Health (NIH) under Grant # 1R15EB024930-01A1, and program grants NIH/NIGMS P20GM103408 and P20GM109095. The project is also supported by the Helmsley Charitable Trust and Boise State University College of Innovation and Design as a Vertically Integrated Projects course in Plasma Medicine.

COMPARISON OF ATMOSPHERIC PRESSURE PLASMA SOURCES FOR BIOFILM DECONTAMINATION

Martina Modic[1], Nataša Hojnik, James Walsh[2], Uros Cvelbar[1]
1. Jozef Stefan Institute
2. University of Liverpool

Biofilms are microbial communities colonising surfaces. Due to their complex architecture and organisation biofilms offer numerous advantages over unprotected planktonic cells, providing protection against immune system defence and the diffusion of antibiotics. Conventional methods to control bacteria are usually inefficient in the case of biofilms. For this reason, there is an urgent need to establish new strategies for the inactivation of established biofilms. Cold atmospheric pressure plasma is an emerging technology that is currently under intense investigation for microbial decontamination applications. In this contribution we focused on the comparison of the efficacy of two widely used atmospheric pressure air plasma configurations to inactivate mixed species biofilms; i.e. a direct plasma jet system and an in-direct plasma surface barrier discharge (SBD) system. The antimicrobial effect of the SBD is attributed to longer lived plasma generated species, such as O3 and NO. Conversely, in the direct system, biofilms are exposed to both short lived species, such as O and OH in addition to long lived species, electric fields and UV photons. Single and mixed-species biofilms composed of Escherichia coli and Staphylococcus epidermidis were used in the study. It was observed that both plasma systems, direct and non-direct, were capable of achieving a significant level of decontamination of the biofilm contamination. Critically, the small contact area of the plasma plume in the jet system was found to be a distinct disadvantage; requiring the sample to be continually moved through the discharge in order to achieve a significant level of inactivation. The SBD treatment was found to be highly effective even at short exposure times; given that many of the highly reactive neutral species produced in the plasma region are not transported to the sample surface it is proposed that the inactivation effect observed is driven by large densities of long-lived neutral species.

INVESTIGATION OF BACTERICIDAL CHARACTERISTICS IN PACKAGED CONDITION IN HIGH FREQUENCY HIGH VOLTAGE PULSE STERILIZATION OF FOOD

Naoya Minemura[1], Masashi Kuwako[1], Kazuya Hoki[1], Hiromi Sato[1], Yasushi Minamitani[1], Aika Yokoi[2], Akira Nakono[2]
1. Yamagata University
2. Ichimasa Kamaboko Co., Ltd

Many foods are sold in the market at wrapped condition for keeping freshness. It also prevents adhesion of microorganisms after packaging, prolonging expiration date, and preventing food poisoning. However, this effect can not be expected if the microorganisms adhere before packaging. Therefore, we propose to use pulsed electric field to sterilize packaged foods [1]. Pulsed electric field sterilization is unheated process that physically destroys the cell membranes. It can sterilize without adversely affecting the quality of foods [2]. We considered that by choosing adequately the frequency component with the applied pulsed electric field, it is possible to lower the impedance of the package and sterilize the included microorganisms. In this paper, we aimed to apply ultra-short pulsed electric field sterilization to packaged foods and investigated conditions for improving the sterilization effect by the high frequency electric field pulse. Especially, we investigated about the effect of packaging on sterilization rate.

[1] Takato Higuchi, Yoshie Kuramochi, Tukasa Saito,Yasushi Minamitani : ”Investigation of non-heating sterilization method of packed fresh foods by pulsed electric field”, 2012 IEEE International Power Modulator and High Voltage Conference(IPMHVC), pp.496-499, (2012)

[2] Takayuki Ohshima, Masayuki Sato :” Pulse sterilization - Safe as it is natural – “Japan Cookery Science Journal Vol.36, No.3 pp.136-141 (2003)

CONSIDERATION OF STERILIZING METHOD FOR STACKED PIECES IN PACKAGED FOODS USING PULSED PLASMA

Katsunari Itakura[1], Daisuke Tsutsuji [1], Koki Saito [1], Yasushi Minamitani[1]
1. Yamagata University

Cold plasma is attractive as a non-thermal sterilization method for a fresh food. In addition, the plasma can be generated at inside of a package by barrier discharge. Therefore it has been studied as the sterilization method for a packaged fresh food [1][2]. However, effect for between stacked pieces of the foods have not been considered well yet.

In this study, we have investigated possibility of sterilizing microorganisms between the stacked fresh foods. For sterilizing, the foods were separated by using a PET filter. In this experiment, Escherichia coli (ATCC11229) was used for the sterilizing target microorganism. Agar mediums were used for simulating the foods. Escherichia coli was set in a place where agar medium and PET filter were overlapped. The sterilization effect was measured in the case of changing the shape of the PET filter. Parameters were charging voltage and repetition rate. From the results, we showed the stacked foods were sterilized by putting the filter between the fresh foods.

[1] D. Ziuzina, et al., J. Appl. Microbiol. 114, 778-787 (2013)

[2] N. N. Misra, S. Patil, T. Moiseer, P. Bourke, J. P. Mosnier, K. M. Keener, P. J. Cullen, “In package atmospheric pressure cold plasma treatment of strawberries”, Jour. Food Eng., 125, pp.131-138 (2014)

GOLD NANOFLUID SYNTHESIS USING LASER INDUCED PLASMAS IN LIQUIDS

Magesh Rajan[1]
1. South Dakota School of Mines and Technology

Gold nanofluids hold enhanced physical, chemical, thermal and transport characteristics compared to the base fluids, which signify a great potential for a variety of applications including biomedical applications and drug delivery etc. Nanofluids are a new class of fluids engineered by dispersing nanoparticles of size less than 100 nm in base fluids.

In this work, we will present the results of producing scalable enhanced nanoparticles in water using laser induced plasmas at liquid-metal phase boundaries. The formation and dynamics of laser plasmas and shock waves at liquid-metal phase boundary was affected by the conditions of strong liquid confinement. The plasma and shock spatio-temporal dynamics and velocities varied for different laser transfer matrix and experimental conditions. The plasma electron density of the laser induced plasma at liquid-Au phase boundaries was measured using a two-wavelength laser interferometry. In order to better understand the relationship and synthesis of effective nanofluids the results of correlating the plasma characteristics with the nanoparticles size and size distribution will be presented.

The characteristics of nanoparticles produced at the liquid-Au phase boundaries using laser induced plasma has a strong relation with the laser transfer matrix. We present the effects of nanoparticle size distribution for different experimental conditions. We will also present data on nanoparticle characterization using static light scattering, dynamic light scattering, SEM, TEM, SEAD, EDS and XRD.

HIGH POWER MICROWAVE PULSE TESTING OF ELECTRONIC DEVICES USING REVERBERATING CHAMBERS

Tomas Hurtig[1], Hanna Sundberg[1], Mattias Elfsberg[1], Sten Nyholm[1], Niklas Wellander[2]

1. Division of Defence & Security, Systems and Technology FOI – Swedish Defence Research Agency

2. Division of Command and Control Systems FOI – Swedish Defence Research Agency

As of yet no definitive standard for high-power microwave (HPM) testing of electronic systems exists and there is a need to investigate different methodologies. HPM-effects testing usually require access to several tunable HPM-sources in order to cover a large frequency spectrum. Although such testing facilities do exist, such as f.ex. the SUP.R.A in Germany or the ORION in USA, they are very expensive and not always practical for effects testing of smaller systems. Using a reverberating chamber (RC) it is possible to reach very high power densities using relatively modest input power. For this reason we focus on a methodology for HPM-effects testing based on the use of an RC. Since destructive testing requires the destruction of potentially expensive systems the aim of such a methodology should be to extract as much data as possible from a small number of tests. A twostep method for rationalizing destructive testing in an RC is proposed. The first step consists of measuring the coupling of electromagnetic energy into the Device Under Test (DUT), this step is similar to measuring the absorption cross section of the DUT. This information is then used to determine at what frequency, or frequencies, destructive testing should be performed. Comparison of coupling measurements and the energy needed to destroy simple objects as a function of frequency are presented. It is shown that, at least for simple objects, it is possible to perform high power testing at a few select frequencies and then use the absorption measurements to predict the energy needed at other frequencies. Thus reducing the testing time and the number of DUT's that need to be tested.

RELIABLE COLLISIONAL RADIATIVE MODEL FOR ZN LASER PRODUCED PLASMA THROUGH ELECTRON IMPACT FINE STRUCTURE RESOLVED CROSS SECTIONS

Shivam Gupta[1], Reetesh Kumar Gangwar[2], Rajesh Srivastava[1]
1. IIT Roorkee India
2. IIT Tirupati India

Smijesh et al. [1] have recently reported spectral measurements of neutral Zn emission lines from an ultrafast laser produced plasma in the pressure range of 0.05 to 10 Torr. They have obtained the plasma parameters viz. electron temperature (Te) and electron density (ne) from their measured optical emission spectra using simple local thermodynamic equilibrium (LTE) model. Thus, it would be interesting and worth developing a detailed collisional radiative (CR) model to obtain the reliable plasma parameters from their spectra.

From laser produced zinc plasma (LPZP) emission measurements of Smijesh et al. [1], we develop a detailed CR model. In such plasma, the electron impact excitation of Zn is a dominant process and for the modeling purposes the excitation cross sections for the various fine structure transitions involved among ground state and excited states are required which we obtained using fully relativistic distorted wave (RDW) approximation theory [2]. We consider 30 fine structure levels along with the ground state of Zn and Zn+. The model incorporates various population transfer kinetic processes among fine structure levels such as electron impact excitation, ionization and radiative decay along with their reverse processes e.g. electron impact de-excitation and three body recombination [3]. The ne and Te of LPZP are evaluated and reported.

References

[1] N. Smijesh and R. Philip, J. Appl. Phys., 114, 093301, (2013).

[2] T. Das, L. Sharma, R. Srivastava and A. D. Stauffer, Phys. Rev. A, 86, 022710, (2012).

[3] S. Gupta, R. K. Gangwar and R. Srivastava, Spectrochimica Acta Part B, 149, 203, (2018).

VISIBLE SPECTROSCOPY TECHNIQUES FOR DIAGNOSING PLASMAS IN HIGH-ENERGY-DENSITY POWER-FLOW SYSTEMS

Mark D. Johnston[1], Sonal G. Patel[1], Michael E. Cuneo [1], E. Stambulchik[2], R. Doron[3], Yitzhak Maron[3]

1. Sandia National Laboratories
2. Weizmann Instititue of Science
3. Weizmann Institute of Science

Pulsed power devices rely on the ability to deliver high voltages and currents to a variety of complex loads with minimal transmission losses. The Z Machine at Sandia National Laboratories can deliver up to 26MA within ∼100 nanoseconds to multiple physics targets. This type of current flow combined with MeV potentials across millimeter A-K vacuum gaps lead to a variety of extreme electrode heating conditions, which liberate both surface and entrained gases, forming plasmas that propagate into the vacuum gap and draw current from the load. Losses of up to 20% have been observed on Z for certain load configurations. An effort is underway to investigate plasma generation in the power flow regions of the Z Machine. Visible plasma spectroscopy is employed to spatially and temporally determine plasma formation and propagation, and to measure plasma parameters such as densities and temperatures. These are some of the first and most detailed measurements of their kind in such a hostile environment. In addition to plasma parameters, measurements of magnetic and electric fields by Zeeman splitting and Stark shifts, respectively, are also conducted [1]. Measurements are made using multifiber arrays input into streak and fast-gated spectrometers. Line shape analyses are performed using detailed, time-dependent, collisional-radiative (CR) and radiation transport modeling. Recent results and future plans will be discussed.

[1] S. Biswas, M.D. Johnston, et. al., "Shielding of the Azimuthal Magnetic Field by the Anode Plasma in a Relativistic Self-Magnetic-Pinch Diode," Physics of Plasmas, 25, 113102 (2018).

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

DEVELOPMENT OF AN LIF-DIP SYSTEM TO MEASURE ELECTRIC FIELD MAGNITUDE

Christopher Durot[1], Jenny Smith[1], John Foster[1]
1. University of Michigan

Modeling gas chemistry interactions with high energy electrons can help answer many basic and applied physics questions, but the electric field generated is a key parameter for modeling that is not always well known. Measurements of electric field under relevant conditions could help to inform and validate plasma chemistry models. In support of NRL gas chemistry studies, the University of Michigan is developing a laser-induced fluorescence dip (LIF-dip) spectroscopy system. LIF-dip is a technique using two lasers to directly measure electric field magnitude. One laser populates the fluorescing state while the other depopulates it to Rydberg states. The electric field can be measured by analyzing the "dip" in the fluorescence signal as the second laser wavelength is scanned. The technique can detect low electric field magnitude because Rydberg states are highly sensitive to the Stark effect. In this contribution, we describe the buildup of this capability and present initial LIF measurements of argon metastables.

DIAGNOSTICS OF CAPACITIVE ENERGY STORAGES

Artur Gromov[1], Andrey Esafov[2], Boris Fridman[1], Alexey Ivanov[1], Stanislav Karpikov[3], Vladimir Kuzmenkov[1], Andrey Pekhotny[1], Roman Ramazanov[4], Roman Serebrov[1], Anna Shalaeva[1]

1. Efremov institute of electrophysical Apparatus
2. JSC 'Avangard"
3. JSC "Avangard"
4. Efremov institute of e;lectrophysical apparatus

Failure in capacitive energy storages result in destruction of faulty elements and other expensive components. Recovery of such failures requires long-term and expensive works to replace and to restore elements of the capacitive energy storage. Diagnostic hardware of the capacitive energy storages makes it possible to limit the consequences of such failures, to reduce the frequency of their occurrence, as well as to monitor the equipment and transmit information on functioning of the pulse current sources to the facility. The paper considers the examples and the main requirements that are imposed on the diagnostic hardware of the capacitive energy storages.

MEASUREMENT ON ELECTRICAL CONDUCTIVITY OF EXPLODING COPPER WIRE DURING CURRENT DWELL TIME

Sungbin Park[1], Kyoung-Jae Chung[1], Jong Hyeon Ryu[1], Kern Lee[1], Y. S. Hwang[1]
1. Seoul National University

We obtain the electrical conductivity of copper along the gas branch of liquid-gas coexistence curve (binodal curve) as a function of temperature and mass density using the fact that an exploding wire cools down along the gas branch of binodal curve during the current dwell time. Under the assumption of uniform wire properties during the wire cooling, electrical conductivity and mass density are easily determined by the time-dependent measurements of wire radius and current-voltage waveforms. For the determination of wire temperature, we utilize continuous spectrum measured by a time-resolved optical pyrometry system covering from 400 nm to 650 nm. This work will be helpful to investigate the thermophysical properties of materials such as electrical conductivity in warm-dense matter regime. In this paper, the details of the measurement and analysis of electrical conductivity and wire temperature of an exploding wire during the current dwell time are discussed in detail.

A FREQUENCY RESPONSE TEST DEVICE FOR NANO-SECOND COAXIAL RESISTOR DIVIDER

Jiayin Yan[1], Weidong Ding, Yanan Wang[1], Saikang Shen[1], Lanxi Li[1], Zheng Zhongbo[1], Chongjian Ge[2]
1. Xi'an Jiaotong University
2. Xi'an Jiaotong

A resistor divider with good frequency response to nano-second signals is usually used in the Calibration of VFFO sensor, serving as comparative measurement. And a coaxial cavity is usually used in the calibration process to simulate the working condition of VFFO sensor. In this paper, a coaxial resistor divider is developed making use of the end matching resistor of the coaxial cavity. The frequency characteristics of the resistor divider is determined through step-response test, in which a step signal with rise time less than 500 ps is applied.

The resistor divider is designed at the end of coaxial cavity. The end matching resistor is used as the high voltage arm. And the low voltage arm is a PCB board on which multiple low-inductance chip resistors are welded. This structure greatly reduces stray inductance of the low voltage arm and improves the high frequency performance.

To evaluate the frequency characteristics of the resistor divider, a compact square wave generator is designed. This test device is compact in structure, small in size with low stay inductance in the whole loop, resulting in a fast rising front of square wave. A wet-reed relay, as the switch of square wave generating circuit, is driven by the external magnetic field and has the advantage of fast conduction. The step response of the resistor divider has a rise time of approximately 300 ps with the overshot less than 10%.

LUMPED PARAMETER MODEL AND ANALYSIS OF WIDE BAND RESISTANCE CAPACITANCE PARALLEL VOLTAGE DIVIDER FOR OVERVOLTAGE MONITORING

Kaisheng Mei, Jiayin Yan[1], Weidong Ding[1], Saikang Shen[1], shuo Chen
1. Xi'an Jiaotong University

Transient overvoltage of power equipment is an important factor affecting the reliability and stability of power systems. Accurate, fast and safe measurement of transient overvoltage is of great significance in the study of overvoltage and insulation design.

In order to monitor overvoltage, a lumped parameter model is established for the wide-band resistance capacitance parallel voltage divider in this paper.,And the step response characteristics of the model are analyzed theoretically; the effects of ground stray capacitance, lead inductance and the value of the parallel resistance on measurement performance are simulated and analyzed.

The simulation results show that when the value of stray capacitance increases from 60pF to 140pF, the partial response time of the voltage divider rises from 11.4ns to 22.9ns. When the lead inductance changes from 2μH to 7μH, the response overshoot of the voltage divider is from 3.3% to 9.6%; when the value of the parallel resistance varies within the range of 400M to 1600M, the voltage divider has better linearity at low resistance. Therefore, under the condition of satisfying the insulation requirement, the appropriate reduction of the paralleled resistance and the ground stray parameters can improve the high frequency response characteristic of the wide band voltage divider, which provides a reference for practical engineering design.

DESIGN AND CALIBRATION OF A SOLENOID USED ON MAGNETIZED PLASMA EXPERIMENTS AND OF B-DOT PROBES FOR MEASURING THE STRONG MAGNETIC FIELDS USING COMMERCIAL ELECTRONIC COMPONENTS

Raul Melean[1], Sallee Klein[1], Heath LeFevre[1], Jackson Williams[2], Mario Manuel[3], Gregory Elijah Kemp[2], Derek Mariscal[2], Paul Campbell[1], Ryan McBride[1], Carolyn Kuranz[1]

1. University of Michigan

2. Lawrence Livermore National Laboratory

3. General Atomics

Magnetic fields play an important role in many HEDP regimes, however, scaling of astrophysical relevant phenomena to a laboratory setting requires the generation of strong magnetic fields (>5T) that can match the high energies achieved by the laser plasmas commonly used in these experiments. Besides the engineering challenges of fabricating a powerful electromagnet design, suitable for laboratory-astrophysics experiments, measurement and calibration of such powerful magnetic fields and field geometries requires the use of precise and often disposable measuring devices that can be easily adapted to any experiment. Here, we present our approach to both sides of this problem. First, we show the construction of a solenoid designed to produce an axial magnetic field with strength in the central gap in the order of 10T, this design is the current iteration of a model introduced in 2014 for use in the Titan target chamber and makes several improvements in both field strength and reliability. Second, we show a method for fabricating B-dot probes using commercially available inductor elements commonly used in circuit board construction with a study of the performance in strong (10T) pulsed magnetic fields. We show that these probes, in addition to being easy and cheap to manufacture, provide accurate and responsive measurements after being properly calibrated, providing a robust and reliable method for creating magnetic probes.

This work is funded by the Lawrence Livermore National Laboratory for the LDRD project 17-ERD-027 under subcontract B628876, and was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344 and NNSA-DP and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0002956. Support for these experiments has been provided by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under FWP SW1626 FES.

DIAGNOSIS OF MICROWAVE PLASMA LINE FOR PLASMA ENHANCED CHEMICAL VAPOR DEPOSITION

Chi Chen[1], Wenjie Fu[1], Xiaoyun Li[1], Yang Yan[1]
1. University of Electronic Science and Technology of China

In this paper, a method combined the Langmuir probe with spectral analysis was been developed to diagnose a microwave plasma line for plasma enhanced chemical vapor deposition(PECVD). The plasma line is generated in a coaxial vacuum chamber, which is 75 mm radius x 1200mm long, and driven by 2.4GHz magnetron. The microwave power is inputted into vacuum chamber through quartz tube, and transported in vacuum chamber at TEM mode. In experiments, the plasma line could be generated at pressure of about 40 Pa to 100 Pa when inputted Argon.

A Langmuir probe is placed in the chamber to measure the plasma density and electron temperature. Meanwhile, the emission spectra of the argon microwave plasma are measured through observe window by using a fiber optic spectrometer. The electromagnetic(EM) and plasma multi-physics simulation have been done to compared with experiment results.

The results of diagnosis and simulations at different microwave power 400W, 600W and 800W show that:

1. Through analyzing Langmuir probe I.V curve in the ion saturation regions by Orbital Motion Limit (OML) theory, the results show that densities of this plasma is about $10^{17}m^{-3}$, and the densities of this plasma is proportional to microwave power.

2. In electromagnetic(EM) and plasma multiphysics simulations, the results of plasma densities generated by microwave is also about $10^{17}m^{-3}$. The simulation results show good agreement with experiments.

3. The normalized spectral lines corresponding to different input microwave powers roughly overlap. This shows that there is no change of plasma mode in the experiment.

4. The Langmuir probe I.V curve in the electron regions that do not have the classical shape can be found. Thus the electron temperature should be calculated by modifying electron current which subtracted ion and the beam and fitted the Langmuir theory.

EXPLORING SIGNATURES OF INNER MITL PLASMA FORMATION USING DEDICATED EXPERIMENTAL PLATFORMS AT THE Z PULSED POWER FACILITY

George Laity[1], Carlos Aragon[1], Nichelle Bennett[1], David Bliss[1], Dan Dolan[1], Andrew Fierro[1], Matthew Gomez[1], Mark Hess[1], Brian Hutsel[1], Chris Jennings[1], Mark Johnston[1], Michael Kossow[1], Derek Lamppa[1], Clayton Myers[1], Sonal Patel[1], Andrew Porwitzky[1], Allen Robinson[1], David Rose[2], Eduardo Waisman[1], Tim Webb[1], Dale Welch[2], Michael Cuneo[1]

1. Sandia National Laboratories

2. Voss Scientific

Large pulsed power accelerators, such as the Z Pulsed Power Facility at Sandia National Laboratories, routinely deliver large current pulses to a variety of high energy density physics experiments including compact x-ray sources, inertial confinement fusion targets, materials compression experiments, and more. The variety of experimental requirements for these studies typically span a large range in impedance and/or pulse shape, resulting in an assortment of coupling efficiencies between the pulsed power driver and physics load. State-of-the-art pulsed power physics models typically focus on the current losses observed in the multi-transmission line architecture of the vacuum post-hole convolute. However, recent investments in plasma modeling have begun to explore the regimes of plasma formation and subsequent current loss that could be generated in the radial inner MITL, where the highest electric and magnetic fields are observed. New plasma models may need to be developed to extrapolate and predict the performance of next generation pulsed power accelerator concepts being studied.

In order to provide validation data to inform these new plasma models, a series of dedicated experiments were performed at the Z Pulsed Power Facility focused on exploring inner MITL current loss. The experiments were designed to vary the anode-cathode transmission line gap, while keeping the combined inner MITL / load inductance constant, effectively constraining the observed convolute voltage. Some features of the inner MITL A-K geometry were designed to both (1) allow for unique diagnostic access, and (2) to accentuate/focus the plasma loss characteristics to this inner MITL region. Various diagnostics were utilized including electrical current measurements, surface velocimetry, optical emission spectroscopy, plasma interferometry, and more. This presentation will report on the design and initial findings of the experimental platform, comparisons to ongoing physics models in development, as well as context for historical trends.

DESIGN OF ULTRA WIDE BAND LARGE CAPACITANCE LOAD PULSE SOURCE

Dongdong Huang[1], Jiangtao Li[1], Shuang He[1], Zheng Zhao[1], Longjie Li[1], Shuhan Liu[1], Jiarui Ren[1], Xinyun Zhang[1]
1. Xi'an Jiaotong University

Considerding the research of the overvoltage of the converter station, the EMTP or EMTDC software is used for digital simulation. However, whether the equipment equivalent model used in the digital simulation can accurately reflect the true dynamic characteristics of the equipment directly affects the accuracy of the simulation analysis results.

In order to establish a high-frequency model of the key equipment of the converter station, the frequency domain method is generally used to measure the high-frequency response of the equipment. But the frequency domain method is far less than the normal working voltage of the equipment due to the output power limitation of the measuring equipment, and the measuring lead The impact on the measurement results is significant. This paper attempts to establish a high-frequency response model of the key equipment of the UHV converter station by using the time domain pulse method.

According to the load characteristics of the key equipment of the converter station and the measurement frequency band (ultra-wideband), this paper develops a pulse generator for high-frequency response time-domain measurement of key equipment of UHV converter station. Resonant charging, magnetic switch, cut-off switch, etc. are used to achieve multi-stage compression of the pulse. Finally, it can be recognized to maintain the 50Hz to 1MHz ultra-wide band when accessing a large capacitive load of the order of ten nf. The test device voltage and current are all available. Measuring range (100V, 1mA or more).

DESIGN AND CALIBRATION OF MAGNETIC PICK-UP COIL (B-DOT) PROBES FOR MEASURING STRONG MAGNETIC FIELDS USING COMMERCIAL ELECTRONIC COMPONENTS

Raul Melean[1], Jackson Williams[2], LeFevre Heath[1], Sallee Klein[1], Paul Campbell[1], Mario Manuel[3], Gregory Elijah Kemp[2], Ryan McBride[1], Carolyn Kuranz[1]
1. University of Michigan
2. Lawrence Livermore National Laboratory
3. General Atomics

Magnetic fields play an important role in the behavior or many HEDP systems, however, the scaling of astrophysical relevant phenomena to a laboratory setting requires the generation of strong magnetic fields (>5 T) that can match the high flow velocities and energies achieved by the plasmas commonly created in these experiments. Accurate measurement of such powerful magnetic fields and field geometries requires the use of precise and often disposable measuring devices that can be easily adapted to any experiment. Here, we present a method for fabricating B-dot probes using commercially available inductor elements, commonly used in circuit board construction, with a study of the performance in strong (10 T) pulsed magnetic fields used in HEDP experiments. We show that these probes, in addition to being easy and cheap to manufacture, provide accurate and responsive measurements after being properly calibrated, and serve as a robust and reliable method for measuring magnetic fields.

This work is funded by the Lawrence Livermore National Laboratory for the LDRD project 17-ERD-027 under subcontract B628876, and was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344 and NNSA-DP and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0002956. Support for these experiments has been provided by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under FWP SW1626 FES.

Z LINE-VISAR: SPATIALLY RESOLVED LOAD CURRENT DIAGNOSTIC AT THE Z PULSED POWER FACILITY*

David Bliss[1], Clayton Myers[1], K Austin[2], Jacob Baker[1], R Bettencourt[2], Erlan Bliss[2], J Celeste[2], Peter Celliers[2], T Clancy[2], S Cohen[2], Michael Crosley[2], Phil Datte[2], David Erskine[2], Duane Fratanduono[2], Gene Frieders[2], J Galbraith[2], James Hammer[3], Mark Hess[1], J Jackson[2], Christopher Jennings[1], Drew Johnson[1], Michael Jones[1], D Koen[2], J Lusk[2], A Martinez[2], W Massey[2], Thomas McCarville[2], Robert McDonald[2], H McLean[2], Kumar Raman[2], S Rodriquez[2], Decker Spencer[1], P Springer[2], Gene Vergel de Dios[2], J Wong[2]

1. Sandia National Laboratories

2. Lawrence Livermore National laboratories

3. Lawrence Livermore National Laboratory

We report on the first operation of the Z-Line-VISAR (ZLV) diagnostic. The diagnostic is motivated by the desire to understand current delivery to loads at the Z Pulsed Power Facility. A team from Sandia and Lawrence Livermore National Laboratories collaborated to implement ZLV. The diagnostic measures the spatial and temporal dependence of the velocity at a surface near the load. From the measured velocity map, the distribution of magnetic drive pressure can be determined and compared with current loss models. With ZLV providing precision spatially resolved velocimetry, we strive to understand the timing and location of current losses near the load.

The primary components of the ZLV system are: 1.) two line-VISAR interferometers with streak cameras, 2.) an eight-channel Gated Optical Imager, 3.) illumination lasers, 4.) a 50-meter transport beam path to the load and 5.) an alignment system with cameras and motion control to remotely align everything.

High-quality ZLV data were obtained on the first shot attempt with radially and temporally resolved velocimetry in the range of a few km/s, over a 4mm field of view with a spatial resolution of ∼50 um and sub-nanosecond temporal resolution. Comparisons to both the point probe data and to numerical models demonstrate that the ZLV diagnostic can measure spatially and temporally evolving current density near the load with high precision. This presentation will discuss the design and fielding of the ZLV diagnostic at Z. For information on ZLV analysis, please refer to Clayton Myers'presentation.

*Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525 and Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security under Contract DE-AC52-07NA27344.

VACUUM ULTRAVIOLET SPECTROSCOPY FOR POWER FLOW STUDIES ON THE 1 MA, 100 NS MAIZE LTD

Trevor Johannes Smith[1], Stephanie Miller[1], Paul Campbell[1], Jeff Woolstrum[1], Nicholas Jordan[1], George Laity[2], Ryan McBride[1]
1. University of Michigan
2. Sandia National Laboratories

The University of Michigan is partnered with Sandia National Laboratories in order to experimentally verify power flow simulations in the anode-cathode gap on Z-machine. Due to the ionization of desorbed neutral constituents of the insulated transmission lines, the electron current flow can become unconfined to the electrode surface and travel across the anode-cathode gap. This flashover of plasma is a limiting factor for the total current to the load. We are building a vacuum ultraviolet spectrometer to characterize desorption rates of the constituents from the insulated transmission lines as a function of heating rate and electromagnetic field strength for use on the 1-MA, 100 ns MAIZE LTD at the University of Michigan. The vacuum ultraviolet region of the spectrum was chosen due to the low intensity black-body radiation in the 100-200 nm band gap, allowing for high resolution measurements. We hope to use this setup as a diagnostic for a series of experiments using scaled current and anode-cathode gap spacing in the future.

This work was supported by Sandia National Laboratories through the Campus Executives Program and the Laboratory Directed Research & Development Program, under Project 20-9240. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

DESIGN AND PERFORMANCE OF A 6 GHZ ANALOG OPTICAL LINK

Matthew Lara[1], Jon Mayes[1]
1. Applied Physical Electronics L.C.

Applied Physical Electronics, L.C. (APELC) has designed and constructed an analog optical link with a bandwidth of 50kHz to 6 GHz. The system is controlled from a LabVIEW-based remote platform that provides the user with control and monitoring of the system standby function, battery charge, temperature, and attenuation. The internal step attenuator provides 60 dB of dynamic range in 1 dB increments. Internal temperature compensation allows the system to operate without recalibrations in environments where the temperature fluctuates over a wide range in one day. The link is housed in a rugged and shielded enclosure for use in external environments with extremely high field strengths. This paper describes design considerations and performance of the system.

DESIGN AND ANALYSIS ON COIL PARAMETER OF LINEAR ROGOWSKI COIL FOR MEASUREMENT OF HIGH FREQUENCY PULSED CURRENT

Kyoko Fujiwara[1], Fumihiro Tamura[2], Akira Tokuchi[3], Kazumasa Takahashi[1], Toru Sasaki[1], Takashi Kikuchi[1]

1. Nagaoka University of Technology

2. National Institute of Technology, Nagaoka College / Nagaoka University of Technology

3. Pulsed Power Japan Laboratory Ltd. / Nagaoka University of Technology

For miniaturization and higher frequency of electronic devices, a reliable technique for measurement of the high-frequency electric signals is required. A linear Rogowski coil based on a transmission line was proposed to measure the high-frequency pulse current by Nassisi and Delle Side (2017). The previous research showed that the linear Rogowski coil observed the pulse current with a rise time of 700 ps.

In our previous study, the equivalent circuit model of the linear Rogowski coil was designed by the transmission line (distributed circuit). The numerical simulation result on the equivalent circuit model confirmed the reflection of the current signal in comparison to the lamped circuit model. Also, we investigated numerically the effect on the coil parameters such as the stray capacitances and the resistance for the skin effect, in the characteristics of the linear Rogowski coil.

In this study, we discuss the design method of linear Rogowski coil. The numerical simulation model for the linear Rogowski coil were constructed based on the previous research. The equivalent circuit model of the linear Rogowski coil consists of four types of the coil parameters, which are the inductance, the resistance with the skin effect, the stray capacitance between the coil wires, and the stray capacitance between the coil and the shielding box. These four coil parameters affect the rise time and the waveform shape of the output current of the linear Rogowski coil. By analyzing the influence of coil parameter values on the measurement characteristics, we propose the design method of linear Rogowski coil.

INVESTIGATION OF THE STRUCTURAL, THERMAL AND ELECTRICAL PROPERTIES OF PLASMA POLYMERIZED O-METHOXYANILINE THIN FILMS

Md. Mehdi Masud[1], Md. Abu Hashan Bhuiyan[2], David A. Strubbe[3]
1. Graduate Student
2. Professor of Physics
3. Assistant Professor of Physics

Plasma polymerized thin films have a wide variety of applications for surface coatings, sensors and opto-electronic devices. Plasma polymerized o-methoxyaniline (PPOMA) thin films of different thickness were synthesized at room temperature on glass substrates. The thickness of the PPOMA films deposited on glass substrates was measured by using the multiple-beam interferometric method. The surface morphology as well as roughness was studied, revealing that the PPOMA thin films were smooth, flawless and pinhole free. The structural differences between monomer (OMA) and PPOMA were identified by infrared spectroscopy and density functional theory calculation. The thermal stability analyses of PPOMA thin films were also carried out. The direct current (DC) conduction mechanisms were intensively studied through the current density-voltage (J-V) characteristics of the PPOMA thin films of different thicknesses at varying temperatures. The J-V characteristics of PPOMA thin films indicate that the conduction current obeys Ohm's law in the low voltage region while it shows non-Ohmic nature in the high voltage region. The conduction mechanism in PPOMA is found to be space charge limited conduction.

ANALYSIS OF CYGNUS ELECTRICAL SIGNALS

Hoai-Tam (Tam) Truong[1], Keith Hogge[1], Michael Misch[1], John Smith[2], Michael Garcia[3], Eugene Ormond[3], Martin Parrales[3]
1. Mission Support and Test Services, LLC
2. Los Alamos National Laboratory
3. Sandia National Laboratories

MSTS product number: DOE/NV/03624-0386

The United States initiated the Subcritical Experiment (SCE) program to support stockpile stewardship mission shortly after the 1992 moratorium on underground nuclear testing was established. Many SCE's are conducted at the Nevada National Security Site (NNSS) in Nevada. Cygnus is a high energy radiation generating device (RGD) located and operated at the NNSS and is a primary diagnostic for the SCE program.

The Cygnus Dual Beam Radiographic Facility consists of two identical radiographic sources, Cygnus 1 and Cygnus 2. From creation of the high power V-I drive to energy transport and X-ray conversion at the rod-pinch diode, the Cygnus machines utilize the following components: oil-filled Marx generator, water-filled pulse-forming line (PFL), water-filled coaxial transmission line (CTL), three-cell vacuum induction voltage adder (IVA), and rod-pinch diode. The diode pulse has the following electrical specifications: 2.25 MV, 60 kA, 60 ns. Each source has the following X-ray specifications: 1-mm diameter, 4 rad at 1 m, and 50 ns radiation pulse.

SCE's are both single-event and high-value, therefore a high level of performance in reliability and reproducibility are key issues of Cygnus. Prior to executing such a SCE, there are a formidable number of shots (e.g. each of the two Cygnus RGD's charging and discharging properly into the rod-pinch diode load) that must be executed to determine reliability and reproducibility of the Cygnus RGD's. For every shot on Cygnus, voltages and currents along the machine are recorded and analyzed. In this paper we summarize attributes of the voltage and current waveforms at different locations using distribution plots. These distribution plots are used to quantify the reliability and reproducibility for Cygnus.

• This work was done by Mission Support and Test Services LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy.

SPARSE GRID DISCONTINUOUS GALERKIN METHODS FOR THE VLASOV-MAXWELL SYSTEM

Zhanjing Tao[1], Wei Guo[2], Yingda Cheng[1]
1. Michigan State University
2. Texas Tech University

In this talk, we present sparse grid discontinuous Galerkin (DG) schemes for the Vlasov-Maxwell (VM) equations. The VM system is a fundamental kinetic model in plasma physics, and its numerical computations are quite demanding, due to its intrinsic high-dimensionality and the need to retain many properties of the physical solutions. To break the curse of dimensionality, we consider the sparse grid DG methods that were recently proposed for transport equations. Such methods are based on multiwavelets on tensorized nested grids and can significantly reduce the numbers of degrees of freedom. We formulate two versions of the schemes: sparse grid DG and adaptive sparse grid DG methods for the VM system. Their key properties and implementation details are discussed. Accuracy and robustness are demonstrated by numerical tests, with an emphasis on the comparison of the performance of the two methods, as well as with their full grid counterparts.

A KERNEL BASED HIGH ORDER "EXPLICIT" UNCONDITIONALLY STABLE CONSTRAINED TRANSPORT METHOD FOR IDEAL MAGNETOHYDRODYNAMICS

FIRAT CAKIR[1], Andrew Christlieb[1], YAN JIANG[2]
1. MICHIGAN STATE UNIVERSITY
2. University of Science and Technology of China

The ideal Magnetohydrodynamics (MHD) equations are challenging because one needs to maintain the divergence free condition, divB=0. Many numerical methods have been developed to enforce this condition. In this work, we further our work on mesh aligned constraint transport by developing a new Kernel based approach for the vector potential in 2D and 3D. The approach for solving the vector potential is based on the method of lines transpose and is A-stable, eliminating the need for diffusion limiters needed in our previous work in 3D. The method is robust and has been tested on the 2D and 3D cloud shock, blast wave and field loop problems.

CONVERGENCE RATIO EFFECTS ON ULTRA-THIN FOIL LINER IMPLOSION AND EXPLOSION STABILITY

Jeff Woolstrum[1], David Yager-Elorriaga[2], Paul Campbell[1], Stephanie Miller[1], N. M. Jordan[3], Charles Seyler[4], Ryan McBride[1]
1. University of Michigan
2. Sandia National Laboratories
3. University of Michigan, Ann Arbor, MI 48109, USA
4. Cornell University

Ultrathin foil liners, with thicknesses on the order of 400 nm, are used in university-scale Z-pinch experiments (∼1 MA) to study physics relevant to inertial confinement fusion efforts on larger-scale facilities (e.g. the MagLIF efforts on the 25 MA Z facility at Sandia National Laboratories). In university-scale experiments, these ultrathin foils have required a central support rod to maintain structural integrity prior to implosion. The radius of this support rod sets a limit to the maximum convergence ratio achievable. In recent experiments with a support rod and pre-imposed axial magnetic field, helical instability structures in the imploding foil plasma were found to persist as the plasma stagnated on the rod and subsequently expanded away from the rod [1]. We have now used 3D MHD simulation code PERSEUS (which includes Hall physics) [2] to study these experiments. The results suggest that it is the support rod which enables the helical structures to persist beyond stagnation. Furthermore, we find that as the radius of the support rod decreases (i.e., as the convergence ratio increases), the integrity and persistence of the helical modes diminishes. In the limit with no support rod, we find that the structure of the final stagnation column is governed by the structure of the central precursor plasma column. These simulation results and their comparisons to experiment will be presented.

[1] Yager-Elorriaga, D. A., Zhang, P., Steiner, A. M., Jordan, N. M., Campbell, P. C., Lau, Y. Y., & Gilgenbach, R. M. (2016). Discrete helical modes in imploding and exploding cylindrical, magnetized liners. Physics of Plasmas, 23(12), 124502. https://doi.org/10.1063/1.4969082

[2] Seyler, C. E., & Martin, M. R. (2011). Relaxation model for extended magnetohydrodynamics: Comparison to magnetohydrodynamics for dense Z-pinches. Physics of Plasmas, 18(1). https://doi.org/10.1063/1.3543799

This work is supported by NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764.

MULTI-SPECIES PLASMA-ELECTROMAGNETIC MODELS FOR PULSED POWER APPLICATIONS

Kris Beckwith[1]
1. Sandia National Laboratories

Many problems of interest in plasma modeling are subject to the 'tyranny of scales', specifically, problems that encompass physical processes that operate on timescales that are separated by many orders of magnitude. At the lowest frequency the plasma is in the regime of magnetohydrodynamics and has been the focus of extensive research in fluid plasma modeling in the past few decades. At somewhat higher frequencies, the electrons and ions can move relative to each other, behaving like two charge separated, interpenetrating fluids. This is the regime of high-frequency, non-neutral two-fluid physics and is relevant to high-density, fast MHD phenomena encountered in pulsed-power devices like dense plasma focus, Z-pinches, plasma thrusters and field-reversed configurations.

Although initial work has been done on efficiently solving fast magnetohydrodynamic phenomena, several open research problems remain. For example, implicit schemes developed for application in slow magnetohydrodynamics can not be applied directly as pulsed-power devices commonly exhibit shocks and other sharp features in the flow. To meet this need, a range of different schemes have been investigated, including physics-based preconditioning combined with Jacobian-Free Newton Krylov solvers, or alternatively, implicit-explicit schemes. Here, we describe the development of these approaches for a variety of fluid-plasma equation systems, including two-fluid electrostatics, magnetohydrodynamics and a two-fluid models coupled to full-wave Maxwell systems. We describe verification efforts for these systems and highlight the challenges of associated with high order discretizations. Finally, we describe recent efforts to develop hybrid fluid-kinetic models of multi-species plasma systems for this application area and highlight some of the challenges involved.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2019-1734 A

USING COUPLED DUST MOTION TO ANALYZE PLASMA-DUST INTERACTIONS

Lorin Matthews[1], Dustin Sanford[1], Peter Hartmann[2], Marlene Rosenberg[3], Eva Kostadinova[1], Truell Hyde[1]
1. Baylor University
2. Wigner Research Centre for Physics
3. University of California at San Diego

Electric fields within a plasma cause positive ions to have a directed flow. The trajectories of the flowing ions are deflected by negatively charged dust grains immersed in the plasma, resulting in an ion wakefield downstream from the dust particles. The positive space-charge region not only modifies the interaction between the charged grains but also contributes to the stability of ordered particle structures. In earth-based laboratory experiments, the electric field in the sheath of a plasma is used to levitate dust grains. Since the ion flow is in the direction of gravity, the weak ion wakefield force is usually masked by the force of gravity. The PK-4 experiment on board the International Space Station removes this complication allowing the underlying physics behind self-ordering of interacting complex plasma dust particles to be investigated. In particular, we are interested in the plasma conditions which result in the formation of ordered field-aligned dust chains.

Here we report results of coupled numerical models of the plasma discharge, ion wakefield and particle interactions in the PK-4 environment. An axisymmetric PIC/MCC and hybrid discharge simulation is used to model the discharge conditions in the PK-4. The local plasma parameters determined by this model are then used as boundary conditions for the N-body code DRIAD (Dynamic Reactions of Ions And Dust) which models the dynamics of the ions and the dust on their individual time scales. The ion dynamics are influenced by the time-varying electric field within the DC discharge and interactions with the charged dust grains. Charging of the grains and the modified grain-grain interactions are self-consistently derived from the ion-dust interactions. The simulation results will be compared against video data form the PK-4 experiments

Support from NASA Grant number 1571701, and NSF Grant numbers 1707215 and 174023 is gratefully acknowledged.

STATISTICS AND PROPAGATION MODELING OF ATMOSPHERIC LIGHTNING

William Brooks[1], David Barnett[1], John Mankowski[1], James Dickens[1], W. A. Harrison[2], David Hattz[2], Andreas Neuber[1]
1. Texas Tech University
2. CNS Pantex

A stochastic model of stepped leader propagation in downward negative lightning with inclusion of final jump process was developed. Results of stochastic gas diffusion are used to determine propagation. The model allows for large volumes of simulated lightning strikes to be evaluated quickly in the presence of complex geometries such as buildings. It enables Monte Carlo methods of arriving at probabilities of shielding failure for buildings less than 100 m in height. These probabilities were evaluated with emphasis on results for low peak return stroke current lighting propagation. A methodology for calculating the total likelihood of a shielding failure event is proposed. This method offers a superior prediction of striking probability in the form of a detailed assessment of striking probabilities specific to intervals of peak return stroke current. Used in combination with long-term predictions of lighting frequency, expectations of the number of strikes to a structure over its life or longer can be made.

Detailed sensitivity of shielding failure rates to building height, footprint area, inset protection, and aspect ratio is assessed for a sample rectangular building of 100 m by 50 m. Shielding failure rates were found to be insensitive to heights less than 30 m with a normalized error of less than 10 %. Building aspect ratio was found to have pronounced impact (up to a 36 % difference) in buildings of fixed footprint area. The extent to which protection may be inset from the building perimeter was evaluated and found to be substantial. Sensitivity to footprint area was found produce less than 10 % error and implies these results are scalable and may translate to other structures. Buildings not Faraday shielded from transient atmospheric phenomena are at risk of being struck by low current lightning. These risks of attachment to under-protected areas are simulated.

NUMERICAL MODEL OF ACOUSTIC WAVE GENERATED BY FREE-BURNING AC ARC

Chen Zhe[1], Li Handong, Wang Xinxin
1. Tsinghua University

Free-burning AC arc is wildly used in arc welding, arc oven and occurs in the arcing fault of the power system. The acoustic wave will be generated in the process of AC arc burning in the air due to the periodic injection and release of the electric energy. This phenomenon is used in monitoring the quality of arc welding and pressure wave protection of substation. In this article, we made a simulation of free-burning AC arc and calculate the acoustic sound pressure generated by the arc. Then we compare the characteristics of the arc acoustic wave generated by the AC arc to the DC biased AC arc. The relationship between acoustic wave and parameters of the arc such as current amplitude and frequency is also discussed.

INVESTIGATING ION ENERGY PARTITIONING IN GAS-PUFF Z-PINCHES WITH THOMSON SCATTERING

Sophia Rocco[1], Jacob Banasek[1], E. Sander Lavine[1], William Potter[1], David Hammer[1]
1. Cornell University

The conditions and dynamics of neon gas-puff z-pinch plasmas during the implosion phase are studied on the COBRA pulsed power generator (current rise time of ∼240 ns and ∼0.9 MA peak current). A 526.5 nm, 10 J, 2.2 ns Thomson scattering diagnostic laser enables probing of the plasma conditions during these implosions with both spatial and temporal resolution. Collective scattering spectral profiles are observed from which electron and ion temperatures and plasma fluid flow velocity can be obtained from the low-frequency ion acoustic spectral feature. Under some plasma conditions electron temperature and density can be obtained from the high-frequency electron plasma wave spectral feature. Scattered laser light from the same scattering volume but collected at differing angles with respect to the laser repeatedly imply ion temperatures that are inconsistent across viewing angles if the width of the ion acoustic spectral feature peaks are interpreted as solely due to ion temperature. Similarly, spectra collected along two Thomson scattering vectors, one parallel and one perpendicular to the imploding sheath and azimuthal magnetic field but from the same scattering volume, yield inconsistent ion temperatures. This indicates the presence of a source of non-thermal peak broadening that changes with scattering angle, and differs depending on orientation with respect to the imploding plasma sheath. The discrepancies may be a result of non-thermal, small scale hydromotion in the scattering volume.

IMPLOSION DYNAMICS AND MAGNETO-RAYLEIGH-TAYLOR INSTABILITY IN GAS-PUFF Z-PINCH EXPERIMENTS AT 1-MA

E. Sander Lavine[1], Sophia Rocco[1], William Potter[2], Jacob Banasek[1], Thomas Hentschel[2], Niansheng Qi[2], John Greenly[2], Dave Hammer[1], Bruce Kusse[1]
1. Cornell University
2. Cornell

COBRA, the 1 million ampere pulsed power facility at Cornell University, enables detailed investigation into magnetically driven implosions of structured cylindrical gas-puff z-pinches thanks to an extensive suite of diagnostics. Such implosions, without an applied axial magnetic field, hold promise as intense x-ray or neutron sources and, with an applied magnetic field, may be of interest for magneto-inertial fusion studies. Here we present observations from 7 cm initial diameter, triple nozzle gas-puff z-pinch experiments of shock dynamics and Magneto-Rayleigh-Taylor (MRT) instability growth leading up to the stagnation of the pinch. In particular, we investigate the effects of gas species, initial radial density profile, and axial magnetic fields on shock structure and MRT growth rates. Diagnostics include: planar laser-induced fluorescence, which provides a measure of the initial neutral gas density profile of the load; three-frame laser shearing interferometry to resolve the local electron density and shock structure; gated extreme ultraviolet (XUV) cameras which reveal the time evolution of the gas puff structure; filtered x-ray pinhole cameras to image the pinch plasma; and photoconducting diamond detectors (PCDs) to measure x-ray emission at various wavelengths. Good agreement is found when the experimental data are compared to simple numerical z-pinch model predictions.

TIME-DEPENDENT HELICAL MAGNETIC FIELD EFFECTS ON CYLINDRICAL LINER IMPLOSIONS

Paul Campbell[1], Tanner Jones[1], Jeff Woolstrum[1], Nick Jordan[1], John Greenly[2], William Potter[2], E. Sander Lavine[2], Charles Seyler[2], Bruce Kusse[2], Dave Hammer[2], Ryan McBride[1]

1. University of Michigan

2. Cornell University

Liner implosions are susceptible to instabilities like the magneto Rayleigh-Taylor (MRT) instability. There are several ways to mitigate instabilities such as MRT. One such method uses the rotating magnetic field of a dynamic screw pinch (DSP), which can be generated using a helical return-current structure. The DSP method has been examined in simulation [1] and now in experiment as well. Using Cornell's COBRA pulsed power driver, both straight and helical return current paths were tested on imploding thin-foil liners (made from 650-nm-thick aluminum foil). Each implosion was driven by a current pulse that rose from 0 to 1.1 MA in 100 ns. For the helical return-current structure tested, this current corresponds to an axial magnetic field of up to 13 T. These experiments revealed remarkable differences in the instability structures between the two cases; i.e., helical modes were observed for the DSP case and were absent for the straight (standard) z-pinch case. The results and analysis of the instability development for both cases will be presented.

1. P.F. Schmit, et al., (2016). Controlling Rayleigh-Taylor Instabilities in Magnetically Driven Solid Metal Shells by Means of a Dynamic Screw Pinch. Phys. Rev. Lett., 117, 205001.

----

* This work was supported by the National Science Foundation under Grant No. PHY-1705418 of the NSF-DOE Partnership in Basic Plasma Science and Engineering. COBRA support was provided by the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764.

HIGH VOLTAGE COAXIAL VACUUM GAP BREAKDOWN FOR PULSED POWER LINERS

Sam Cordaro[1], Simon Bott-Suzuki[2], Levon Atoyan[3], Tom Byvank[3], William Potter[3], Bruce Kusse[3], John Greenly[3]

1. University of California, San Diego

2. University of California San Diego

3. Cornell University

The dynamics of Magnetized Liner Inertial Fusion (MagLIF)1, a new and promising approach to pulsed power fusion, are presently under detailed study at Sandia National Laboratories. Alongside this, a comprehensive analysis of the influence of the specific liner design geometry in the MagLIF system on liner initiation is underway in the academic community.

Recent work utilizing high voltage pulsed systems at UC San Diego (30kV, 150ns, 0.3Hz) and Cornell University (1MA, 100ns) to analyze the vacuum breakdown stage of liner implosion. Such experimental analyses are geared towards determining how the azimuthal symmetry of coaxial gap breakdown affect plasma initiation and current distribution within the liner for the duration of the current pulse. The final aim of the experimental analysis is to assess to what scale symmetry remains important at very high (MV) voltages, and how breakdown voltage and timing are effected by gap size. An analysis of the above will utilize plasma self-emission from an optical MCP (PI-576G) for signal amplification and ns time resolution, current measurements via Pearson coil (model 6585, 1.5ns rise time), voltage measurements near the gap via voltage probe (AHVP39, 220Mhz), exact location of breakdown via two dimensional b-dot probe triangulation, as well as measuring the evolution of the magnetic field along the length of the liner via b-dot probe array. Results will be discussed along with analytical calculations of the breakdown mechanism across the vacuum gap.

CHARACTERIZATION OF SLOW CURRENT DRIVEN X-PINCH BASED X-RAY SOURCE

Sanjay Andola[1], Jigyasa Batra[1], Ashutosh Jaiswar[1], Alok Kumar Saxena[1], Trilok Chand Kaushik[1]

1. Applied Physics Division, Bhabha Atomic Research Centre, Mumbai

Studies on X-pinch plasmas produced at current rise rate of 1kA/ns and above have widely been reported [1] but hot-spot formation and X-ray emission from such sources, operated at lower current rise times is still being explored [2]. Here we report on experiments exploring X-pinch on about 0.1 kA/ns system by optimizing material and diameters of molybdenum (Mo) and tungsten (W) wires to enhance X-ray quality and yield. The scheme consisting of two or four wires driven by a capacitor bank providing a peak current of 110 kA with rise time of 1μs, has been developed and characterized. The X-ray yield and timings are recorded using Si-PIN diodes coupled with suitable X-ray filters. The source size is characterized using time integrated pinhole and slit wire cameras.

Initial experiments on X-pinch formed by $2\times$ 13μm diameter molybdenum and tungsten wires, show reproducibility within 14 and 20 ns (averaged over 5 shots) in start of X-ray burst at 378 and 410 ns respectively with yield of soft X-rays (>1.5 keV) being $\sim$40 mJ and $\sim$80 mJ respectively. To improve the X-ray yield, loads of higher linear mass have also been experimented. The results indicate a reduced yield with 4×13 μm W wires and best performance by $2\times$ 7.5 μm W wires among all configurations considered. This evidently brings out the fact that X-ray yield can be increased in lower mass of X-pinch plasma using high Z material. Details on experimental systems, characterization of X-ray source and feasibility of its utilization in point projection radiography of high density plasma will be presented.

INVESTIGATION ON THE EARLY STAGE PLASMA INSTABILITIES IN MAGNETIZED CYLINDRICAL LINERS

Guanqiong Wang[1], Xiaoguang Wang[1], Delong Xiao[1], Yang Zhang[1], Ning Ding[1], Chongyang Mao[1], Shunkai Sun[1], Chuang Xue[1], Xiaojian Shu[1]
1. Institute of applied physics and computational mathematics

With the development of pulse power technology, the fast Z-pinch shows the potential of direct drive inertial confinement fusion, such as the magnetized liner inertial fusion (MagLIF) concept. The magneto Rayleigh-Taylor (MRT) instability is one of the most negative effects on the liner integrity and the implosion quality, and the level of MRT instability growth is significantly determined by the amplification of seed perturbations. The initial seed for MRT may be provided by the early time instability development during the plasma formation, such as the electrothermal instability (ETI) and the traditional sausage instability.

By using a two-dimensional MHD code (ZUES2D) we firstly study the early plasma formation in the initially solid aluminum liners driven with a 6.7 MA, 58 ns rise time (10%–90%) current pulse on the PTS facility. It is found that electrothermal instabilities characterized by the temperature perturbations immediately grow once the current pulse starts, and the stratified structures produced by ETIs can be seen obviously in both density and temperature contours. By analyzing instability spectrum, the dominant wavelengths of the perturbations are 8.33 μm–20.0 μm, which agree qualitatively with the theoretical predictions. It is also interesting to show that ETI provides a significant seed to the subsequent MRT instability.

Then, we also theoretically investigate the effect of external axial magnetic field on the early plasma instabilities. The dispersion relation is based on the resistive MHD model, where both the uniform axial magnetic field and the electrothermal effect are taken into account. For small wavelength, the instabilities are caused primarily by the electrothermal mechanism. For large wavelength, the axial magnetic field effect becomes dominant, especially the modes with wavelength larger than the gradient scale length of magnetic field tend to destabilize more easily.

NUMERICAL STUDY ON MAGNETO-RAYLEIGH-TAYLOR INSTABILITIES FOR THIN LINER IMPLOSIONS ON THE PTS FACILITY

Xiao-guang Wang[1], Shun-kai Sun, De-long Xiao, Guan-qiong Wang, Yang Zhang, Shao-tong Zhou, Xiao-dong Ren, Qiang Xu, xian-bin Huang, Ning Ding, Xiaojian Shu

1. Institute of Applied Physics and Computational Mathematics, Beijing 100088, China

The thin aluminum liners with an aspect ratio R/Dr $>>$ 1 have been imploded on the primary test stand (PTS) facility, where R is the outer radius of the liner and Dr is the thickness. The x-ray self-emission images present azimuthally correlated perturbations in the liner implosions. The experiments show that at -10 ns before the stagnation, the wavelengths of perturbation are about 0.93 mm and 1.67 mm for the small-radius and large-radius liners, respectively. We have utilized the resistive magnetohydrodynamic code PLUTO to study the development of magneto-Rayleigh–Taylor (MRT) instabilities under the experimental conditions. The calculated perturbation amplitudes are consistent with the experimental observation very well. We have found that both mode coupling and long implosion distance are responsible for the more developed instabilities in the large-radius liner implosions.

THE INTERACTION OF A HIGH-POWER SUB-NANOSECOND MICROWAVE PULSE WITH PRELIMINARILY FORMED PLASMA IN A WAVEGUIDE

Yang Cao[1], John Leopold[2], Y. P. Bliokh[3], Ya.E. Krasik[4], Vladislav Rostov[5]
1. Technion-Israel Institute of Technology
2. Technion
3. Physics Department, Technion, Israel Institute of Technology
4. 1 Physics Department, Technion, Israel Institute of Technology
5. Institute of High Current Electronocs

We present the results of analytical modeling and numerical particle-in-cell simulations showing that the propagation of a high-power sub-nanosecond microwave pulse through a plasma-filled cylindrical waveguide[1] should lead to the formation of a wakefield with significant periodic plasma density modulation. The latter can be controlled by varying the waveguide radius, the plasma density, and the microwave power. To study this phenomenon, two backward wave oscillators (BWO), operating in the super-radiant mode at frequencies of 9.6 GHz[2] and 28.6 GHz[3], were designed and tested. These BWOs were driven by an electron beam ($\sim$280 keV, $\sim$1.5 kA, $\sim$5 ns) generated in a magnetically insulated foilless diode and propagating through a slow-wave-structure guided by an axial magnetic field. Microwave pulses of $\sim$0.4 ns width, up to $\sim$500 MW peak power at 9.6 GHz and up to $\sim$1.2 GW at 28.6 GHz were obtained. A cylindrical wire-array waveguide is placed at the exit of the BWO and filled with plasma produced by an array of flashboards. The high power microwave pulses traverse this plasma interacting with it in a non-linear parameter range never studied before. First experimental results at 9.6 GHz will be presented.

* This work was supported in part by the PAZY under Grant No. 2020960 and in part by the research program of the RAS #10.

[1] Phys of Plasmas, 24, 063112 (2017).

[2] J. Appl. Phys. 121, 033301 (2017).

[3] Phys. Plasmas 26, 023102 (2019).

THE EXPERIMENTAL STUDY OF TIME RESOLVED INDUCTIVELY COUPLED PLASMA FOR FAST CONTROL OF HIGH POWER MILLIMETER-WAVE

Mun Seok Choe[1], Ashwini Sawant[1], Ingeun Lee[1], Wonjin Choi[1], Hong Eun Choi[1], Taegyu Han[1], EunMi Choi[1]
1. Ulsan National Institute of Science and Technology (UNIST)

The suppression of neo-classical tearing modes (NTMs) which is one of plasma instability is a critical issue to prevent the disruption of H-mode plasma in fusion plasma tokamak. To operate steady-state drive, we should understand not only physical phenomena of tearing modes but also optimized conditions of electron cyclotron current drive (ECCD) to suppress time resolved NTMs in range of a few kHz repetition. We propose an external switching system which can be settled in existing transmission lines and gyrotrons. The idea of switching system simply comes from interactions between millimeter-wave and glow discharged cold plasma. The cut-off and propagation of millimeter-wave can be determined by the plasma switching. A helical type inductively coupled plasma chamber is designed for high transmission of Gaussian beam (linear polarized E-field having Gaussian profiled) and generation of high-density bulked plasma. For proof-of-concept study, we conducted cold test using vector network analyzer (low power millimeter-wave, $<$ 1mW, continuous waves) and successfully demonstrated proto-type test of millimeter-wave switching having 2 kHz repetition. For hot test, a gyrotron at UNIST (95 GHz, few kW of power) is used as a high-power millimeter-wave source. Although the gyrotron pulse length (20 us) is not enough to measure switching results (plasma switching time is 200 us), we observed wave absorption in plasma and increase of plasma density simultaneously. This result will help to understand mechanism of millimeter wave heating in inductively coupled plasma. Furthermore, this study will also contribute to understand plasma instabilities in fusion plasma.

THEORETICAL INVESTIGATION OF A NOVEL MICROWAVE DRIVEN ICP PLASMA JET

Michael Klute[1], Horia-Eugen Porteanu[2], Ilija Stefanovic[3], Nikita Bibinov[1], Wolfgang Heinrich[4], Peter Awakowicz[3], Ralf Peter Brinkmann[5]

1. Ruhr University

2. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenzte

3. Ruhr-Universität Bochum, Faculty of Electrical Engineering and Information Technology, Institute for Electrical Engineering and Plasma Technology, Germany

4. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany

5. Ruhr University Bochum

Microwave and radio frequency driven plasmas-jets play an important role in many technical applications. They are usually operated in a capacitive mode known as E-mode. This mode, however, couples considerable power to ions which limits the plasma density and the efficiency and gives rise to negative side effects such as erosion. The inductive coupling, known as H-mode, eliminates these disadvantages and is attractive for large scale plasmas. A novel small scale, microwave driven plasma-jet has been proposed by *Porteanu et al.*[1]. It is operated as an inductive discharge and that has been recently characterized using optical emission spectroscopy (OES) by *Stefanovic et al.*[2]. In this work the proposed plasma-jet is examined theoretically. A global model of the new device is presented based on the volume-integrated balances of particle number and electron density, and a series representation of the electromagnetic field in the resonator. An infinite number of modes can be found ordered by the azimuthal wave number m. The mode m=0 can be identified with the inductive mode and will be called H-mode, the mode m=1 is the capacitive mode and will be called E-mode. By equating the electromagnetic power that is absorbed by the plasma with the loss power, stable operating points and hysteresis effects can be investigated. In a second step the spatially resolved electromagnetic field strength will be considered. All results will be compared to the results of the OES measurements and imagines obtained from CCD-imaging.

[1]Porteanu et al.*Plasma Sources Sci.Technol.***22**, 035016 (2013)

[2] Stefanovic et al.*Plasma Sources Sci.Technol.***27**, 12LT01 (2018)

[3] Porteanu et al.*Plasma Sources Sci.Technol.* accepted (2019)

INDUCTIVELY COUPLED PLASMA AT ATMOSPHERIC PRESSURE, A CHALLENGE FOR MINIATURE DEVICES

Horia-Eugen Porteanu[1], Ilija Stefanovic[2], Bibinov Nikita[2], Michael Klute[3], Peter Awakowicz[2], Ralf-Peter Brinkmann[3], Wolfgang Heinrich[4]

1. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenzte

2. Ruhr-Universität Bochum, Faculty of Electrical Engineering and Information Technology, Institute for Electrical Engineering and Plasma Technology, Germany

3. Ruhr-Universität Bochum, Faculty of Electrical Engineering and Information Technology, Institute for Theoretical Electrical Engineering, Germany

4. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany

Inductively coupled plasma (ICP) sources are preferred to the capacitive (CCP) sources because of their higher electron density and plasma purity. The use of microwaves for the plasma excitation allows not only to obtain a dense plasma with a low gas temperature but also to generate such a plasma at higher pressures. We present a miniaturized device capable of working up to atmospheric pressure. The plasma is generated in a quartz tube with an outer diameter of 7 – 12 mm. The microwave plasma interaction has been studied using an original method, the “Hot-S-Parameter” spectroscopy, presented in detail in [1]. The variation of the resonance frequency and generally of the reflected power as a function of frequency provides information about the type of coupling and about the plasma conductivity, i.e., electron density and scattering frequency. The microwave data are correlated with photographs of the plasma shape and with results of the optical emission spectroscopy (OES) of nitrogen [2]. At 1000 Pa, and 80 W at 2.45 GHz, a nitrogen plasma reaches an electron density of 3 10^{19} m^{-3} and a gas temperature of 1600 K [2]. The miniaturized source includes an impedance matching circuit. Based on microwave and optical measurements we estimate the power absorbed by the plasma at 1000 Pa to be about 60 % of the incident power. This efficiency is much higher than in standard reactors driven at 13.56 MHz. The source has been successfully tested with argon at atmospheric pressure. This fact opens new perspectives for the use as an array of remote plasma sources for thin-film depositions.

[1] Porteanu H-E, et al. “ Correlated Mode Analysis of a Microwave Driven ICP Source“, 2019 PSST. https://doi.org/10.1088/1361-6595/ab06a7.

[2] Stefanović I, et al. “Optical Characterization of a Novel Miniature Microwave ICP Plasma Source using Nitrogen”, 2018 PSST, https://doi.org/10.1088/1361-6595/aaefcc

VARIABLE-FREQUENCY CAPACITIVELY COUPLED PLASMA AS A TUNABLE RF ELEMENT

Andrei Khomenko[1], Sergey Macheret[1]
1. Purdue University

Plasmas are attractive for next-generation reconfigurable RF systems because plasmas can be turned on/off, have their properties varied in a wide range, and handle much higher power than semiconductors can. Tunable capacitors and inductors are key elements of any reconfigurable system. In a capacitively coupled discharge, the impedance of both the sheaths and the plasma can be controlled by the excitation RF frequency and power, resulting in tunable impedance for a weak "probing" RF signal. In this work we studied two different plasma devices. The first one is a benchtop device with 5 cm diameter parallel-plate electrodes separated by 2 cm and operating in air at 1 Torr with an RF amplifier operating at a constant voltage in a very wide range of frequencies. The impedance characteristics and both the sheath and plasma parameters were inferred from the current and voltage measurements supplemented with optical imaging and microwave diagnostics. At very high excitation or probing RF frequencies, the sheath impedance becomes negligible, and due to negative permittivity of the plasma, the overall impedance becomes inductive. The results are in good agreement with a simple theory. The second plasma device is much smaller, about 0.5 cm, and uses a small gas discharge tube with 0.6 mm interelectrode spacing as a plasma cell. Its resistance and reactance were measured for different excitation and probing frequencies and different applied power, and wide tunability from capacitive to inductive behavior was demonstrated

MODELING A MICROWAVE PLASMA ENHANCED CHEMICAL VAPOR DEPOSITION SYSTEM USING FINITE ELEMENT METHOD

Yilang Jiang[1], Kaviya Aranganadin[1], Ming-Chieh Lin[1], Jing-Shyang Yen[2], Hua-Yi Hsu[2]
1. Hanyang University
2. National Taipei University of Technology

Microwave Plasma Enhanced Chemical Vapor Deposition (MPECVD) has a great potential to be used for developing material thin films with excellent electrical properties, good substrate adhesion, and excellent step coverage. Due to these advantages, MPECVD films have been widely used in very large-scale integrated circuits, optoelectronic devices, MEMS and other applications. In the MPECVD system, the plasma consisting of ionized gas species, i.e., ions and electrons, is generated and sustained by applying microwave energy. Recently, the MPECVD has gained popularity in modern fabrication of novel materials and has become one of the promising candidates for synthesizing CNTs, graphene, and diamond films at low temperature and large scale growth. In this work, the design and modeling of an MPECVD chamber operated at 2.45 GHz of frequency have been conducted using a finite element method (FEM) simulation. The design consists of a coaxial waveguide and a cylindrical chamber at the center connected with four slots quarterly distributed around. The placement of slots affects the resonant modes in the chamber. The placements of slots in the middle and the bottom positions of the plasma chamber would mainly produce the TE111 and TM011 modes inside the plasma chamber at 2.45GHz, respectively. The detailed analysis in the operating characteristics of the MPECVD system with different gas pressure and input microwave power using FEM simulations will be presented and discussed.

1. H. Song, J. M. Hong, K. H. Lee, and J. J. Choi, "Stable microwave coaxial cavity plasma system at atmospheric pressure", Rev. Sci. Instr. 79, 054702 (2008).

----

* This work was supported by the research fund of Hanyang University (HY-201400000002393), the National Research Foundation of Korea, and the National Taipei University of Technology and MASTEK, Inc. in Taiwan.

TOWARD A WIDEBAND AND HIGH-ISOLATION POWER LIMITER

Abbas Semnani[1], Zach Vander Missen[1], Dimitrios Peroulis[1]
1. Purdue University

Power limiters are critical elements in radars and other systems that may be subject to high input power. High-performing limiters are important since they are at the front end of the signal chain; put simply the ultimate goal of a limiter is to provide sufficient isolation across a wide bandwidth with the smallest possible loss, high linearity, short response time, and high power handling.

Plasma presents an interesting platform to develop such limiters, especially for high-power applications. Plasma forms through the gas breakdown which means that in the pre-breakdown state, it is not present, leading to high linearity advantages. Once breakdown occurs, the gas conductivity increases significantly and this is leverageable to a power limiting effect. Additionally, plasma tolerates high power and temperature, and is therefore able to extend the operational range of a limiter.

In this talk, a novel circuit design for a wideband high-power limiter is discussed. A two-stage topology is utilized by cascading a coplanar-waveguide plasma limiter as the quick-responder primary protection and a commercial RF MEMS switch to complement the required isolation. In our preliminary measurements, maximum insertion loss of 0.5 dB, return loss better than 14 dB, power handling more than 50 W, and limiting isolation greater than 24 dB were achieved over the 1–3 GHz frequency bandwidth. Relaxation and response times of the proposed limiter are on the order of microseconds.

NANOSECOND RISE-TIME, LASER DIODE DRIVEN, WIDE BANDGAP PHOTOCONDUCTIVE SWITCHES AS FAST, HIGH-VOLTAGE MOSFET REPLACEMENTS FOR BIOELECTRICS AND ACCELERATOR APPLICATIONS*,†

Stephen Sampayan[1], Kristin Sampayan[1]
1. Opcondys, Inc.

High-voltage MOSFETs are fundamentally limited in rise-time and PRF because of the slow transit-time of carriers through the drift region that supports the high-voltage. Large numbers of low voltage devices are used to overcome this limitation, but systems are complex, rise-time limited, and can exhibit electrical instability caused by fast transients. In contrast, photoconductive switches have been developed as nanosecond rise-time, high-voltage, high peak current devices for pulsed power applications. Triggering is usually accomplished with single-shot/low duty-cycle, high peak power Nd:YAG lasers. However, recently introduced, nanosecond rise-time, ≈100-W, integrated laser diode modules and methods to increase optical efficiency make a fast, integrated, photoconductive MOSFET-like switch module possible. By using wide bandgap materials, a linear transconductance-like control property is exhibited. As an initial proof-of-concept for electric grid applications, we present results of a 50% duty-cycle, 20-kV, vertically integrated device that demonstrated a PRF ten-times faster than an equivalent MOSFET; fiber isolation enables cascaded/floating device applications. Control over a large range was observed by varying the laser intensity. Bulk illumination and conduction eliminated carrier transit-time and resulted in rise-times limited only by the laser. We also report on progress driving the switch with a ≈2-ns rise-time laser diode, but at lower duty-cycle for ns-PEF/bioelectrics (e.g., sanitization, therapeutics, etc.) and accelerator applications. Delivered pulse-width was easily varied with the TTL-level input pulse duration to the fast laser driver. Finally, we detail the physics of the carrier dynamics explored with a 70-fs rise-time super-continuum laser: carriers are excited in sub-picosecond times and recombination is controlled by trap density introduced into the mid-bandgap. As a result, fidelity of the output pulse can be optimized by trading laser power against carrier recombination time.

*Supported in part by the US Department of Energy, ARPA-E CIRCUITS under contract number DE-AR-0000907.

†US Patent 8,563,930, 9,142,339, 9,748,859; international patents pending.

LASER TRIGGERED SOLID STATE PULSE CHARGING SYSTEM UTILIZING GAAS PCSS TECHNOLOGY

Nathan Zameroski[1], Jonathan Parson[1], John Krile[1], Ricky Rodriquez[1], Josh Grimes[1], Charlie Anderson[1], Andreas Neuber[2], Jim Dickens[2], Jeff Pierce[3]
1. Scientific Applications and Research Associates
2. Texas Tech University
3. Systems Optical

The near simultaneous laser triggering of hundreds to thousands of Photoconductive Semiconductor Switches (PCSSs) is an enabling technology being pursued by both the Department of Energy (DOE) and Department of Defense (DOD) for pulse power (PP) and directed energy (DE) systems. Applications include the development of EMP or HPM phased array sources and large-scale pulsed power systems requiring high energy, low jitter, synchronized trigger pulses for many thousands of spark gaps. Laser triggering of commercially available Gallium Arsenide (GaAs) PCSS provides: electrical isolation, low jitter, fast rise times, long switch lifetime, system scalability and compactness, potentially low cost per trigger channel, and the ability to precisely time the delivery of stored energy to drive various loads.

The development of a compact, low jitter ($\leq$300ps), laser triggered pulse charged (PC) system based on GaAs PCSS technology with the potential to provide several hundred synchronized output pulses is reported on. The flashlamp pumped Q-switched laser driver can operate from single shot to a few Hz. The laser trigger system utilizes optical fiber fanouts to synchronize the delivery of 0.3 mJ of optical radiation centered at 840 nm in 25 ns to nine GaAs PCSS. These GaAs PCSS are connected to 1 nF capacitors pulse charged to a differential voltage of 100 kV in $\leq$ 10 μs. The laser triggered & GaAs PC system is envisioned to be a direct replacement for high voltage (HV) electrical trigger pulse generators utilized in spark gap switched Marx generators, capacitor banks, and LTDs. The system under development may provide up to one hundred, synchronized, several Joule, 100 kV open circuit trigger signals and yield an order of magnitude improvement in jitter and risetimes in comparison to existing HV electrical trigger pulse generators.

PERFORMANCE COMPARISON OF COMMERCIAL GAN HEMT UNDER REPETITIVE OVERCURRENT OPERATIONS

Jose Rodriguez[1], Matthew Kim[1], Stephen Bayne[1], Heather O'Brien[2], Aderinto Ogunniyi[2]
1. Texas Tech University
2. Army Research Laboratory

Gallium nitride (GaN) high-electron-mobility transistors (HEMT) are of great interest for pulsed power applications due to the proven capabilities of wide band gap semiconductors, such as silicon carbide (SiC) transistors. With further advances in GaN power semiconductors, there's an interest in the evaluation of their performance under repetitive overcurrent operation in power electronics applications beyond the manufacturer's prescribed operating parameters. The 650V/30A GS66508T-E02-MR from GaN System and the 600V/31A IGT60R070D1ATMA1 from Infineon were evaluated in a pulsed ring down testbed at 475 V with a peak current above 80 A over a switching frequency range from 138 to 277 Hz. The testbed employed a temperature chamber to maintain the case temperature of the device at 25 °C during testing. The devices'electrical characteristics, such as transconductance, forward I-V curve and breakdown voltage were measured throughout testing and have not shown significant degradation. The collected data from these measurements allowed a comparison of the devices'performance and shows their ability to handle transient overcurrent conditions commonly found in power semiconductor device applications.

Keywords – gallium nitride; GaN; HEMT; power electronics; pulsed power; reliability testing; performance evaluation

ANALYSIS OF A NEW 15-KV SIC N-GTO UNDER PULSED POWER APPLICATIONS

Matthew Kim[1], Tsz Tsoi[1], Jonathan Forbes[1], Stephen Bayne[1], Heather O'Brien[2], Aderinto Ogunniyi[2], Sei-Hyung Ryu[3]

1. Texas Tech University

2. Army Research Laboratory

3. Wolfspeed

SiC (silicon carbide) GTOs (gate turn-off) are a substantiated choice for increased power density and thermal dissipating capabilities in pulsed power and power electronics applications due to their wide-bandgap characteristics. For the transition of Si (silicon) power devices to SiC, it is imperative to evaluate the long-term reliability of newly-developed SiC devices. The testbed consists of a PFN (pulse forming network) that subjects the device under test, a 1.0 cm^2 15 kV SiC n type (n-doped epi layer) GTO, up to a current level up to 800 A with a pulse width of 100 us. An IR (inferred radiation) camera integrated to the PFN monitored the thermal characteristics of the DUT during testing. The electrical characteristics of the device, such as forward I-V curve, breakdown voltage, forward and reverse gate conduction, and forward and reverse conduction, were taken between testing. A SEM (scanning electron microscope) was used to find physical evidence of degradation on the device. the DUT was subjected to 35,000 very high-current density pulses, at which point it exhibited a decrease in blocking capability. This paper will include analysis of the pulsed safe operating area and mode of failure outside of that operating area.

Keywords – SiC; GTO; wide-bandgap; PFN; pulsed power; reliability testing; power electronics

IMPROVING FAST SIC MOSFET SWITCHING USING AN INDUCTIVE GATE DRIVE APPROACH

Micah LaPointe[1], Landon Collier[1], James Dickens[1], John Mankowski[1], Andreas Neuber[1]
1. Texas Tech University

The use of solid-state semiconductor switches in compact pulsed power systems requires high-voltage, high-current, and fast switching capabilities. The recent advancements in wide bandgap semiconductor switches have allowed for development of SiC MOSFETs with increased hold-off voltage (from 1's to 10's of kV) and low on-state resistance (10's of mΩ) that are suitable for many of these pulsed power applications; however, robust gate driving techniques are required to achieve fast risetimes on the order of 10-20 ns necessary for proper operation. Due to the high dI/dt, and subsequent inductive kickback, experienced by the switching elements under pulsed conditions, parasitic inductance drastically affects the performance of commercially available totem-pole gate drivers. In addition, traditionally packaged MOSFETs exhibit further degradation of switching characteristics due to the introduction of additional parasitics.

Previously, an inductive gate drive approach, utilizing a high-voltage inductive kick to rapidly charge the gate capacitance, was able to achieve high turn-on dI/dt up to 25 kA/μs and risetimes less than 20 ns. Due to the high turn-off dI/dt associated with the MOSFET source inductance, long fall times greater than 50 ns resulted. This effect was exacerbated for the traditional TO-247 package. This paper details further improvements to the inductive gate driving topology, including expansion of the gate driving methodology to improve the turn-off time of the switching element, utilizing a similar negative inductive kickback to rapidly discharge the gate capacitance. In more detail, the effects of inductor value, peak inductor current, and MOSFET parasitics are examined. Verification and optimization of the gate driving circuitry is performed using SPICE simulations

SWITCHING CHARACTERIZATION OF MULTI-GAP AND MULTI-APERTURE HIGH POWER PSEUDOSPARK SWITCH (PSS)

Udit Narayan Pal[1], Mohit Kumar Verma[2], B. L. Meena[3], Ram Prakash Lamba[3], Klaus Frank[4]

1. CSIR-Central Electronics Engineering Research Institute, Pilani, India

2. Electrical Engineering Department, National Institute of Technology (NIT), Calicut-673601, India

3. Microwave Devices Area, CSIR- Central Electronics Engineering Research Institute (CEERI), Pilani, Rajasthan-333031, India

4. Department of Physics, Friedrich-Alexander-University (FAU), Erlangen, D-91058, Germany

There is still an ongoing interest and need for high power (30-70kV/5-10kA) gas-filled switches in high energy accelerator facilities and pulsed power applications. Principally low-pressure, one-gap cold cathode pseudospark switches (PSS) have demonstrated to be an alternative to thyratrons for hold-off voltages up to 30kV. In present and future high energy accelerator facilities, the design of power modulators mainly depends on the availability of fast, reliable, durable, and commercially available high voltage switches. Multi-gap thyratrons momentarily are unique for that. Former basic studies have shown that in similar way two- or three-gap PSS are a promising alternative. In this paper the design, development and switching characterization of a coaxial three-gap PSS prototype are presented. A high dielectric ferroelectric trigger unit is incorporated in the cathode region for breakdown initiation in the first gap and subsequent synchronous breakdown of the next gaps. To guarantee long lifetime with high currents, high hold-off voltages and optimized plasma coupling, kidney shaped ring slot electrodes with baffles are used. Each of the gaps is designed for voltage hold-off up to 30kV with a total voltage hold-off for the three-gap PSS of approximately 70kV. Studies of switching behavior have been carried out at different operating conditions, such as varying gas type (hydrogen/helium/argon/nitrogen) and gas pressure (10-80Pa), hold-off voltages (5-60kV), use of various trigger configurations, and change of circuit parameters. The short-time scale analysis of the voltage waveform manifest steps in the voltage fall at low gas pressure and low hold-off voltages, which indicate a time delay in plasma coupling by the drift region. This effect was not observed at higher voltages ($\geq$15kV) and gas pressure ($\geq$ 20Pa). The overall performance of the three-gap prototype PSS has been analyzed in terms of hold-off voltage, fall time, current rise time, peak current, delay time, jitter, and related parameters.

DEPENDENCE OF TRIGGER PULSE PARAMETERS ON CURRENT QUENCHING IN PSEUDOSPARK DISCHARGE

Jiaqi Yan[1], Saikang Shen[1], Weidong Ding[1], Lanxi Li[1]
1. Xi'an Jiaotong University

Pseudospark switch is a special kind of low pressure switch with the advantages of high repetition rate, large dynamic operation range, high current conduction capacity and low electrode erosion rate. However, quenching phenomena in the pseudospark discharge cause serious waveform distortion on the load and excessive commutation loss in the switch. Previous studies have shown that the probability of quenching can be effectively reduced by adjusting the gas species, optimizing electrode materials and increasing trigger energy. In this paper, nanosecond pulse circuit based on avalanche transistor and submicrosecond pulse circuit based on magnetic compression are used as trigger generator. The effects of rising time, width, injected charge and polarity of trigger pulse on quenching of pseudospark discharge are studied. A charge injection trigger unit based on BaTiO3 with high ϵ is installed in the hollow cathode cavity. The results show that under the same conditions, the conduction delay, jitter and quenching probability of the pseudospark switch decrease with the increase of the injected charge and the rising rate of front edge; besides, the negative polarity shows better performance on suppressing current quenching. The mechanisms are discussed and it is believed that the parameters of trigger discharge affect the hollow cathode phase of pseudospark discharge. This exploration provide a convenient method to solve the quenching problem of pseudospark switches.

GTO LIKE THYRISTORS TRIGGERED IN IMPACT-IONIZATION WAVE MODE

Thomas Kramer[1], Sergei Lyubutin[2], Viliam Senaj[1], Boris Slovikovsky[2], Anton Gusev[2], Sergei Rukin[2], Vitaly Patrakov[2], Michael Barnes[1]
1. CERN
2. Institute of Electrophysics UB RAS

Commercially available, low dI/dt (0.4 kA/μs), silicon thyristors have previously been investigated as fast, high-power, switches. Fast switching is achieved by applying a steeply rising (dV/dt $>$ 1 kV/ns) overvoltage pulse across the thyristor's main electrodes: fast turn-on occurs when the voltage amplitude is twice the static breakdown voltage. Under such conditions, the thyristor goes into the conductive state within $\sim$200 ps. Current rise rate up to 130 kA/μs, limited by the discharge circuit, was obtained for commercial thyristors with impact-ionization triggering mode. GTO like thyristors, comprising of highly interdigitated gate and cathode structure, similarly to a GTO, are used at CERN for an emergency beam dump system. These devices, the 5STH-20H450002 (4.5 kV, 18 kA/μs), were developed by ABB semiconductors. Nevertheless, a new principle of operation such as impact-ionization triggering can enhance dI/dt capability and reduce turn-on delay time. This work reported in this paper is aimed at studying the operation of the GTO like thyristors triggered in impact-ionization wave mode. A SOS generator providing a dV/dt of several kV/ns was used as a source of triggering pulses. Under such triggering conditions a thyristor switching time of approximately 200-300 ps was observed. Maximum discharge parameters were obtained for two series connected thyristors at charging voltage of 10 kV, and capacitor stored energy of $\sim$300 J: peak current of 43 kA, dI/dt of 115 kA/μs, FWHM of 1.5 μs. The switching efficiency was 92%.

THREE DECADES OF PULSED POWER DEVELOPMENT FOR ROCK FRACTURING AND ASSOCIATED APPLICATIONS

Steven Pronko[1], William Moeny[1]
1. Tetra Corporation

For over thirty years, researchers have explored the use of Pulsed Power techniques to fracture hard rock, thus providing an alternative to chemical explosives and lesser efficient mechanical methods. Virtues of Pulsed Power driven rock fracturing lead to higher rate drilling and continuous mining concepts with fewer hazards than those associated with chemical explosives. Early work was centered about harnessing the electro-hydraulic effect whereby an energetic electrical spark in a fluid produces an intense shockwave that in turn, affects the surrounding material. It was recognized early on that the conversion of electrical energy into a shockwave via the electro-hydraulic effect was a highly inefficient process and the required pulsed power systems were very large and of limited life. Continued research led to various methods of coupling the pulsed electrical energy to the rock to improve electrical efficiency and fracturing yield. These methods included arc-driven propellants and direct arc formation inside the rock. Both approaches exploit the rock structural defects and tensile weakness as opposed to overcoming the high compressive strength, therefore requiring far less electrical energy input. In parallel with this applied research, advancements in key technologies relevant to Pulsed Power components were also occurring; namely in the areas of high power switching and energy storage technologies. Solid-State switching technology like Silicon Carbide and advanced materials for high energy-density capacitors have enabled the development of Pulsed Power systems that can meet the volume and temperature requirements while still being economically viable. Tetra Corporation has become the world leader in advancing the state of the art in Pulsed Power rock fracturing technology with over 60 patents and a path and plan for commercialization of its "Electrocrushing" Drill technology. This discussion will provide a historical overview of this exciting application with an emphasis on the key, enabling advances in Pulsed Power Technology.

ENHANCEMENT OF SHOCK WAVE FROM UNDERWATER ELECTRICAL WIRE EXPLOSION BY REPLACING ONE THICKER WIRE WITH MANY THINNER WIRES

Dun Qian[1], Liuxia Li[1], Xiaobing Zou[1], Xinxin Wang[1]
1. Tsinghua University

An energy-efficient method for significantly enhancing the shock wave generated by underwater electrical wire explosion was developed. The method is to replace one thicker wire with many thinner wires under the conditions that the total mass of the wires and the initial storage energy are kept unchanged. It was found that maximum pressure of the shock wave rises from 30MPa to about 90MPa when one wire of 0.2mm in diameter is replaced with 16 wires of 0.05mm in diameter for a given initial energy of 200J. For a given wire and wire current, the maximum pressure of the shock wave linearly rises with the increase of the total number of the wires, which implies that the shock wave has decayed to acoustic wave after propagating a distance of 50mm from the wires to the pressure probe.

MODIFICATION OF THE FUNCTIONAL SURFACE COVER, STRUCTURAL DEFECTS AND TECHNOLOGICAL PROPERTIES OF NATURAL DIAMONDS UNDER THE NONTHERMAL INFLUENCE OF REPETITIVE HIGH-POWER NANOSECOND PULSES

Igor Bunin[1], Nataliya Anashkina[1]
1. Institute of Comprehensive Exploitation of Mineral Resources of the Russian Academy of Science

For optimization of diamond enrichment (mineral processing) technologies, the effect of repetitive high-power (high-voltage) nanosecond pulses (HPEMP; video pulses: pulse front 1–5 ns; pulse duration 50 ns; pulse amplitude 25 kV; electric field strength 10 (to degree 7) V/m; pulse repetition frequency 100 Hz; duration of electric pulse treatment – 10–150 s) on physical-chemical and technological properties of diamond crystals was studied. Using the methods of Fourier Transform Infrared Spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), analytical electron microscopy (SEM-EDX), electroosmosis and contact angle measurements, changes in structural, physical-chemical and electrical properties of natural diamonds surface as a result of HPEMP exposure were investigated. We concluded that the high-voltage nanosecond pulses cause changes in the functional cover of diamond surface and also lead to detachment and partial destruction of surface secondary mineral hydrophilic phase films. The growth of crystal hydrophobicity and flotability, and an increase in the number of B2 defects (platelets) were observed after 50 s of treatment with electric pulses. Lengthening the period of irradiation to 150 s resulted in oxidation of the diamond surfaces by products of water-air medium radiolytic decomposition, which led to the production of hydroxyl and/or carbonyl groups on the crystal surfaces, a further shift of the diamond electrokinetic potential into the region of negative values, and deterioration of the diamond's hydrophobic properties. The action of nanosecond HPEMP causes formation of the microdamages type electrical breakdown canales in the kimberlite rock constituents (calcite, olivine, and serpentine), and the decrease in microhardness of rock-forming minerals was from 40% to 70%. The obtained experimental result indicates possibility of applying pulsed energy effects to intensify the diamond flotation and to advance efficiency of the weakening of kimberlite rock constituents without damaging the precious crystals and ensuring their preservation by the subsequent grinding of refractory ores.

EFFICIENCY OF ROCK DESTRUCTION BY A PULSE GENERATOR BASED ON A LINEAR PULSE TRANSFORMER

Ivan Lavrinovich[1], Denis Molchanov[2]
1. HCEI SB RAS
2. IHCE SB RAS

Many researchers around the world note the high efficiency of electropulse drilling. During drilling shallow wells in the tens of meters deep, when the high voltage generator is located on the surface near the well, the specific energy consumption of electric pulse drilling is much less than traditional rotary drilling. To effectively drill deep wells (from hundreds of meters to several kilometers) with this method, it is necessary to develop a compact high-voltage downhole generator. In our opinion, such a generator can be built on the basis of a linear pulse transformer (LPT). In this paper is presented experimental results that show the efficiency of using such drilling system on the example of an existing laboratory bench. The tests were carried out on the rocks close in their physical characteristics, to rocks encountered at great depths. Before testing, rock samples were soaked with working fluid - technical water. As a result, it was shown that the effectiveness of this scheme is not inferior to the previously used Marx generators, however, according to other parameters, such as the mass-dimension parameters, simplicity of design, the LPT generator has unmatched advantages. Also, the obtained results allow us to formulate recommendations for optimizing the generator parameters based on LPT to increase the efficiency of drilling.

COMPUTATIONAL STUDY OF A PULSED POWER SOURCE BASED ELECTROMAGNETIC MANUFACTURING PROCESS

DEEPAK KAUSHIK[1], M. Joy Thomas[2]
1. IISc Bangalore
2. Indian Institute of Science

Electromagnetic Manufacturing (EMMa) is one of the newer manufacturing techniques which is gaining popularity. It uses an intense transient magnetic field generated by a pulsed power source to apply a transient force on the work piece and deform it without any direct mechanical contact. For an optimal choice of the pulsed power parameters for the EMMa, an understanding of the electromagnetic, mechanical, material and thermal phenomena associated with this type of manufacturing is imperative. A good understanding of the coupled effects of electromagnetic and mechanical forces and how they affect the material and thermal properties of the material is required to estimate the deformation taking place on the work piece. It requires numerical modelling of the forming process as well as to apply suitable numerical models to predict the relevant physical phenomenon.

EMMa system use a coil to apply the required electromagnetic force on the work piece during the discharge of a capacitor bank. In case of a multi-turn coil, the mechanical stress generated in the coil also needs to be studied. The coil design influences the distribution of the electromagnetic forces both on the work-piece as well as the coil. The pulsed current flowing through the coil also results in significant amount of heat being generated in the coil. The challenging feature of the numerical modelling of the deformation process and its effect on the coil is solving a highly coupled system of partial differential equations.

Therefore, in the present work, a numerical technique has been developed to model the EMMa process and to simulate the transient effects of the pulsed magnetic field on the work-piece and the coil. Specific attention is given to the study of the important process parameters, and the effect of their mutual interaction. The results would be presented and discussed in the final paper.

CHARACTERISTICS OF NEAR-FIELD SHOCKWAVES INDUCED BY UNDERWATER PULSED DISCHARGES

Liangli Xiong[1], Yi Liu[1], Mingan Wu[2], Fuchang Lin[1], Yuan Pan[1], Siwei Liu[1]
1. State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science & Technology, Wuhan, Hubei Province, China
2. School of Electrical Engineering and Automation, Wuhan University, Wuhan, Hubei Province, China

Powerful dynamic shockwaves induced by pulsed discharge plasma in water is adopted in rock fragmentation of oil and gas well. In order to evaluate the effect of rock damage under shockwaves, the dynamic loads factors (pressure, speed and energy of shockwaves) are required to be predictable. However, most papers focus on the relationship between discharge circuit parameters and shock wave peak pressure by using qualitative methods, the analysis of other dynamic loads factors are ignored.

In this paper, the shock wave characteristics are studied and the energy attenuation variation per unit distance is better quantified. Firstly, for the purpose of quantifying shock wave energy, the discharge gap distance is set to the reference value d between 20mm and 40mm, and the normal oil well of experiment with the inner diameter of 130mm. Therefore, this paper mainly studies on the shock wave in the range of 0-3.5d. Then, based on a liquid pulsed electrical discharge test platform (discharge voltage level is between 25kV and 35kV), the near-field wave-front of shockwaves are observed with a high-speed camera. By using three piezoelectric sensors combined with a signal processing system, the time domain pressure waveforms of shockwaves are measured combined with n times reference value d. And the attenuation of peak pressure and wave velocity are depicted. At the same time, the mechanical energy can be calculated by the measured shockwaves, the shock wave energy per distance can be obtained, the ratio of pre-peak pressure wave energy and post-peak pressure wave energy is also calculated. Finally, the peak pressure of discharge gap and its peak shock wave energy could be derived.

This paper provides a foundation for quantitatively exploring the effect of rock fragmentation and its dynamic expansion characteristics under shockwaves induced by pulsed discharges.

IMPACT VELOCITY CONTROL FOR ELECTROMAGNETIC PULSE WELDING BASED ON MODULAR DISCHARGE CURRENT SHAPING

Yan Zhou[1], Chengxiang Li, Jian Du, Xianmin Wang, Zhigang Liao
1. Chongqing University

Electromagnetic pulse welding (EMPW) technology is an innovation and potential application of pulse power technology for dissimilar metal jointing. Impact velocity has an important role in the EMPW process, which directly affects the welding effect. This study proposes a new and flexible method to control the discharge current to obtain a maximum impact velocity when the metal collided to improve the welding effect, which uses the superposition of pulse current generator modules to produce a large discharge current. The same modules synchronous overlap add, same modules asynchronous overlap add, different modules overlap add were described and analyzed in this study, which were used to produce the suitable discharge current for different metal workpiece. Different discharge current amplitude and rising time were simulated in PSPICE by different overlay form. A model including magnetic fields, solid mechanics and deformed geometry has been built in COMSOL Multiphysics to verify the validity of the proposed method by controlling the discharge current to control the welding results. And the results show that different discharge current will affect the skin depth, Lorentz force, and impact velocity in the EMPW process. Changing the discharge current based on the current superposition method can obtain the largest impact velocity, which will improve the welding effect for different metal workpiece.

A HIGH-REPETITION RATE, MAGNETIC CORE, PULSE TRANSFORMER BASED, FAST 120 KV GENERATOR

Jessica Stobbs[1], Bucur Novac[2], Peter Senior[1], Tom Huiskamp, Frank Beckers[3], Guus Pemen[3]

1. Loughborough University

2. Loughborough

3. Eindhoven University of Technology

**A high-repetition rate, magnetic core, pulse transformer based,

fast 120 kV generator**

Jessica Stobbs, B.M. Novac and P. Senior

Loughborough University, UK

T. Huiskamp, F.J.C.M. Beckers and A.J.M. Pemen

Eindhoven University of Technology, The Netherlands

We present a high repetition rate, high-voltage pulse generator based on a compact high-voltage pulse transformer. The magnetic-core transformer is capable to charge a HV 1-nF capacitor load to over 120 kV. It has a turns ratio of 1:12 and is energized by a primary capacitor bank of 150 nF charged to an initial voltage of about 13 kV and a corona stabilized switch. By employing bespoke nanocrystalline cores and a careful design, the leakage inductance of the transformer is minimised, which results in a very fast charging time of the HV capacitor to the nominal peak voltage in about 250 ns. Results from operating the transformer in single-shot mode and at a pulse repetition rate of 1 kHz will both be presented.

AN ALTERNATIVE CIRCUITRY FOR A TRANSFORMER COUPLED LC INVERSION GENERATOR

Rainer Bischoff[1]

1. French-German Research Institute of Saint-Louis (ISL)

A new alternative circuitry for the transformer coupled LC inversion generator (TCLCG) is presented.

In principle, a TCLCG consists of one in-phase 1:1 transformer and two capacitors per elementary stage. First, the two capacitors will be charged via the primary winding of the transformer in opposite polarity. Afterwards, voltage multiplication is being achieved by a closing switch which shortcuts the two capacitors. The odd-numbered capacitor discharges slowly through the primary inductance of the transformer, whereas the even-numbered capacitor discharges fast through only the leakage inductance of the transformer and thus inverts.

However, one of the main drawback of the classical TCLCG circuitry is caused by the fact that connection of the transformers of the higher generator stages is done through the transformers of the lower stages. Consequently, compensation techniques must be applied, i.e. adjustment of the even capacitors and/or transformer inductance values, in order to ensure effective voltage multiplication by means of constructive superposition of each stage. This limits the maximum achievable generator stage number and rise time.

In the alternative TCLCG circuit principle, the connections to the primary and secondary inputs of the transformers of the higher stages are being done directly from the closing switch. Now, the transformers are in parallel to each other, not in series as in the classical TCLCG circuitry. As a result, the even numbered capacitors see the same leakage inductance and compensation techniques are no longer necessary. First experimental verification was done by direct comparison of the classical and alternative circuitry for two compact 2-stage TCLCGs with identical transformers and capacitances. The results showed that the alternative circuitry leads to a fast generator rise time of 25 ns, about 35% faster than the classical circuitry, while still reaching the same generator efficiency of 67%.

A 30KV, 200KHZ SOLID-STATE PULSED POWER GENERATOR BASED ON THE DRIFT STEP RECOVERY DIODES

wang haiyang [1]
1. Xi'an jiaotong university

A all-solid-state high voltage fast risetime high repetition rate pulse generator was developed for the EMP(Electromagnetic Pulse) effects. The pulse generator is based on an opening switch topology that uses Drift Step Recovery Diodes (DSRDs) as the opening switches in an inductive-capacitive storage circuit. The pulse generator is capable of delivering voltage pulses with an amplitude of 30 kV and a risetime of 4ns at a repetition rate of 200kHz to a 50-resistive load. The pulse generator can be used for EMP effects and also in an apparatus for purifying air pollution.

8-STAGE PULSE GENERATOR FOR GENERATION OF BIPOLAR RECTANGULAR PULSES

Martin Sack[1], Dennis Herzog[2], Martin Hochberg[1], Georg Mueller[2]
1. Karlsruhe Institute of Technology
2. Institute for Pulsed Power and Microwave Technology (IHM), Karlsruhe Institute of Technology (KIT), Germany

For lab-scale experiments related to the decontamination of liquids from bacteria an eight-stage pulse generator for generation of bipolar rectangular pulses has been set up. The generator consists of stacked modules in H-bridge configuration. For ground-symmetric operation of the load the generator has been grounded at its center. This is especially important when connecting a PEF-treatment chamber for continuous treatment of a liquid with plate-type electrodes to the generator. The generator has been designed for a charging voltage per stage of 1 kV and a pulse current of up to 600 A. It is able to generate biploar pulses, each with an adjustable pulse length of between 1 μs and 10 μs and an adjustable time between both pulses. The generator is capable of a pulse repetition rate of up to 200 Hz. Under full load conditions a rise time of both voltage and current across a resistive load of 120 ns (10% to 90%) has been measured. The inner inductance of the generator has been determined to be 0.1 μH per stage. Each stage of the generator has been equipped with an independent over-current protection. To test this feature, four stages i.e. one half of the generator has been operated in single pulse operation with its output shorted to ground. A short-circuit current of up to 1.7 kA has been interruped successfully several times. In the contribution selected design details and results of first tests of the generator will be presented.

A NOVEL HIGH-FREQUENCY PULSE GENERATOR BASED ON BIPOLAR AND MARX TOPOLOGIES

Shoulong Dong[1], liang Yu, Jianhao Ma, Xiaoyu Wang, hongmei liu[1], Chenguo Yao
1. Chongqing University

With the in-depth application of pulse power technologies in the wide range of biomedicine, food processing, electromagnetic forming, plasma generation, etc., it has posed new requirements to pulse generatorsfor high-volt high frequency, bipolar, and all solid state,. In this paper, a novel bipolar high-volt pulse generator circuit topology is proposed for the needs. Theoretical analysis, simulation and experimental results show that it combines the advantages of solid-state Marx and bridge circuits including high voltage output through simple stacking of modules, flexible adjustment of output for polarity and pulse width by sequential logic control of the switch , and inherent high repetition rate with long lifetime. The experimental prototype has been developed with characteristic parameters following, an output voltage amplitude of ±5 kV, a repetition rate of 2.5 MHz in the pulse train, and a pulse width of 200 ns-10 μs.

DESIGN AND PERFORMANCE OF A 2 M EUT MIL STD 461 (RS-105) TEST SYSTEM

Jon Mayes[1], Bill Nunnally[2], Eric Perry[1], Matthew Lara[1], Chris Hatfield[1], Jeremy Byman[1], David Kohlenberg[1], Paul Flores[1], Tim Henke[1], Stephane Del Rosario[1]
1. Applied Physical Electronics L.C.
2. Applied Physical Electronics, LC

Applied Physical Electronics, L.C. (APELC) has built a moderate scaled test system to meet MIL STD 461, under the RS-105 test configuration. The system is designed to test objects of up to 2 m x 2 m x 2m, with peak electric fields of up to 60 kV/m. This system uniquely uses a coaxial Marx generator, coupled with a planer peaking circuit to produce the MIL STD waveform, which is characterized by a 1.8 – 2.8 ns rise time, and a pulse width of approximately 23 ns. This paper will describe the pulsed power source, as well as the nuances of driving a guided wave structure.

2016 CYGNUS REFURBISHMENT

Steve Huber[1], Bill Skarda[1], PAUL FLORES[1], Isidro Molina[2], Monty Larsen[1], Keith Hogge[1], John Smith[3], Mike Garcia[4], Eugene Ormond[4], Stephen Mitchell[1], Nichele Prock[1], Joe Delash[1]
1. Mission Support and Test Services, LLC
2. Keystone International
3. Los Alamos National Laboratory
4. Sandia National Laboratories

Cygnus, a dual-beam x-ray source, supports the Subcritical Experiments Program at the Nevada National Security Site for both Los Alamos and Livermore national laboratories. Since 2004, Cygnus has been successfully fired over 4000 times and refurbishment activities were completed in 2012 and 2016. The major refurbishment in 2016, conducted over a six-month period, has ensured Cygnus operations for many more years. In this paper we describe discoveries and resulting actions performed during the 2016 refurbishment period, particularly those related to arc damage and oil leakage in the inductive voltage adder (IVA) ring stack. Many engineering enhancements and improvements were made to Cygnus in 2016, including the addition of inspection windows for the Marx tank, diverter switch, and IVA oil manifold. Finally, many safety improvements were also implemented, such as installation of elevated work platforms for the Marx tank and IVA assembly.

DYNAMIC MODELING OF PULSED ALTERNATORS USING LTSPICE

Cesar Negri[1], Saeed Daneshvardehnavi[1], Michael Giesselmann[1]
1. Texas Tech University

We are reporting on the formulation and performance of dynamic models for Pulsed Alternators for LTspice. The models are modular and hierarchical and cover both the electrical and mechanical aspects of the electric machine including the mechanical torque, speed and inertia. The models also include the effects of the damper cage and the excitation winding to accurately represent the sub-transient and transient behavior. The models can be also used to represent synchronous generators in steady state operation. LTspice is a powerful, widely available software package that can be used to model Pulsed Power circuits.

We are presenting the detailed models as well as results of the simulations.

PULSED POWER AS A SCIENCE: PREDICTIVE SIMULATIONS FOR BEAMS, Z-PINCHES, AND OTHER APPLICATIONS

Tom Mehlhorn[1]
1. Naval Research Laboratory

This presentation will overview my 40 years of research and the people with whom I have had the pleasure of working, both domestically and internationally. In 1978 Sandia's electron beam fusion program emerged from a weapons simulator community that was machine-oriented and relied on design principles and "JCM" criteria. Simulation tools were primarily used retrospectively. Fusions'extraordinary requirements stimulated tremendous innovation in pulsed power, beams, pinches, and simulation tools. I started by developing ion beam deposition and transport models that were integrated into radiation-hydrodynamics codes; validated by experiments on Gamble II and Proto I; and helped initiate Sandia's light ion beam fusion program. SDI program research led to the development of the ITS suite of electron-photon Monte Carlo codes (1985). Research on PBFA-I and PBFA-II on generating, transporting, and focusing ion beams required developing transport, diagnostic simulation, and analysis tools, which were used in focusing protons to 5 TW/cm^2 (1991) and lithium beams to 2 TW/cm^2, heating hohlraums to 65 eV (1996). They also helped identify anode plasma formation by electron heating as the source of diode impedance collapse leading to efforts to include electron-electrode interaction models into PIC codes and initiating hybrid fluid-PIC development (IPROP, LSP). Electrode physics remains a powerflow grand challenge for high yield fusion. In 1999 I led rad-MHD development (ALEGRA-HEDP) and oversaw EOS and conductivity model development using QMD/DFT, resulting in predictive capabilities for dynamic material experiments. Improved z-pinch dynamic hohlraum modeling and experiments resulted in thermonuclear neutrons (2004). 3-D wire array dynamics were modeled and understood. We developed advanced radiographic sources and built an LTD test bed. At NRL I have overseen advances in modeling and experiments in beams, pinches, pulsed power, and their applications (2009-). My goal throughout has been to develop and validate predictive simulation tools; making Pulsed Power a Science.

USE OF HERMES-III FOR PULSED NEUTRON PRODUCTION PRODUCED BY INTENSE ION BEAMS AT THE 14 MEV LEVEL AT SANDIA NATIONAL LABORATORIES*

Timothy Renk[1], Paul Ottinger[2], Russell Durrer[3]
1. Sandia National Laboratories
2. Syntek Technologies
3. Sigma Science, Inc.

Timothy J. Renk

Sandia National Laboratories Albuquerque, NM 87185 USA

Paul F. Ottinger

Syntek Technologies, Fairfax, VA 22030 USA

Russell Durrer

Sigma Science, Inc, Albuquerque, NM 87185 USA

The HERMES-III accelerator (18 MV, 700kA, 40 ns) uses Inductive Voltage Adder (IVA) architecture to drive a magnetically insulated transmission line (MITL) with a 34-ohm vacuum impedance. In normal operation, the load is a Bremsstrahlung diode operated in negative polarity, from which an intense electron beam can be extracted for gamma generation. The relatively high output voltage makes HERMES attractive as a source for high-energy ions which could be used to generate pulsed neutrons using high-cross section metal targets. To preserve the dominant negative polarity mode, ion beams are generated and propagated to neutron targets and objects for neutron exposure inside the HERMES center conductor. A radial self-field (no external coils) ion diode is designed to be compatible with the MITL impedance, and operated undermatched ($\sim$17 ohms) to capture the incoming MITL flow (2/3 of the output current).

Previous experiments indicate a diode operating voltage of 13-14 MV, with proton beam currents propagating in both the 'forward'(e.g. into the accelerator) and 'backward'directions, with each beam in the 50-100 kA range, all consistent with LSP simulations. Extensive use has been made of the MCNP code design the neutron target to maximize a) neutron energy spectrum, and b) neutrons in the forward direction. Compared to a reference thick-target tantalum plate, two combined sub-range Co-Nb foils produce twice the total neutron yield, 3 times the number of neutrons > 1 MeV energy (about 70% of the total), and factor 1.4 in the forward as opposed to rear direction. Additional experiments are planned, and latest results will be discussed.

----

* Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

THERMIONIC AND FIELD EMISSION MODEL OF 2D MATERIALS CATHODE

Lay Kee ANG[1], Yee Sin ANG[1]
1. Singapore University of Technology and Design

Electron emission from a material through an interface to vacuum or another material is a fundamental process in cathode, diode, ionization, electric contact and many other areas. Depending on the energy used, it can be broadly characterized into 3 different processes known as thermionic emission TE (by thermal energy), field emission FE (by quantum tunneling) and photoemission PE (by absorption of photons or optical tunneling). The basic models for these processes (TE, PE, PE) have been formulated many decades ago, known as the Richardson law, Child-Langmuir (CL) law, Fowler-Nordheim (FN) law, and the Keldysh model. With the development of two-dimensional (2D) atomic scale materials in the 2000's (like graphene), the above-mentioned classical laws may require revisions to account for new material properties. In this talk, we will present the new emission models (thermionic and field emission) for 2D materials like graphene, and to show that the traditional models are no longer valid. The new models include the effects of linear energy dispersion over a wide energy range, and the momentum non-conservation. These new models will exhibit smooth transition to the traditional models and also new scaling laws agreeable with recent experiments. The applications of the models are not limited to cathodes but to other applications such as charge injection across electrical contact composed of 2D materials and bulk materials widely used in electronics and photonics.

INCORPORATING RESISTANCE INTO THE UNIFICATION OF FIELD EMISSION AND SPACE CHARGE-LIMITED EMISSION WITH COLLISIONS

Adam Darr[1], Amanda Loveless[2], Allen Garner[2]
1. Purdue University West Lafayette
2. Purdue University

Electron emission plays a vital role in device design for systems with pressures ranging from vacuum to atmospheric pressure. This presentation outlines the theoretical unification of field emission modeled by the Fowler-Nordheim (FN) equation and space-charge limited emission (SCLE) represented by the Child-Langmuir (CL) law at vacuum and the Mott-Gurney (MG) law with collisions [1]. We show that the asymptotic solutions for FN, CL, and MG intersect at a triple point and that electron emission transitions to CL with increasing voltage independent of pressure. Since practical devices often include a series resistor, we extend this work to assess the impact of the resistor, as done previously for vacuum [2]. The triple point is uniquely defined by the electron mobility, gap distance, or voltage with an associated triple point gap impedance. For series resistance less than the triple point gap impedance, electron emission transitions from FN to MG to CL to Ohm's law with increasing applied voltage while SCLE is bypassed entirely at higher resistance.

1. A. M. Darr, A. M. Loveless, and A. L. Garner, "Unification of field emission and space charge limited emission with collisions," Appl. Phys. Lett., vol. 114, 2019, art. no. 014103.

2. J. W. Luginsland, A. Valfells, and Y. Y. Lau, "Effects of a series resistor on electron emission from a field emitter," Appl. Phys. Lett., vol. 69, pp. 2770-2772, 1996.

Work supported by a Purdue Doctoral Fellowship, a Directed Energy Professionals Scholarship, a Purdue Summer University Research Fellowship, the Air Force Office of Scientific Research under award number FA9550-18-1-0218 and by the Office of Naval Research under Grant No. N00014-17-1-2702.

EXACT SOLUTION FOR TWO-COLOR LASER INDUCED PHOTOEMISSION FROM A BIASED METAL SURFACE

Yi Luo[1], Peng Zhang[1]
1. Michigan State University

Laser-induced electron emission is essential to the development of ultrafast electron microscopes, tabletop particle accelerators and x-ray sources, and novel quantum nanocircuits [1-3]. In particular, two-color laser induced photoemission from a metal nanotip [4] provides great flexibility for the coherent control of emitted electron distribution by using the interference effect. By solving the time-dependent Schrödinger equation [5,6], we construct an exact analytical solution for nonlinear ultrafast electron emission from a dc biased metal surface illuminated by two-color laser fields. Our results reveal various emission processes, including photo-induced over-barrier emission, and tunneling emission, for different dc and laser fields, and recover the trend in the experimentally measured energy spectra [4,7]. We find a strong dc electric field not only opens up tunneling emission channels, but also introduces intense modulation to the two-color emission current. Different combinations of the dc field and phase difference of the two lasers could offer a promising method of controlling electron dynamics in ultrashort spatiotemporal scales.

[1] P. Zhang, et al., Appl. Phys. Rev. 4, 011304(2017).

[2] E. Forati, et al., Nat. Communications 7, 13399 (2016).

[3] P. Zhang, and Y. Y. Lau, J. Plasma Phys. 82, 595820505 (2016).

[4] M. Forster, et al., Phys. Rev. Lett. 117, 217601 (2016).

[5] P. Zhang and Y. Y. Lau, Sci. Rep. 6, 19894 (2016).

[6] Y. Luo, and P. Zhang, Phys. Rev. B, 98, 165442 (2018).

[7] M. Schenk, et al., Phys. Rev. Lett. 105, 257601 (2010).

Work supported by AFOSR YIP Award No. FA9550-18-1-10061.

SHOCKS INDUCED BY FAST HIGH-FLUENCE ELECTRON BEAM DEPOSITION ON ALUMINUM TARGETS: HYDRODYNAMIC SIMULATIONS INITIALIZED BY ELECTRON BEAM MEASUREMENTS.

Nicolas Szalek[1], Béatrice Bicrel[1], Bruno Cassany[1], Alain Galtié[1], Jacques Gardelle[1], David Hébert
1. CEA

Shocks induced by fast high-fluence electron beam deposition on Aluminum targets: hydrodynamic simulations initialized by electron beam measurements.

N. Szalek, B. Bicrel, B. Cassany, A. Galtié, J. Gardelle and D. Hébert.

CEA/CESTA, 15 avenue des Sablières, CS 60001, 33116, Le Barp, France

We present recent results of fast hydrodynamic response of aluminum at CESTA. We are using the CESAR generator which delivers single shots ($\approx$ 800 keV, $\approx$ 300 kA, 60 ns) electron beams. After focusing by an external magnetic field towards an aluminum target located inside an air-filled chamber, fast beam energy deposition produces a shock-wave and vaporizes matter. Then, the rear face of the target moves quickly, and its velocity is measured by Photonic Doppler Velocimetry (PDV). Recently, we increased beam fluence ($>$ 500 cal/cm2) and we improved our knowledge of the beam parameters at the target location. Thanks to several new diagnostics, such as a Cerenkov imaging line, we have improved the initialization of beam-target simulation tools. The energy deposition is computed with the Monte Carlo code DIANE and we perform hydrodynamic calculations with the code HESIONE. One of the main outputs of the latter is the velocity of the rear face of the target, at given radial positions and as a function of time, which was compared with PDV data. We obtained good agreement with the experiment for the maximum velocity, which is within the experimental error bars. However, we observed differences in computed and measured temporal shapes for the two equations of state of aluminum we have tested: BLF (Bushman-Lomonosov-Fortov) and SESAME 3720 table.

MERLIN INDUCTIVE VOLTAGE ADDER

Mark Sinclair[1]
1. AWE

Place holder abstract as requested by Josh Leckbee, will be waiting on confirmation of clearance process

THE EFFECTIVE WAY OF IMPROVING THE PERFORMANCE OF A NOVEL MULTIPACTING CATHODE WITH HIGH CURRENT DENSITY

Ye Dong[1], Qingxiang Liu[2], Xiangqiang Li[2], Haijing Zhou[3], Zhiwei Dong[3]
1. 1. School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, China; 2. Institute of Applied Physics and Computational Mathematics, Beijing, China
2. School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, China
3. Institute of Applied Physics and Computational Mathematics, Beijing, China

The possible ways of improving the performance of a novel multipacting cathode is numerically investigated by using Particle-In-Cell (PIC) method. Firstly, the prototype configuration and physical model of the novel multipacting cathode are briefly introduced. Secondly, by using the self-programmed 2.5D PIC code, possible ways of improving the performance of the novel multipacting cathode are detailed studied. The simulated results could be concluded as follows. Prolong the length of multipacting cathode could partly improving the cathode performance due to the longer interaction range of multipacting. Increasing the secondary electron yield of material could partly improving the cathode performance due to the higher yield of secondary electrons. Improving the axial electric-field could partly improving the cathode performance due to the higher impact energy. Improving the radial electric-field could partly improving the cathode performance due to the stronger suppression of space-charge field. Thus, synchronously improving the axial and radial electric-field could partly improving the cathode performance. Improving the axial magnetic-field could not certainly improving the cathode performance due to lower impact energy of electron. The most effective way of improving the cathode performance of the novel multipacting cathode is synchronously improving the axial and radial electric-field and the axial magnetic-field. Through this way, the output current could be notably increased. Meanwhile, the flight time and travel distance of electron could be shortened but the impact energy is not changed. Thereby, the electrons could be in low energy-spread and good emittance.

GENERATION OF INTENSE PULSED X-RAY AND REPETITIVE PULSED X-RAYS

Jianqiang Yuan[1], Weiping Xie[1], Lidong Geng[1], Hongwei Liu[1], Lingyun Wang[1], Hongtao Li[1], Xun Ma[1], Ping Jiang[1]
1. Institute of Fluid Physics, China Academy of Engineering Physics

Both intense pulsed X-ray and repetitive pulsed X-rays play an important role in the investigation of various physical processes in hydrodynamic experiments.

In order to generate intense pulses X-ray, 1.2 MV pulsed power generator and rod-pinch diode are designed and constructed at Institute of Fluid Physics, CAEP. The generator is composed of a Marx generator, an upstream oil line, a pulse forming line, an oil switch, a transfer line and a load. An optical system is built to center the rod as precisely as possible in the center of the cathode aperture. The X-ray dose of 1.4 R at 1 m in the forward direction and the spot size of 1.47 mm are achieved. The rod-pinch diode model validated by experiments can be used to predict the characteristics of rod-pinch diode at higher voltage.

In order to generate repetitive pulsed X-rays, a stacked Blumlein line (SBL) type pulsed power source (200 kV, 1 kA, 1 kHz) based on photoconductive semiconductor switches (PCSSs) and industrial cold cathode diode have been constructed. More uniform electron emission has been achieved by employing spoke-shaped metal-ceramic surface flashover cathode. Repetitive pulsed X-rays with FWHM of 40 ns and repetition rate of 1 kHz were generated.

To achieve higher burst rate of pulse X-rays, a branch of pulse X-ray machine (210 kV, 5 kA), which is composed of a PFL-Marx and diode, has been construced. Pulse X-ray with FWHM of 40 ns and spot size of less than 1.6 mm were generated.

This work was supported by National Natural Science Foundation of China (51007085, 51207147, 51407170 and 51477185)

EXPERIMENTAL STUDY OF A MILLIMETER WAVE RELATIVISTIC BACKWARD WAVE OSCILLATOR*

Ahmed Elfrgani[1], Firas Ayoub[1], Artem Kuskov, Dmitrii Andreev[1], Antonio De Alleluia[1], Braulio Martinez-Hernandez[1], Kevin Wang Huang[1], Stacie Hernandez[1], Edl Schamiloglu[1]

1. University of New Mexico

The results of an experimental investigation of a relativistic backward wave oscillator (RBWO) in E-band are presented. An overmoded slow wave structure (SWS) was designed to generate a higher order mode (TM03) at 78GHz.1 Rectangular corrugations were used for the SWS having surface waves with upper cutoff frequencies above 90 GHz (E-band). The characteristics of this millimeter wave source were studied for electron energies 400 – 500 keV and beam currents 2.5 – 3.5 kA.

The RBWO was driven by a voltage pulse that has a half sinusoidal wave-like shape and FWHM duration of 12 ns (SINUS-6 accelerator). Open-shutter photography and a neon bulb array were used to capture the radiation pattern of the TM03 output mode.

1. A. Elfrgani, A. Kuskov, M.I. Fuks, and E. Schamiloglu, "Millimeter Wave Overmoded Relativistic Backward Wave Oscillator," in Proc. IVEC 2018 (Monterey, CA, 2018), p. 1.

---

* Work supported by DARPA Grant #N66001-16-1-4042

MULTIPLE BEAM POWER GRID TUBES FOR HIGH FREQUENCY AND HIGH POWER OPERATION

Lawrence Ives, Michael Read[1], David Marsden[1], Thuc Bui[1], Ricky Ho[2], Leroy Higgins[2], Bruce Henderson[2]
1. Calabazas Creek Research, Inc.
2. Communications & Power Industries, LLC

Calabazas Creek Research, Inc. (CCR), in collaboration with, Communications & Power Industries, LLC (CPI) is developing a multiple beam triode for ion, proton, and electron accelerators. Traditional, high power triodes are limited to frequencies below 300 MHz and power levels less than 100 kW. Efficiencies exceeding 70% are routinely achieved and as high as 90% have been reported. This program is developing a multiple beam triode to produce more than 200 kW of RF power.

The triode consists of a gridded electron beam source and collector in a vacuum enclosure. RF power is achieved by mounting the triode inside coaxial input and output cavities at the desired frequency. The multiple beam triode will be designed to provide RF power from 350 MHz to 650 MHz using the appropriate, tuned, resonant cavities.

The program is using the grid-cathode assembly from CPI's YU-176 planar triode [1]. Each YU-176 grid-cathode assembly provides beam power to produce 25 kW of RF power. This program is using eight assemblies to achieve 200 kW with a target efficiency exceeding 80%. An 8-beam, triode powered, RF source at 350 MHz would be approximately 36 inches long and 18 inches in diameter and weigh approximately 150 pounds. This is significantly smaller than any other vacuum electron device at this frequency and power level.

The gain is limited to approximately 15 dB. Consequently, a single beam triode-based source will serve as a driver for the multiple beam device. The cost and efficiency of the system will still exceed the performance of other RF sources at this frequency, including solid state sources.

CCR and CPI are leveraging advanced, 3D codes to simulate the beam optics and thermomechanical performance. Key issues include grid cooling, uniformity of RF electric fields on the grids, and efficiency.

1. http://www.cpii.com/division.cfm/9

A 1.3 GHZ 100 KW ULTRA-HIGH EFFICIENCY KLYSTRON

Michael Read[1], Lawrence Ives, Jeff Neilson[2], Aaron Jensen[3]
1. Calabazas Creek Research, Inc.
2. SLAC National Accelerator Laboratory
3. Leidos Corporation

Calabazas Creek Research, Inc. is developing a high efficiency, 1.3 GHz, 100 kW klystron for driving accelerators. The goal for the efficiency is at least 85%. Designs for the RF circuit, electron gun and collector are presented.

Using the COM design method for klystrons put forth by [1,2] (COM: Core Oscillation Method), CCR has created a design with an efficiency of 82%, as calculated using MAGIC. The circuit length was 2 m. Details of the circuit, electron gun and collector electrical and mechanical designs will be presented at the conference.

1. A. Yu.Bajkov, D.M.Petrov "Problems of creation powerful and super- power

klystrons with efficiency up to 90%", International University Conference "Electronics and Radio physics of Ultra-high Frequencies", St. Petersburg, May 24–28, 1999, pp. 5–8.

2. A. Yu.Bajkov, D.M.Petrov "Problems of creation powerful and super- power klystrons with efficiency up to 90%", International University Conference "Electronics and Radio physics of Ultra-high Frequencies", St. Petersburg, May 24–28, 1999, pp. 5–8.

COAXIAL-ALL-CAVITY-EXTRACTION ON THE HARMONIC RECIRCULATING PLANAR MAGNETRON

R. M. Gilgenbach[1], Geoffrey Greening[2], Christopher Swenson[2], Nick Jordan[2], Brad Hoff[3], Drew Packard[2], Y. Y. Lau[1], Jason Hammond[4], Steven Exelby[2]

1. University of Michigan, Ann Arbor, MI 48109, USA

2. University of Michigan

3. Air Force Research Laboratory

4. Air Force Research Lab

The Multi-Frequency Recirculating Planar Magnetron (MFRPM) [1,2] is a novel high power microwave (HPM) source designed to generate two frequencies simultaneously. The MFRPM is capable of producing MW power levels near 1 GHz and 2 GHz with an L-Band Oscillator (LBO) and S-Band Oscillator (SBO), respectively. The MFRPM is the first magnetron to demonstrate harmonic frequency locking, wherein the SBO frequency locked to the second harmonic of the LBO frequency. The locking mechanism between the two oscillators is presently hypothesized to be harmonic content in the electron spokes.

The Harmonic Recirculating Planar Magnetron (HRPM) has been designed and fabricated to test this hypothesis. Like the MFRPM, the HRPM still consists of an LBO and SBO. A novel scheme known as coaxial-all-cavity-extraction (CACE) [3] has been deployed to extract power from the HRPM SBO. Simulation results will be presented in addition to early experimental data obtained by driving the HRPM with the Michigan Electron Long Beam Accelerator with Ceramic insulator stack (MELBA-C). MELBA-C generates pulses 0.3-1.0 μs in length at -300 kV, with currents in the range 1-10 kA.

1. G. B. Greening, Ph.D Dissertation, “Multi-Frequency Recirculating Planar Magnetrons,” University of Michigan, 2017.

2. Greening et al, “Harmonic Frequency Locking in the Multi-Frequency Recirculating Planar Magnetron”, IEEE T-ED, vol. 65, 2347, 2018

3. Franzi et al, “Coaxial All Cavity Extraction in the Harmonic Recirculating Planar Magnetron,” IEEE International Vacuum Electronics Conference, 2014.

----

* Supported by the Office of Naval Research under grant numbers N00014-13-1-0566 and N00014-16-1-2353, DEPS Fellowship support to DP, AFRL for ICEPIC, and L-3 Technologies Electron Devices Division.

INCLUSION OF CIRCUIT LOSS IN AN EXACT TREATMENT OF A HELIX TRAVELING WAVE TUBE

Abhijit Jassem[1], Yue Ying Lau[1]
1. University of Michigan

A recent treatment of a thin tape helix traveling wave tube (TWT) yielded an exact hot tube dispersion relation [1]. This work modified Pierce's classical theory by introducing a new parameter, "q", which accounts for space charge effects on the phase velocity of the circuit mode. This is analogous to the familiar Pierce space charge parameter, Q, which accounts for the space charge effect on the beam mode. However, the crucial assumption in [1] is that there is no cold tube loss, i.e., the Pierce's loss parameter d = 0. Here we propose a method of including the effects of this loss by introducing an imaginary component of permittivity to the dielectric support structure [1]. The effect of local resistive sever is also studied. We thank D. Chernin and P. Wong for many useful discussions.

[1] P. Wong, D. Chernin, and Y. Y. Lau, IEEE Electron Device Lett. 39, 1238 (2018).

MODELING STABILITY OF VACUUM ELECTRONIC DEVICES USING GENERALIZED IMPEDANCE MATRIX APPROACH

Igor Chernyavskiy[1], Alexander Vlasov[1], John Rodgers[1], Baruch Levush[1], Thomas, Jr. Antonsen[2]

1. Naval Research Laboratory

2. Leidos, Inc.

The new 2D code TESLA-Z [1] was developed at the US Naval Research Laboratory as a tool for geometry-driven large-signal modeling of linear-beam vacuum electronic devices (VEDs). The modeling approach is based on the representation of VED's structure as a generalized network of ports (including actual input/output ports and interaction gaps) whose frequency dependent properties (response) can be described by a generalized impedance matrix Z representing linear relationship between imposed currents and induced voltages at all gaps/ports. The impedance matrix Z can be pre-computed using a 3D Computational Electromagnetic (CEM) code and then utilized by the large-signal algorithm in TESLA-Z to model the VED beam-wave interaction. Due to the geometry-driven nature of the approach employed in the code TESLA-Z algorithm allows modeling of wide class of VEDs. The code was successfully validated by modeling a folded-waveguide traveling wave tubes (TWTs) and a multiple-beam klystrons (MBKs).

As a next step in the development of the code we are working on extending TESLA-Z algorithm to make it suitable for studying stability in various VEDs. We will discuss the latest advances in the development of the code TESLA-Z algorithms and will present preliminary results of our stability modeling using impedance matrix approach.

1. I. A. Chernyavskiy T.M. Antonsen, Jr., J.C. Rodgers, A.N. Vlasov, D. Chernin, and, B. Levush, "Modeling Vacuum Electronic Devices Using Generalized Impedance Matrices," IEEE Transactions on Electron Devices, Vol. 64, No. 2, pp. 536-542, Feb. 2017.

---

*Work supported by the US Office of Naval Research

AN ELECTRON GUN FOR A SHEET BEAM WITH A 3 TO 1 ASPECT RATIO: DESIGN AND OPTIMIZATION

Alex Burke[1], Aaron Jensen[1], John Petillo[1], John Pasour[2]
1. Leidos
2. Naval Research Laboratory

An electron gun is being designed for an amplifier at Ka-Band that requires a sheet beam with a 3 to 1 (width-to-height) aspect ratio. The design process includes running MICHELLE simulations manually for "one at a time" iterations of the gun geometry, and also "many at a time" MICHELLE simulations using automated optimization tools. We run MICHELLE, a charged particle beam optics code [1,2], in two different user environments: 1) Analyst–MP (Multi Physics) within the National Instruments AWR Design Environment (NI AWRDE) [3] which includes CAD, parametric optimization support, multiple RF solvers and a magnetostatic solver. 2) The AFRL Galaxy Simulation Builder (GSB) [3] framework for large-scale optimization using the DAKOTA [4] optimization library. The gun design approach and optimization results will be presented.

1. John Petillo, et al., IEEE Trans. Plasma Sci., vol. 30, no. 3, June 2002, pp. 1238-1264.

2. John Petillo, et al., IEEE Trans. Electron Devices Sci., vol. 52, no. 5, May 2005, pp. 742-748.

3. Analyst-MP is a commercial electromagnetic analysis software package developed by the AWR Group of National Instruments (http://www.awrcorp.com/

products/additional-products/analyst-mp)

4. Stellar Science Ltd Co. Galaxy Simulation Builder (GSB) User Guide, Version 6.6. High Power Electromagnetic Division, Air Force Research Lab, Kirtland, NM, 2017.

5. B. Adams et al., "DAKOTA, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.0 User's Manual," Sandia Technical Report SAND2010-2183, 2015

----

* Work supported by NRL

W-BAND 2D PERIODIC LATTICE OSCILLATOR

colin whyte[1], Amy MacLachlan[2], Craig W. Robertson[1], Adrian Cross[1], Liang Zhang[1], Alan Phelps[1], Kevin Ronald[1]
1. University of Strathclyde
2. University of Strathclyde / Cockcroft Institute

Two dimensional (2D) periodic surface lattices PSLs [1-6] have applications in both fast-wave sources [1] and slow-wave sources [4]. Analytical theory and numerical PIC simulations have been used to design an electron beam driven W-band millimeter-wave oscillator, in which a cylindrical two dimensional (2D) periodic surface lattice (PSL) forms an over-sized mode-selective cavity. The 2D PSL consists of shallow periodic cosinusoidal perturbations in both the azimuthal and axial directions on the inner wall of a cylindrical waveguide. Electrochemical deposition of copper on a cylindrical aluminum former was used to construct the 2D PSL. The ratio of the diameter of the cylindrical structure to the operating wavelength is $\sim$5. The performance of this slow-wave oscillator is being measured and will be compared with the numerical simulations.

Work supported by AFOSR awards FA8555-13-1-2132 and FA9550-17-1-0095.

[1] N.S. Ginzburg, et al., "Theory of free-electron maser with two-dimensional feedback driven by an annular electron beam", J. Appl. Phys., vol. 92, pp. 1619-1629, Aug. 2002.

[2] A.W. Cross, et al., "Studies of surface two-dimensional photonic band-gap structures", J. Appl. Phys., vol. 93, pp. 2208-2218, Feb. 2003.

[3] I.V. Konoplev, et al., "Cylindrical, periodic surface lattice – Theory, dispersion analysis and experiment", Appl. Phys. Lett., vol. 101, 121111, Sept. 2012.

[4] N.S. Ginzburg, et al., "Theoretical and experimental studies of relativistic oversized Ka-band surface-wave oscillator based on 2D periodical corrugated structure", Phys. Rev. Accel. Beams, vol. 21, 080701, Aug. 2018.

[5] A.J. MacLachlan, et al., "Volume and surface mode coupling experiments in periodic surface structures for use in mm-THz high power radiation sources", AIP Advances, vol. 8, 105115, Oct. 2018.

[6] A.J. MacLachlan, et al., "Resonant excitation of volume and surface fields on complex electrodynamic surfaces", Phys. Rev. Appl., vol. 11, 034034, Mar. 2019.

A STUDY OF MAGNETIZED JET STABILITY USING HIGH ENERGY DENSITY PLASMAS

Hannah Hasson[1], Pierre Gourdain[1], Marissa Adams[1], Dave Hammer[2], Bruce Kusse[2], Roman Shapovalov[1], James Young[1], Matt Evans[1], John Greenly[2], Imani West-Abdallah[1]

1. University of Rochester

2. Cornell University

Astrophysical jets are ubiquitous structures observed in diverse environments, ranging in scale from young stellar objects to supermassive black holes. Most theories assume a gravitational engine to be responsible for generating the powerful axial flows of the jet from an accretion disk. However, the processes that maintain jet collimation and stability remain poorly understood. To understand the mechanisms at play, we propose to conduct a stability study of magnetized jets generated by pulsed-power drivers.

Though many orders of magnitude larger in size, astrophysical jets share the collimation, turbulence, and magnetic drag of high energy density plasma generated in the laboratory. Making an argument of magnetohydrodynamic stability, we may justify our scaling of the system by matching dimensionless parameters of the plasma jet: the Reynolds number (Re), Magnetic Reynolds number (R_M), Mach number (M), and plasma beta (β). We may carefully control the properties of the magnetized jets generated in the laboratory, and then perturb them to quantitatively measure the stability conditions.

Our experiment will use a quasi-axisymmetric load, driven by 1MA and capable of producing a strongly collimated, magnetized plasma jet. We will then quantitatively study the jet's resilience to external perturbations from flows, magnetic fields, and localized heating.

We present results from simulations of the experimental geometry using the 3D extended MHD code PERSEUS, as well as some preliminary experimental results using the COBRA pulsed-power driver. After simulating several versions of the load with varying axial magnetic field strengths, we show that the scaling parameters for our setup indeed lie within the regimes of astrophysical jets: $Re > 10^3$, $R_M \sim 10^3$, $\beta \gg 1$, and $M > 1$.

THOMSON SCATTERING MEASUREMENTS OF BOW-SHOCKS IN RADIATIVELY-COOLED MAGNETICALLY ACCELERATED PLASMA FLOWS

Simon Bott-Suzuki[1], Sam Cordaro[1], Tobias Oliver[1], William Potter[2], Jacob Banasek[2], Sophia Rocco[2], Bruce Kusse[2], Dave Hammer[2]
1. University of California San Diego
2. Cornell University

Shock formation in dense, hot plasma flows where radiation loss is important continues to be an interesting topic for a variety of physics areas in HEDP and beyond. Characterization of the upstream and downstream plasma conditions can help determine the energy balance across the shock and access fundamental parameters including the plasma compressibility. Pulsed power-driven, large spatial scale flows can generate long timescale, stationary shocks for such detailed studies.

Data are presented from 2 pulsed power drivers; the 1MA, 100ns COBRA device at Cornell University and a 200kA, 1us driver at UC San Diego. Shocks are imaged using interferometry and gated self-emission, along with time-integrated x-ray imaging and optical spectroscopy. In addition, optical Thomson scattering is applied to examine the plasma velocity across the shock and the local temperature where possible.

Bow-shock formation using different Z materials show clear differences in the Mach cone angle and cooling profiles. Heating ahead of the shock position is indicative of an upstream radiative precursor a high flow densities. In experiments with multiple colliding shocks, both regular reflection and possible transition to Mach reflection is observed.

–

*Work is funded National Nuclear Security Administration Stockpile Stewardship Academic Alliance program (NNSA SSAA) under U.S. Dept. of Energy Cooperative Agreement DE-FC03-02NA00057

AN ABSORPTION SPECTROSCOPY PLATFORM TO MEASURE PHOTOIONIZATION FRONTS IN THE LABORATORY

Heath LeFevre[1], William Gray[1], Joshua Davis[1], Paul Keiter[2], Carolyn Kuranz[1], R Paul Drake[1]

1. University of Michigan

2. Los Alamos National Laboratory

In present day star forming regions, large, young stars introduce ionizing radiation sources to cold gas clouds. This radiation acts to heat the surrounding gas cloud, causing expansion and a rocket effect. The heat wave that propagates through the gas cloud, causing these changes, is driven by the ionizing radiation in the high-energy tail of the stellar emission, which we call a photoionization (PI) front. Photoionization is the dominant source of heating in this kind of front. Recent work shows it is possible to create this type of heat front in the lab with achievable experimental conditions.

Recent experiments using the Omega-60 laser, attempted to observe PI fronts by heating a N gas cell using an about 80 eV soft x-ray source. Ten 1 ns laser pulses stitched together to form an effective 5 ns pulse with an irradiance of 10^{14} W cm^{-2}, which is incident on a thin Au foil to create an about 80 eV x-ray source. This source should drive a PI front in the N gas. We used absorption spectroscopy of a 1% Ar dopant to probe the system 1250 μm from the source at different times using the 2-4 keV emission from a capsule implosion as the absorption source. Here we show the results of that experiment, where we demonstrated a platform for absorption spectroscopy of a relatively high-pressure gas cell. This includes the characterization of the capsule implosion in $>$2 keV x-ray images, $<$ 600 eV x-ray images, and time resolved flux measurements as well as spectrally from two different angles.

NERNST THERMOMAGNETIC WAVES IN MAGNETIZED HIGH ENERGY DENSITY PLASMAS

Alexander Velikovich[1], John Giuliani[1], Steven Zalesak[2]
1. Naval Research Laboratory
2. Syntek Technologies

The Nernst effect plays the dominant role in the subsonic transport of magnetic flux in high-energy-density (HED) plasmas, where the plasma beta is high, and the temperature diffusivity is much greater than the magnetic diffusivity [1]. This is the parameter range characteristic of MagLIF and other magneto-inertial fusion approaches near stagnation. We demonstrate the transport of magnetic flux in HED plasmas proceeds via the Nernst thermomagnetic waves propagating at the Nernst velocity with respect to the plasma particles down the temperature gradient. The plasma resistivity strongly damps their propagation in the opposite direction. The Nernst wave propagation is a manifestation of an anomalous skin effect transporting magnetic flux into a conducting fluid where it cannot penetrate by diffusion. The Nernst waves, physically similar to those theoretically predicted in the 1960's [2] and observed in metals at cryogenic temperatures [3], have never been discussed for strongly driven, highly inhomogeneous, magnetized HED plasmas at keV temperatures. We report semi-analytic self-similar and numerical solutions of the plasma transport equations involving the Nernst waves, describe the numerical challenges of their modeling and the use of such solutions for extended-MHD and kinetic code verification. We also discuss the effect of the Nernst waves on the losses of heat and magnetic flux from magnetically insulated hot plasmas.

1. A. L. Velikovich, J. L. Giuliani, and S. T. Zalesak, "Magnetic flux and heat losses by diffusive, advective, and Nernst effect in magnetized liner inertial fusion-like plasma," Phys. Plasmas v. 22, 042702 (2015).

2. L. E. Gurevich and B. L. Gel'mont, "Hydrothermomagnetic waves in a weakly inhomogeneous plasma," Sov. Phys. JETP v. 19, 604 (1964).

3. V. N. Kopylov, "Dispersion of thermomagnetic waves in bismuth," Sov. Phys. JETP v. 51, 99 (1980).

----

* Work supported by the US Department of Energy/NNSA.

ELECTRICAL EXPLOSIONS OF CYLINDRICAL WIRE ARRAYS IN DIFFERENT MATERIALS

David Yanuka[1], Savva Theocharous[1], Simon Bland[1], Ya.E. Krasik[2]
1. Imperial College London
2. Technion

Underwater electrical wire explosions have attracted much attention in the recent decade due to the high energy density deposition into the wire, which is possible because of the high breakdown voltage of water compared to air and vacuum, preventing surface breakdown. Moreover, water's small compressibility also contributes to higher energy density deposition, with the plasma maintaining a higher resistivity state for a relatively long time.

During explosion the wire transforms to the plasma state which allows the study of equations of state and transport parameters in warm dense matter conditions. As the wire expands, shock waves are launched into the surrounding water; with cylindrical or spherical wire arrays, one can obtain converging shock waves which also generate extreme pressures on the axis of convergence.

Recently, a study in the Technion – Israel Institute of Technology, showed that using glycerol instead of water as a medium for cylindrical array explosions, increased the shock wave velocity by $\sim$20%, and hence the pressure by $\sim$2 times in the vicinity of convergence. In this presentation, we show the results of cylindrical wire array explosions in other different liquids, such as tungstate water, nitromethane, and in cast plastic. These materials have different densities and sound velocities which influence the generated shock wave velocities and thermodynamic parameters on axis. Also, explosions in plastic, in addition to having higher shock velocities, have the advantages of not needing waterproof systems, and the ability to make wire arrays in different adjustable shapes.

This work was sponsored by Sandia National Laboratories, First Light Fusion, and DOE Cooperative Agreement Nos. DOE Cooperative Agreement No DE-NA0003764

EXPLORING PROPERTIES OF WARM DENSE MATTER USING MICROSECOND TIMESCALE PULSE POWER DRIVE

Robert Reinovsky[1], christopher rousculp[1], Sergey Garanin[2], Sergey Kuznetsov[3]
1. Los Alamos National Laboratory
2. RFNC - VNIIEF
3. RFNC-VNIIEF

The properties, such as equation of state, electrical and thermal conductivity, of warm dense matter is an emerging area of study that applies to the astrophysics of gas giants; to the early stages of ICF capsule implosion; to the initial process of wire or foil cylinder explosions and to the formation of surface plasmas on conductors under fast rising high current densities.

"Warm-dense matter" (WDM) includes conditions near solid density (from 10% of solid density to slightly above solid density) and modest temperatures ($\sim$1-10 eV) and has properties that differ from both condensed matter and traditional plasmas. Warm dense matter conditions can be achieved by laser or particle beam heating of very small quantities of matter on timescales short compared to the subsequent hydrodynamic expansion timescales (isochoric heating) and a vigorous community of researchers have applied these techniques but the microscopic size scale of the WDM produced in this way limits access to many continuum physics properties.

Pulsed power techniques to generate significant quantities of longer-lived WDM include: liner compression of modest density, low temperature plasma to densities approaching solid density, the explosion and subsequent expansion of a conductor (wire) against a high pressure (density) gas background (isobaric expansion), explosion of (non-imploding) foil cylinders confined by material with well-known EOS, and shock compression of low density porous materials (foams). If very large amounts of electrical energy are available, heating and confinement of initially solid samples by high velocity liner impact seems conceptually possible as well.

At modest energy scales, systems like the Pulsed High Energy Liner eXperiment (PHELX) can access WDM conditions using several approaches. In this paper we will provide a review of PHELIX-based techniques that might be applied to explore this interesting new application of pulse power and high magnetic field technology.

NANOSECOND-PULSED CORONA DISCHARGE IN LIQUID NITROGEN AND PRODUCTION OF NITROGEN POLYMERS

Danil Dobrynin[1], Roman Rakhmanov[1], Alexander Fridman[1]
1. Drexel university

Nanosecond-pulsed discharges in liquids have gained attention in recent years. Non-thermal nature coupled with localized high pressures, energetic electrons and reactive species makes these type of discharges an attractive tool for production of materials with unusual properties. Here we present the recent results on characterization of nanosecond corona discharge ignited directly in liquid nitrogen, including fast imaging of the discharge dynamics and time-resolved temperature estimations from the discharge emission spectrum. We also report the results on generation of unstable nitrogen-based energetic materials and their characterization.

* This work is supported by the Army Research Office (grant # W911NF-17-1-0597, PI: Dobrynin).

INVESTIGATION OF ATMOSPHERIC PRESSURE PLASMA JET IN DOUBLE COAXIAL DIELECTRIC BARRIER TUBES CONJUGATED WITH MICROSECOND VOLTAGE PULSE

Duc Ba Nguyen[1], Md. Mokter Hossain[2], Van Toan Nguyen[2], Young Sun Mok[2], Quang Hung Trinh[3], Won Gyu Lee[4]

1. Department of Chemical and Biological Engineering, Jeju National University
2. Jeju National University
3. Duy Tan University
4. Kangwon National University

Atmospheric pressure plasma jet (APPJ) is gaining growing interest in a number of bio-applications. Among various APPJ sources, a dielectric barrier discharge (DBD) reactor has been considered as the most straightforward plasma system to generate APPJ, because one or more dielectric layers isolating metal electrodes can avoid abnormal increase of current during plasma generation. Several DBD configurations have been successful in generating APPJ, e.g., one-ring electrode, one-ring electrode conjugated with a centered pin electrode, and two-coaxial-ring electrodes. In this study, the plasma jet was generated by a particular DBD reactor configuration that comprised two coaxial dielectric tubes with different diameters and two-ring electrodes covering the outside of the larger tube. In order to avoid sparks between the electrodes, the electrodes were immersed in electrical insulating oil. With the two coaxial dielectric tubes, laminar flows of plasma jet (He/Ar) and shielding gas (N2/Air) can be created. The primary plasma discharge occurred with plasma gas inside the discharge zone, whereas there was no or weak plasma discharge of shielding gas due to high-voltage breakdown. The effects of shielding gas on the plasma jet parameters (plume length, temperature), optical emission spectrum, and gas emission will be examined under various applied voltages (microsecond voltage pulse).

A COMPARISON BETWEEN AG/ZSM5 AND CU/ZSM5 CATALYSTS COUPLED WITH PLASMA IN HYDROCARBON CATALYTIC REDUCTION OF NOX AT LOW-TEMPERATURES

Van Toan Nguyen[1], Duc Ba Nguyen, Md. Mokter Hossain, Young Sun Mok
1. Department of Chemical and Biological Engineering, Jeju National University

The temperature of exhaust gases in diesel engines usually fluctuates in the range of 100∼400 °undefined; unfortunately, the performance of hydrocarbon selective catalytic reduction (HC-SCR) that is the most common technology to remove nitrogen oxides (NOx) is not satisfactory at low-temperatures. The temperature window for the HC-SCR can be expanded to a wider range by the combination with atmospheric-pressure plasma. In the present work, the HC-SCR of NOx has been investigated with a packed-bed dielectric barrier discharge (DBD) plasma reactor system in the temperature range up to 350 °undefined. The active metals such as silver (Ag) and copper (Cu) were supported on ZSM5 zeolite. Several hydrocarbons such as C2H4, C3H8 and C7H16 have been proposed as a reducing agent for the process. A comparison between Ag/ZSM5, Cu/ZSM5 and Ag-Cu/ZSM5 for the HC-SCR coupled with plasma has been made in terms of reaction temperature, NOx reduction efficiency, and hydrocarbon consumption, varying temperature increase rate to simulate fluctuating temperature of real exhaust gas. The experimental observations provide critical information on the practical applications of plasma-coupled HC-SCR over ZSM5-supportedcatalysts.

NANOSECOND-PULSED OXYGEN DBD TREATMENT OF WATER AND PRODUCTION OF ”PLASMA ACID”

Ryan Robinson[1], Alexander Fridman[1], Danil Dobrynin[1]
1. Drexel University

Plasma treatment of water has been investigated extensively for the last decade in relation to a number of promising applications in biomedical, environmental, and agricultural fields as well as food processing. Plasma treated water typically has high oxidative properties and wide range of reactive species produced including ·OH, ·O, H2O2, NO3-, ONOO-. In this study we focus on DBD plasma in oxygen or oxygen/noble gas mixtures which has been shown to produce acidic water solutions, sometimes referred as “plasma acid”, with strong but temporary oxidizing properties. The conjugate base of this oxygen plasma-produced acid remained unidentified. The results presented here suggest that “plasma acid” contains unstable O2- and O3- as possible anion species.

----

* This work is funded by the NSF/DOE Partnership in Basic Plasma Science and Engineering (DOE grant DE-SC0016492, PI: Dobrynin).

SUPPORTED VANADIUM OXIDES MODIFIED BY NON-THERMAL PLASMA FOR NITROGEN FIXATION

Rim Bitar[1], Moazameh Adhami Sayad Mahaleh[1], Anton Nikiforov[1], Karen Leus[1], Pascal Van Der Voort[1], Rino Morent[1], Nathalie De Geyter[1]
1. Gent University

Plasma-assisted surface modification of silica supports and fully synthesized vanadium oxides was performed in a direct current hollow cathode discharge plasma sustained in O_2 gas. Operational plasma parameters, such as pressure, discharge power, and exposure time were also optimized to reach the highest possible plasma treatment effect. The modified catalysts were characterized using different techniques such as X-ray diffraction, X-ray photoelectron spectroscopy, scanning electron microscopy, Brunauer–Emmett–Teller, Fourier transform infrared, and inductively coupled plasma atomic emission spectroscopy. The results showed that the surface active sites of these catalysts were enhanced with the treatment of plasma, which improved the dispersion of the catalysts [1]. In addition, the average pore size was slightly enlarged, and the pore size distribution of the catalyst became wider. The XPS results revealed that the non-thermal plasma increased the oxygen functional groups on the catalyst's surface, which contributed to their increasing activity [2]. Next, these active catalysts were introduced into a negative direct current multi-pin-to-plate glow discharge reactor generated in N_2/O_2 gas mixture in order to be used for N_2 oxidation. It was shown that the use of the catalyst resulted into the synthesis of NO_x products. This study confirms that non-thermal plasma treatment is an effective tool to manipulate the catalyst surface properties for N_2 fixation processes.

[1] X. Zhang, W. Sun, C. Wei, Effect of glow discharge plasma treatment on the performance of Ni/SiO_2 catalyst in CO_2 methanation, Journal of Fuel Chemistry and Technology, 41 (2013) 96-101.

[2] C. Liu, J. Lan, F. Sun, Y. Zhang, J. Li, J. Hong, Promotion effects of plasma treatment on silica supports and catalyst precursors for cobalt Fischer–Tropsch catalysts, RSC Advances, 6 (2016) 57701-57708.

STUDY OF PLASMA CATALYST INTERACTIONS BY TIME RESOLVED DIFFUSE REFLECTANCE INFRARED FOURIER TRANSFORM SPECTROSCOPY

Shiqiang Zhang[1], Yudong Li[2], Andrew Knoll[1], Jinkai Jiang[3], Peter Bruggeman[3], Gotlieb Oehrlein[2]

1. University of Maryland College Park
2. University of Maryland, College Park
3. University of Minnesota

Cold atmospheric pressure plasma (CAP) assisted thermal catalysis has shown promise to enhance catalytic efficiency by a process called plasma-catalyst synergy (PCS). The overall goal of this work is to obtain mechanistic insights on surface phenomena in PCS. The system under investigation is partial oxidation of methane using a Ni supported catalyst assisted by an atmospheric pressure plasma jet (APPJ). The evaluation of gas phase and surface changes as a function of feed gas composition, catalyst temperature and time provides information on plasma-catalyst interaction during the chemical conversion process. In prior work by our group, results of remote gas phase characterization by IR absorption spectroscopy has been reported for this system A synergistic effect of plasma assisted catalysis was observed for gas phase CO production. The synergistic effect is found to be strongly enhanced by plasma power and reduced for increased catalyst temperature. In this work we complement these results with the measurement of the surface response of the supported Ni catalyst assisted by the APPJ by diffuse reflectance infrared Fourier transform spectroscopy (DRIFTs). A synergistic effect for surface bonded C-O was observed during the exposure of the Ni catalyst to the APPJ for low oxygen conditions. When the supported Ni catalyst was subjected to the plasma-generated particle fluxes for highly oxidizing conditions, the presence of surface bonded C-O was suppressed. The surface behavior of C-O correlates with the measured plasma-catalytic CO production in the gas phase measured downstream when plasma source is switched from low oxygen portion case to a high oxygen portion case, especially at high catalyst temperature (500 oC). The behavior of other surface adsorbed species, e.g. CHx, for different plasma-catalyst operating conditions will also be reported and discussed.

We gratefully acknowledge funding from US Department of Energy (DE-SC0001939) and National Science Foundation (CBET-1703211).

MULTISPECIES NONEQUILIBRIUM PLASMA FLUID SIMULATION OF AN ABLATING ARC DISCHARGE IN ATMOSPHERIC PRESSURE

Adnan Mansour[1], Kentaro Hara[1]
1. Texas A&M University

A one-dimensional fluid plasma model is developed to study an ablating arc discharge using graphite electrodes in atmospheric pressure conditions. The plasma physics and chemistry are coupled with the plasma-wall interactions, e.g. sheath, electron emission, evaporation, and deposition. In the plasma model, chemical, thermal, and velocity nonequilibrium are accounted for and equilibrium effects are observed as a consequence of large intermolecular collision frequency. A cathode deposit model is developed to estimate the size of the cathode deposit based on the principle of energy minimization, i.e. there is an optimal deposit area (or deposit temperature) which minimizes the energy loss on the deposit due to evaporation and radiation for a given electron current. The numerical results show good qualitative agreement with previous experimental results, showing the transition between high and low ablation modes. In our numerical simulations, it is found that the radiative heat transport between the electrodes plays an important role in determining the anode temperature, which is a potential mechanism for the enhanced ablation characteristics observed in experiments.

THE DEVELOPMENTS OF LINEAR TRANSFORMER DRIVERS IN XI'AN JIAOTONG UNIVERSITY

Jian Wu[1], Fengju Sun[2], Xingwen Li[1], Aici Qiu[1], Xiaofeng Jiang[2], Zhiguo Wang[2], Hongyu Jiang[2], Huantong Shi[1], Li Chen[1], Penghui Li[1]
1. Xi'an Jiaotong University
2. Northwest Institute of Nuclear Technology

Xi'an Jiaotong University in collaboration with the Northwest Institute of Nuclear Technology, is developing fast linear transformer driver (FLTD) technology for high energy density physics applications. Recently, the advances in gas switches, bricks, cavities and triggering system have been made.

First, a new type of three-electrode field distortion gas switch was developed, and FLTD bricks composed of two 100nF capacitors and one switch was built. Each brick can deliver a 49.2kA pulse current to a compactly connected 78nH/2.2Ω load under a charging voltage of ±100 kV. The discharge current waveform indicates that the inductance of the brick is ∼ 160 nH. Second, a multi-gap gas switch, with resistors and capacitors mounting in parallel with the switch gaps, was developed. At a charging voltage of ±80 kV and operating at 60% of the self-breakdown voltage, the trigger voltage was reduced from 110 kV to 75 kV while the 3.2 ns jitter of the switch was preserved. Third, a FLTD cavity composed by 23 bricks and one built-in trigger brick was built. One single trigger pulse was used to trigger the triggering brick, and the other 23 bricks were triggered by the discharge of the trigger brick, which used the modified multi-gap gas switch. The cavity can deliver a 0.9-MA 120 ns pulse to a 5nH/0.06Ω load when charged to ±80 kV. Finally, a four-cavity 1 MA FLTD voltage adder is under construction. The FLTD module will use gas insulation and a transmission line insulated with deionized water. Some new ideas including: multistage cascade trigger and sharing common cavity will be tested.

EXPERIMENTAL RESULTS FROM THE THE 1.2 MA, 2.2 M DIAMETER LINEAR TRANSFORMER DRIVER CAVITY AT SANDIA NATIONAL LABS

Jon Douglass[1], Brian Hutsel[1], Josh Leckbee[1], Brian Stoltzfus[1], Matthew Wisher[1], Mark Savage[1], William Stygar[1], Eric Breden[1], Jacob Calhoun[1], Michael Cuneo[1], Owen Johns[1], Michael Jones[1], Diego Lucero[1], James Moore[1], Matthew Sceiford[1], Mark Kiefer[1], Thomas Mulville[1], Robert Hohlfelder[1]
1. Sandia National Laboratories

In this presentation we describe the design, simulation and performance of a 118-GW linear transformer driver (LTD) cavity at Sandia National Laboratories. The cavity consists of 20 to 24 “bricks”. Each brick is comprised of two 80 nF, 100 kV capacitors connected electrically in series with a custom, 200 kV, three-electrode, field-distortion gas switch. The brick capacitors are bi-polar charged to a total of 200 kV. Typical brick circuit parameters are 40 nF capacitance (two 80 nF capacitors in series) and 160 nH inductance. The switch electrodes are fabricated from a WCu alloy and are operated with breathable air. Over the course of over 10,000 shots the cavity generated a peak electrical current and power of 1.19 MA and 118 GW. Experimental results are consistent (to within uncertainties) with circuit simulations for normal operation, and expected failure modes including pre-fire and late-fire events. New features of this development that will be presented include: high-impedance solid charging resistors that are optimized for this application and evaluation of maintenance-free trigger circuits using capacitive coupling and inductive isolation.

LOW-INDUCTANCE LOAD TEST OF A NEW 300-KA, 150-NS PULSER FOR FAST X-PINCH SOURCES

Roman Shapovalov[1], Marissa Adams[1], Matt Evans[1], Hannah Hasson[1], James Young[1], Imani West-Abdallah[1], Pierre Gourdain[1]
1. University of Rochester

X pinches are well-known sources for point-projection radiography: given the right conditions, they generate very bright, x-ray bursts launched from a very small, dense plasma source. To advance the performance of these x pinches, a new, compact pulser was built at the University of Rochester. The pulser is a spin-off of Linear Transformer Driver technologies: it consists of 5 LTD bricks (which is two capacitors and high-current switch all are connected in series) directly coupled to the transmission line, with bricks hanging from the transmission line rather than positioned radially outward, as it is the case in usual LTD designs. The pulser can store up to 1-kJ of initial energy when charged to $\pm$100 kV, and simulations predict it can deliver up to 300-kA of peak current into an inductive x-pinch load with less than 150-ns time-to-peak. In this paper we present short-circuit measurements of the pulser. The load is 2.54-cm-long, 96-cm-diameter metal cylinder installed in the anode-cathode gap with inductance of only 1.13 nH. The current oscillations into this load allow us to directly measure the driver internal inductance and resistance. The data will be compared with the Screamer simulations.

CURRENT ADDING STRATEGIES IN COMPACT LINEAR TRANSFORMER DRIVERS

Pierre Gourdain[1], Marissa Adams[1], Matt Evans[1], Hannah Hasson[1], Roman Shapovalov[1], James Young[1], Imani West-Abdallah[1], Rick Spielman[2]
1. University of Rochester
2. Idaho State University

Linear transformer drivers have now become the technology of choice for the next generation of pulsed-power devices. The main advantage of LTDs over Marx generators, is the lack of pulsed compression hardware. Dropping this requirement has enabled the design of more efficient, highly modular systems. But capacitor technology is still a limiting factor, with two hard limits: peak current and charge voltage. Research needs dictate current and voltage at the load and capacitors must be arranged in series to meet voltage constraints, and in parallel to meet current constraints. As more and more capacitors are added in parallel to increase current, the diameter of the LTD cavity becomes so large that it becomes impractical to stack cavities in series, de facto limiting the voltage of the driver. In this talk, we will show how current requirements can be met using compact LTD cavities. While this design can be applied to multi-mega-ampere designs, we will focus on University-scale machines, limiting our discussion to one mega-ampere. Based on a post hole-convolute approach, nested transmission lines located inside the cavity bore are used to add currents together. Using high resolution electromagnetic simulations with full electrical circuit coupling, different topologies will be discussed, and a final design will be presented.

NEW TYPE OF CAPACITOR-SWITCH ASSEMBLY FOR LTD TECHNOLOGY

Ivan Lavrinovich[1], Semen Vagaytsev[2], Aleksander Erfort[2], Dmitry Rybka[3], Denis Molchanov[4], Anton Artemov[2], Alexander Zhigalin[5], Aleksander Lensky[2]

1. HCEI SB RAS

2. Institute of High Current Electronics

3. Institute of High Current Electronics SB RAS, Tomsk, Russia

4. IHCE SB RAS

5. Institute of High Current Electronics SB RAS

In LTD technology, the critical element that has the greatest impact on the output parameters of the generator is the primary storage unit - the capacitor-switch assembly (or “brick”). The electrical parameters of the capacitor-switch assembly (CSA), its dimensions and number determine the parameters of the LTD stage and, as a result, of the total LTD generator. This paper presents a new type of CSA 160-0.1, describes the features of its design and output parameters. The results of high-voltage tests of the new CSA with the matched load and intermediate results of life tests are presented. We have evaluated the prospect of using the developed CSA in the LTD technology.

THE DEVELOPMENT OF ALL-SOLID PULSE GENERATOR BASED ON MULTI-TURN LTD

shoulong dong[1], Jianhao Ma, yilin wang, weirong zeng, Chenguo Yao
1. Chongqing University

An all-solid-state pulse generator based on multi-turn LTD is designed for the application of pulse power techniques with high-voltage, large-current and wide pulse width. The magnetic core of the LTD pulse generator adopts the method of multi-turn winding, which can output pulse of wide pulse width. The isolation of drive power supply and energy charging with co-direction winding of LTD modules is designed, and the isolation voltage of magnetic cores at is the working voltage of LTD modules. The multi-turn LTD pulse generator is composed of 10 LTD modules. Each module is connected in parallel by 18 energy storage capacitors and MOSFET discharge switches, and its synchronous drive circuit is designed. Through the analysis and selection of the components model and circuit, a modular all-solid-state pulse generator based on multi-turn LTD is development, which can output pulse parameters for the voltage amplitude 0-5 kV, the output pulse current up to 500 a, pulse width 200 ns - 5 μs, pulse rise time 30 ns, pulse falling time 16 ns, and its parameters can adjusted flexibly such as pulse width and amplitude. Moreover, higher voltage pulse can be achieved by increasing the number of LTD module.

CONSTRUCTION OF THE BLUE LINEAR TRANSFORMER DRIVER (LTD) AT UNIVERSITY OF MICHIGAN

Brendan Sporer[1], Ryan McBride[1], Nick Jordan[1]
1. University of Michigan

The BLUE linear transformer driver (LTD) system is being constructed in the University of Michigan's Plasma, Pulsed Power, and Microwave Lab. The system will be comprised of four LTD cavities, which were previously part of the 21-cavity Ursa Minor facility at Sandia National Laboratories. The system will be capable of delivering up to 8kJ to a proper load in a 200kA, 100ns pulse. Dual 100kV, 12kW Spellman power supplies theoretically allow rep-rate as high as 1.5 Hz for high-power microwave or gas puff Z-pinch experiments. In addition to the power supplies and some high-voltage Ross relays, several vacuum components have been ordered. These components include custom adapters and a custom 24" OD load chamber. An additional adapter will be needed to mate the cavities to a gigawatt-class, high-power microwave (HPM) load. Meanwhile, assembly of the first cavity is nearly complete. 3D printing has proved invaluable for cheap prototyping and production of non-standard nylon parts. To this end, custom feedthroughs were developed to allow quick disconnection of HV cables at the cavity, so the cavities could be easily moved even if filled with oil. The next challenge is to consider a novel method of switch diagnostics, one that may extend the approach currently used on the existing MAIZE LTD system. With the archetype cavity nearly complete, the three remaining cavities should assemble more swiftly. The custom vacuum components should arrive in a few months. Presented in this poster is the design and current construction progress of the BLUE system.

ASELSAN ELECTROMAGNETIC LAUNCH LABORATORY: FIRST SHOT

Mustafa Karagoz[1], Baran Yildirim, Emre Burak Yurdakul, Emre Durna, Ozgur Cavbozar, Ulas Gocmen, Evren Tan, Yasin Cevik, Anıl Civil

1. ASELSAN

ASELSAN Inc. has been conducting experimental research on electromagnetic launchers since 2014. A 1 MJ first generation and 3.25 MJ second generation Pulsed Power Supplies are built and tested with 25 mm x 25 mm square bore EMFY-1 Electromagnetic Launcher at open area test range by ASELSAN. In 2018 ASELSAN constructed a laboratory in Ankara to conduct experiments up to 2 MJ muzzle energy. For this goal stored energy of the second generation pulsed power supply will be increased to 8 MJ. ASELSAN started to use this laboratory with new EMFY-2 Electromagnetic Launcher since beginning of 2019.

This paper describes ASELSAN Electromagnetic Launch Laboratory and represents results of the first shot of EMFY-2 Electromagnetic Launcher fed by 3.25 MJ PPS in this laboratory.

Keywords: Pulsed Power Supply; Electromagnetic Launch; Electromagnetic Launcher; Hypervelocity; Railgun

NUMERICAL ANALYSIS OF THE MAGNETIC EXPANSION FORCE ON THE SOLENOID COIL IN A FOUR-STAGE INDUCTION COILGUN WITH PULSED POWER SUPPLIES

Myung-Geun Song[1], Hui Min Kim[1], Yong Kyu Lee[1]
1. Launcher Systems R&D Center, Research Institute, Hanwha Defense Corporation

The induction type multi-stage coilgun with pulsed power supplies has been widely developed to apply on the missile launcher system as cold-launching technology using electromagnetic forces. In this coilgun system, the electromagnetic energy generated by pulsed power module is transferd to the kinetic energy to accelerate the armature coil equipped with a projectile. It has advantages that the projectile is being contactless, flame-free launching process, and high reusability.

In general, in order to accelerate a heavy projectile to several tens of meters in height using an induction type coilgun, a high voltage pulsed power source which is about 1 kV to 10 kV is applied to the solenoidal exciting coil. Since the exciting coil is almost in a short circuit state, a large current flows instantaneously in the stator coil when a high-voltage pulsed power is applied. At this time, the magnetic expansion force is generated by the exciting current on the solenoid coil in radial direction of the stator coil.

This paper is focused on the mathematical calculation and numerical analysis of the magnetic expansion force acting on the solenoidal exciting coil induced by high-voltage pulsed power supplies. Above all, the analysis of the electromagnetic force on the stator coil is one of the essential basic design process to evaluate the structural stability and electromagnetic property for the launcher system. In this paper, the mathematical modeling of magnetic expansion force was proposed and the computed results from the proposed equation are verified through simulaed ones using finite element analysis.

INVESTIGATIONS ON THE ENERGY CHAIN SUPPORTING A NAVAL RAILGUN

Stephan Hundertmark[1]
1. ISL

Due to the large muzzle velocities achieved by railguns, they are especially usefull to further extend the reach of artillery systems. At gun exit velocities of about 2.5 km/s a heavy artillery round is able to cover distances far above 100 km. In contrast to conventional, explosively driven guns, railguns apply constant acceleration pressure over the full acceleration length, resulting in a short, compact barrel. The weigth and volume of the required pulsed power supply (PPS) puts currently a question mark on the ability of the railgun to replace conventional artillery guns on existing mobile systems. For a shipboard railgun the ISL investigates since several years the possiblities of capacitively or inductively driven railguns. To allow for a focused discussion, a specific, realistic scenario was developed. A 25 MJ muzzle energy railgun accelerates a 8 kg heavy launch package to 2.5 km/s. As further parameter, the number of rounds to be fired per minute was fixed to 6. In a subsequent analysis, this scenario was used to compare a coil based PPS to a capacitor based PPS. It could be shown that both systems have specific advantages and disadvantages. The main disadvantage for a capacitor based system seems to be its weight and volume, while the coil based system suffers from its inability to store energy for longer than a fraction of the launch time. In a continuation to further define the investigated system this study includes batteries as primary energy stores and evaluates numbers for the overall system weight and volume. As batteries are able to store a large amount of energy, the system battery—PPS—railgun is a (close to) independent system that could be used as a “plug-in” replacement for the currently used deck gun on vessels.

.

MAGNETIC SHIELDING EFFECTIVENESS OF LAYERED MEDIUM-WALLED STRUCTURES

Tyler Buntin[1], Landon Collier[1], Colt James[2], James Dickens[1], John Mankowski[1], Andreas Neuber[1]
1. Texas Tech University
2. Raytheon

A 3-axis custom built probe is utilized to measure the diffused magnetic field magnitude inside a shielded structure with walls composed of conductive and magnetic materials. The probe has a sensitivity of 2 mV per tesla per second at a spatial resolution of approx. 0.3 cm3 per coil. The probe's temporal resolution of 1.5 microseconds is more than sufficient to capture the sinusoidal magnetic field with an approximate frequency of 6.3 kHz.

Layers of aluminum and mild steel are used to create alternating highly conductive and high permeability shields. The shielding performance of these material layers is analyzed and compared to determine the most effective method of shielding that reduces overall wall thickness while minimizing diffused magnetic field for external field amplitudes of 200 mT with 9,000 T/s as the measured dB/dt rise. Introducing an approximately 2.5 mm air gap between two half skin depth thick walls resulted in a reduction of diffused internal field by roughly 20%.

The impact of partially filling a shielded structure with conductive material away from the shield surface is also analyzed. As the magnetic flux that diffuses through the shield is largely independent of the structure's leftover air-volume, the magnetic flux density inside the structure increases as the volume becomes filled with conductive material. Experimental results were compared with the previously simulated, obtained with FEM simulations performed with COMSOL Multiphysics, which indicated a factor of two increase in the internal magnetic field when the volume was 60% filled. That is, without making any changes to the shield walls themselves, the induced voltage in a victim circuit inside the shielded structure would also increase simply by filling up the structure with more conducting material.

FACTORS INFLUENCING THE EFFICIENCY OF AN INDUCTION COILGUN

Ranashree Ram[1], Chiranjeev S. Sirola[2], M. Joy Thomas[2]
1. IISc Bangalore
2. Indian Institute of Science Bangalore

In this paper, the results of a study of the parameters which influence the efficiency of an induction coilgun are presented. Efficiency in the present context is defined as the ratio of final kinetic energy ($\frac{1}{2}\mathrm{m}v^2$) of the projectile to the total input electrical energy of all the stages taken together ($\sum_{k=1}^{n} \frac{1}{2} C_k V_k^2$), where m is the mass of the projectile, v is the muzzle velocity of the projectile, C_k is the capacitance used in k^{th} stage, V_k is the k^{th} stage voltage and n is the total number of stages. In the first part of the analysis, one of the parameters of the coilgun among the following parameters, viz., aspect ratio (length/diameter) of the projectile, inductance and resistance of the coil, capacitance and voltage of the single stage, is varied keeping all the other parameters fixed and the variation in the efficiency is studied. In the second part, the design parameters as obtained from the first part are used in the design of a multistage coilgun and it is shown that it is more efficient than a single stage coilgun and that it also gives a higher projectile velocity.

These results would be helpful for the optimal design of an induction coilgun i.e. selecting the aspect ratio of the projectile, inductance of the coil, optimum capacitance and voltage value for a constant input electrical energy. The variation in current through the coil and the rate of change of current ($\frac{di}{dt}$) are also analysed while keeping the total input energy constant and varying the stage capacitance and its charging voltage which would be beneficial for the optimum choice of the parameters of the pulsed power supply source for the induction coilgun.

FLYER ACCELERATION USING UNDERWATER WIRE EXPLOSIONS

Savva Theocharous[1], David Yanuka[2], Simon Bland[1], Luis Sebastian Caballero Bendixsen

1. Imperial College London

2. Technion - Israel Institute of Technology

We present early results for a novel flyer acceleration method using pulsed power. Flyer plate impact is of interest for material equation of state research, and more recently for a novel fusion ignition scheme being developed at First Light Fusion Ltd. Generation of the desired planar shock is dependent on maintaining a symmetric flat flyer face, with the front surface of the flyer in a solid state at impact. Flatness can be compromised by non-uniform driving force, and the front surface of the flyer can be melted by shocks, either imparted directly into the flyer or formed within by steepening of a compression wave.

In this method, an underwater planar wire array is exploded using a current pulse, generating an approximately planar shock in the water that reaches and accelerates the flyer. This method may provide more control over the spatial profile of the force accelerating the flyer than other methods such as magnetic stripline acceleration, by controlling the current path using wires of varying diameter, material and position. Reverberation of the shocks between the front and back of the water-filled cavity allows the use of multiple weak shocks to accelerate the flyer – aiming to provide a quasi-isentropic drive and prevent damage to the front surface.

Initial results indicate velocities of around 400 m/s using a 10 mm by 10mm, 1 mm thick aluminium flyer, with a peak current of $\sim$600kA. Work is in progress to improve and further diagnose this, as well as investigate the energy coupling efficiencies between the wires, water and the flyer plate.

This work was sponsored by EPSRC, First Light Fusion ltd, Sandia National Laboratories and the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764

DESIGN AND ELECTROMAGNETIC ANALYSIS OF A MULTI-STAGE INDUCTION COILGUN SYSTEM FOR HEAVY PROJECTILE

Byeong-Soo Go[1], Dinh-Vuong Le[1], Myung-Geun Song[2], Minwon Park[1], In-Keun Yu[1]

1. Changwon National University

2. Hanwha Defense Corporation

Electromagnetic launchers using pulsed power are more advantageous than chemical guns because they use electromagnetic force to accelerate amateurs at a higher velocity. The railgun can accelerate a light projectile to hypervelocity, while the induction-based coilgun is used for accelerating heavy projectiles (weighing hundreds of kilograms). The induction-type coilgun systems are therefore a subject of considerable research interest. In particular, the capacitor-driven multi-stage induction coilgun, which features almost no physical contact between the barrels and the projectile, has a longer gun lifetime as well as higher efficiency when compared to other electromagnetic launchers. The coilgun system have high efficiency but experience electromagnetic forces in coil assembly parts. It is therefore necessary to analysis the electromagnetic characteristics of the coilgun system to provide high efficiency and reliability.

In this paper we present design and electromagnetic analysis of a multi-stage induction coilgun system for heavy projectile.

The final goal of the coilgun system is to accelerate the heavy projectile more than 20 m/s with high efficiency. The fundamental specifications of the induction type coilgun system was investigated via mathematical analysis model using MATLAB considering pulse power module. The electromagnetic characteristics of the multi-stage coilgun system was analyzed using electromagnetic analysis using FEM programs. The electromagnetic analysis results were compared with mathematical analysis results.

As the results, voltage, current, force, velocity, and projectile acceleration of the multi-stage coilgun system were very similar to mathematical analysis results, and the designed coilgun system satisfy the target velocity with high energy efficiency. The stress of the coil structure was less than the allowable stress of the materials, and the increasing temperature was within the permissible range. The design specifications and the FEM analysis results of the coilgun for heavy projectile can effectively be utilized to develop a multi-stage induction type coilgun system.

NONLINEAR STRUCTURES UNDER THE INFLUENCE OF POLARIZATION FORCE IN NON-MAXWELLIAN DUSTY PLASMA

Nareshpal Singh Saini[1]
1. Guru Nanak Dev University, Amritsar

Dust is an ubiquitous component of space and astrophysical environments and has a wide ranging applications in the different fields as well as in the study of astrophysical and space environments. Most of the space and astrophysical observations confirmed the presence of non-Maxwellian distribution of particles in different plasma environments. Nonthermal ions from the Earth's bow shock have also been observed by the Vela satellite and in and around the Earth's foreshock. The effects of dust grain charge fluctuations, external magnetic field and obliqueness are found to modify the properties of this dust acoustic nonlinear structures significantly. Nonthermal ion populations have also been found to occur in the magnetospheres of Jupiter and Saturn. The deformation of the Debye sheath around the dust particulates in the background of non-uniform plasmas is termed as polarization force, which is an important front-line area of research in dusty plasma from the last few decades. This polarization force modifies the characteristics of dust acoustic waves (DAWs). It is interesting to study the interaction between dust acoustic nonlinear structures travelling in opposite directions in a dusty plasma with charged particles featuring non-Maxwellian distribution under the effect of polarization force and is investigated by employing extended Poincaré-Lighthill-Kuo method. We have also studied the shocks structures under the influence of superthermal polarization force. Further, We have investigated the head-on collision between multi-solitons, shocks etc. It is found that the effect of polarization force and the presence of non-Maxwellian ions have an emphatic influence on the phase shifts after interaction. In a small amplitude limit, the impact of polarization force on time evolution of nonlinear structures is also illustrated. It is remarked that the present theoretical pronouncements may be useful in laboratory experiments and in space/astrophysical environments (such as in planetary ring systems and cometary tails).

SOME PROPERTIES OF ION-ACOUSTIC AND DUST-ACOUSTIC INSTABILITIES IN NON-MAXWELLIAN SPACE PLASMAS

Warda Nasir[1], M N S Qureshi[2]
1. Forman Christian College
2. GC University, Lahore

In this study, for the first time ion-acoustic and dust-acoustic currentless instabilities have been studied in such non-Maxwellian space plasma environment in which solar wind plasma penetrates the cometary plasma in the presence of interstellar dust. We use Vlasov equation to derive the expressions of real frequency and growth rates when both electrons and ions follow double spectral generalized (r,q) distribution function which have been commonly observed in space plasmas such as Earth's magnetosheath and magnetosphere. The spectral indices r and q in the distribution characterize the flat top at low energy and high energy tail, respectively. The generalized (r,q) distribution function reduces to the kappa and Maxwellian distributions in the limiting cases. The electrostatic instabilities thresholds are found to be modified by the presence of nonthermal distribution. Comparison of our numerical results based on the (r,q) distribution function with the Maxwellian results is also presented using the observed plasma parameters from space plasmas. We hope that results presented in this study would be helpful in the understanding of physical mechanisms going on in such space plasmas.

FIELD-ALIGNED CHAINS WITHIN THE PK-4 ENVIRONMENT

Truell Hyde[1], Lorin Matthews[1], Peter Hartmann[2], Marlene Rosenberg[3], Oleg Petrov[4], Vladimir Nosenko[5], Jie Kong[1], Ke Qiao[1], Eva Kostadinova[1], Jorge Carmona-Reyes[1]
1. CASPER - Baylor University
2. Wigner Research Centre for Physics, Budapest, Hungary
3. University of California at San Diego
4. Joint Institute for High Temperatures, Russian Academy of Sciences
5. DLR Institute of Materials Physics in Space

Complex plasmas have proven a versatile analog for the study of soft matter systems, particularly those whose global behavior is determined by the combined effect of the particles'low kinetic energy, interparticle interactions mediated by the streaming ion flow and local confinement forces. On Earth, the streaming ion flow plays a major role in shaping the interparticle interaction and in turn the overall particle alignment. However, the effects of the ion flow are in general much weaker than other system forces and usually masked by gravity for terrestrial experiments. The Plasma Kristall-4 (PK-4) experiment currently in operation on the International Space Station (ISS) provides a microgravity environment which avoids this issue. This talk will discuss the underlying physics behind the formation of the extended particle chains observed in the PK-4 ISS system. Data from the PK-4 ISS will be compared to data collected from the PK-4-B device at Baylor and to numerical simulations of the complex plasma, dust charging and plasma-dust interactions.

Support from NASA Grant number 1571701 and NSF Grant numbers 174023 and 1707215 is gratefully acknowledged.

PLASMA KRISTALL-4: ANOMALOUS DIFFUSION AND VORTICITY IN A MULTI-CHAIN DUSTY PLASMA

Evdokiya Kostadinova[1], Joshua Padgett[2], Constanze Liaw[3], Peter Hartmann[4], Marlene Rosenberg[5], Lorin Matthews[1], Truell Hyde[1]

1. Baylor University

2. Texas Tech University

3. University of Delaware

4. Hungarian academy of sciences

5. University of California at San Diego

Understanding the thermodynamics of dusty plasmas requires knowledge of the energy transfer, or convection, in this open driven dissipative system. Convection is the global flow of heat due to particle transport, which includes the two subprocesses: advection (directed flow) and diffusion (random motion). The interaction with the ion flow and the presence of gradients in the dust charging can induce long-distance correlations, resulting in anomalous dust diffusion and global instabilities in the dust structure. The coexistence of subdiffusion (trapping) and superdiffusion (enhanced transport) in different regions of the same dusty plasma structure have been previously related to the onset of global cooperative motion in the form of a vortex flow.

Here we present a study of anomalous diffusion and vorticity in multi-chain dusty plasmas formed in the Plasma Kristall-4 facility on board the International Space Station. Video data from these experiments have been analyzed to characterize the diffusive behavior of dust chains throughout the cloud as well as the presence of global vorticity. The connection between the observed diffusion regime and global dynamics is investigated analytically using a spectral technique, where long-distance correlations within the system are modeled by a fractional Laplacian operator. As the analytical method relies on spectral analysis while the experimental results are kinetic in nature, the agreement between the two provides a new and powerful technique for the study of complex transport phenomena.

Support from NASA Grant number 1571701, and NSF Grant numbers 1707215 and 174023 is gratefully acknowledged.

THE EFFECT OF VARIABLE DUST SIZE AND CHARGE ON THE PROPAGATION OF ROGUE WAVES IN MAGNETIZED SOLAR WIND DUSTY PLASMA

Atef Elbendary[1]
1. Assistant Professor at Egypt

Abstract:

In the solar wind, Dust acoustic rogue wave are investigated in a three component magnetized solar wind plasma. The boundary layer regions are the sources for inhomogeneous dusty plasmas and are natural laboratories to study wave phenomena. In this regions, the distribution of the particles differ from Maxwellian and are found to be non-thermal. Therefore, amplitude of the waves propagating through these regions can vary differently compared to the homogeneous plasma. In this study, the effect of variable dust size and charge on the propagation of rogue waves in magnetized solar wind dusty plasma with nonextensive electron is examined. The electrons are considered to be having non-thermal Cairn's type distribution. The theoretical model to evaluate the nonlinear inhomogeneous DAWs is governed by the Korteweg-de Vreis (KDV) and (mKDV) equations and by using a reductive perturbation technique, the nonlinear Schrodinger (NLS) equation with variable coefficient investigated. Analytical solution of the NLS equation shows that the dependence of the dust charges on the plasma parameters, the effects of different plasma parameters on the velocity, the amplitude and width of DAWs. Also, high nonextensive as well as large size dust grains lead to the wave amplitude increases and DA rogue waves concentrates therefore a significant amount of energy.

DUST-ION ACOUSTIC TRAVELLING WAVES AND CHAOS IN A MAGNETO-ROTATING DUSTY PLASMA

YASHIKA GHAI[1], Barjinder Kaur, N.S. Saini[1]
1. Guru Nanak Dev University

It is important to identify the behavior of a dynamical system, whether it is chaotic or regular on introducing a perturbation. Many authors have observed the chaos through different routes viz. quasi-periodic route to chaos, crisis route to chaos, period doubling route to chaos, etc. Coriolis force plays a very significant role in cosmic phenomena and other plasma environments including rotating plasma in space as well as laboratory plasmas. Number of authors have attempted to examine the nature of propagating waves in rotating plasmas while considering the effects of Coriolis force. In Tokamak and most of the astrophysical environments, viz. Neutron stars, pulsars, quasars, etc., the plasma rotate quite rapidly and should be strongly magnetized. Motivated by magneto-rotating dusty plasma environments, we investigate a three dimensional magneto-rotating four component plasma system consisting of fluid ions, non-extensively distributed electrons and positrons along with negative dust grains. Using the reductive perturbation method, we derive a ZK equation for dust-ion acoustic waves and travelling wave solution of this equation are studied via dynamical systems approach. Further, by employing an external perturbation to dust ion-acoustic travelling waves, their chaotic behavior is investigated through quasi-periodic route to chaos. The different plasma parameters viz. Rotational frequency, non-extensivity of electrons and positrons, dust and positron concentrations significantly affect the characteristics of travelling waves and their chaotic character.

DUST ACOUSTIC KINETIC ALFVEN WAVES IN THE PRESENCE OF SUPERTHERMALLY TRAPPED IONS IN POLARIZED DUSTY PLASMA

KULDEEP SINGH[1], NIMARDEEP KAUR[1], N. S. SAINI[2]
1. Guru Nanak Dev University, Amritsar, India-143005
2. Department of physics, Guru Nanak Dev University

Most of the space and astrophysical environments have witnessed the presence of dust and has wide-ranging applications in the different fields as well as in the study of astrophysical and space environments. The different observations have revealed the presence of superthermal particles in different kinds of space and astrophysical environments of plasmas. The deformation in the Debye sheath formed by ions around the negatively charged dust grains is termed as polarization force, which is an important frontline area of research in dusty plasma from last few decades. The polarization force is eloquently modified due to the presence of superthermally trapped ions and thus produces drastic changes in wave dynamics. Kinetic Alfven waves arise when the perpendicular wavelength of ordinary Alfven wave is comparable to the ion Larmor radius. Kinetic Alfven waves play an important role in transporting energy in various space and astrophysical plasma environments, coronal plasma heating, plasma transport in magnetopause as well as in heating Tokamak plasmas, thus heating the plasma to fusion temperatures. Thus, it is imperative to study the dynamics of kinetic Alfven waves in order to understand various energy transport mechanisms in plasmas. The trapping of the particles was shown to be important while investigating the nonlinear characteristics of waves. In the present work, we have discussed the effects of the vortex-like distribution of ions on obliquely propagating dust acoustic kinetic Alfven waves in a low β plasma. Using the two potential theory and employing the Sagdeev potential approach, we have investigated the existence of arbitrary amplitude coupled dust acoustic kinetic Alfvenic solitary waves in the framework of trapped ions distribution. The present investigation may be beneficial in understanding the propagation of nonlinear coherent structures in different space and astrophysical environments where trapped populations of ions have been observed.

LEAST-SQUARE WEIGHTED RESIDUAL METHODS FOR SOLUTION OF GLOBAL MODEL EQUATIONS

Sergey Averkin[1], Tom Jenkins[1]
1. Tech-X Corporation

Global models have become a popular tool for estimating volume-averaged plasma parameters such as number densities of plasma components, or electron temperature in partially-ionized plasmas of practical interest (with possibly thousands of chemical species and hundreds of thousands of chemical reaction paths in the discharge). Due to the usage of a volume-averaged approximation, global models do not contain any information regarding spatial distributions. In addition, they rely on the assumption of uniform power deposition and uniform electron temperature. In this work, we present a verification of a novel formulation of global model equations that allows us to predict plasma parameters not only qualitatively (as is the case in conventional global models) but also quantitatively. In this model we choose a rational functional representation with undetermined coefficients to represent various plasma properties. We then use least-square weighted residual methods to determine these coefficients in a way that minimizes the L^2 norm of the residual of 1D multi-fluid equations. This allows us to get optimal fitting parameters for all plasma components. In this work we focus on verification of the method by comparing our simulation results with analytical solutions of simplified fluid equations. Due to its use of prescribed functional representations, this model is computationally less expensive than models which compute solutions of fluid equations. As well, it allows us to retain chemical complexity without unduly increasing simulation times. Another important advantage of the presented method is that it can be applied for more complicated cases, such as flows in nozzles or multi-chamber discharges, for which global models are not yet available.

Work supported by U.S. Department of Energy, SBIR Phase II award DE-SC0015762.

LOW-IMPEDANCE S-BAND MILO

Matthew Abide[1], Tyler Buntin[1], James Dickens[1], Andreas Neuber[1], Ravi Joshi[1], John Mankowski[1]
1. Texas Tech University

The development of a low-impedance magnetically insulated line oscillator (MILO) driven by a compact Marx generator developed by Texas Tech University is discussed. The goals of the project aim to develop a MILO operating within the S-Band that can provide an RF peak output power of greater than 1 GW with greater than 10% efficiency. The device design followed a set of base design equations that were applied to a CST Studio Suite for a Particle-in-Cell, PIC, simulation to model the MILO. These simulation results then inform changes to the model to optimize the prospective performance of the device.

The simulations were developed to account for realistic material properties that were then applied to critical surfaces of the device. Additionally, a circuit simulation was included to model a Marx generator feeding the input of the MILO to simulate the eventual experimental setup. Current results verify an expected RF peak power of approximately 4.5 GW at 2.5 GHz operating in the TM01 mode when excited with an input signal that has a peak voltage of 600 kV while providing a peak current of 58 kA. The simulation confirms the design should perform within these constraints.

COMPUTER SIMULATION AND THE PHYSICS OF MIRAM CURVES

John Petillo[1], David Chernin[1], Y. Y. Lau[2], Serguei Ovtchinnikov[1], Aaron Jensen[1]
1. Leidos
2. University of Michigan, Ann Arbor, MI 48109, USA

The Miram curve for a specific cathode surface describes the normalized current density as a function of cathode temperature. Understanding and predicting this curve is key to understand the performance vs. lifetime of many electrons gun sources [1]. As the cathode lifetime decreases rapidly with increased operating temperature, in many practical devices, the electron gun is operated just over the onset of space-charge-limited emission in the Miram curve. We have made significant progress toward understanding the shape of the Miram curve through simulation using the MICHELLE code [2] based on work function sampling of the surface. These simulations shed new light on the primary mechanisms that determine the Miram curve shape in terms of the work function makeup of the surface.

In a Miram curve, the emitted current density qualitatively follows the thermionic Richardson-Laue-Dushman law at lower temperatures which shows a strong exponential growth with temperature. As the temperature rises the 2D Child-Langmuir space-charge-limited effect eventually takes over [3] and the total emitted current mostly reaches a plateau that is weakly affected by further temperature increase, or by the detailed distribution of the work function. We will present our findings and will compare and contrast these MICHELLE "first-principles" predictions with a recently developed semi-analytical model.

1. A. S. Gilmour, Microwave Tubes, Artech House (1986).

2. John Petillo, et al., IEEE Trans. Plasma Sci. 30, 1238 (2002); IEEE Trans. Electron Devices 52, 742 (2005).

3. R. J. Umstattd and J. W. Luginsland, Phys. Rev. Lett. 87, 145002 (2001).

* Work supported by DARPA contract HR0011-16-C-0080. The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

A MODEL OF THERMAL-FIELD CURRENT FROM MICROSCOPIC STRUCTURES

John Petillo[1], Kevin Jensen[2], Michael McDonald[3], Serguei Ovtchinnikov[1], Aaron Jensen[1]
1. Leidos
2. Naval Research Laboratory
3. Naval Research Laboraroty

The surfaces of electron sources exhibit non-planar features (intentional ordered arrays here but the methods apply also random surface roughness), the dimensions of which are typically microscale and therefore much smaller than the active emission area [1, 2, 3]: because emission area is already small by comparison to device dimensions, such differences in magnitude are a challenge to beam optics codes. Moreover, such structure complicates both the inference of physical properties such as work function and field enhancement from current data, and the determination of transverse velocity components that are essential for determining a cathode's intrinsic emittance. We report on the development of semi-numerical methods based on point and line charge [4] models for modeling ordered and rotationally symmetric emitters, and the use of a general thermal-field model for calculating emitted current [5]. The emitter protrusions are the equpotentials of a Point Charge Model (PCM) where the locations and charge magnitudes can be adjusted with great flexibility. A Ballistic- Impulse model that modifies trajectories near the surface of the cathode is implemented via altering the launch velocity in a form to be specified. We analyze how the microscale features undermine the estimation of oft-used parameters such as field enhancement and total emission area, and how well the models account for beam's velocity components. For the latter, a comparison is made to numerical simulations using the Particle-in-Cell code MICHELLE [6].

References

[1] K.L. Jensen, et al., PRST-AB 17, 043402 (2014).

[2] K.L. Jensen, et al., JAP117, 194902 (2015).

[3] N.A. Moody, et al., Physical Review Applied 10, 047002 (2018).

[4] J.R. Harris, et al., Journal of Physics D: Applied Physics 48, 385203 (2015).

[5] K.L. Jensen, et al., J. Appl. Phys. 123, 065301 (2018).

[6] John Petillo, IEEE Trans. Plasma Sci. 30, 1238 (2002); IEEE Trans. Electron Devices 52, 742 (2005).

LASER-DRIVEN SEMICONDUCTOR SWITCH FOR GENERATING NANOSECOND PULSES FROM A MEGAWATT GYROTRON

Julian Picard[1], Samuel Schaub[1], Guy Rosenzweig[1], Jacob Stephens[1], Michael Shapiro[1], Richard Temkin[1]

1. Massachusetts Institute of Technology

This work presents a laser-driven semiconductor switch (LDSS) employing silicon (Si) and gallium arsenide (GaAs) wafers that has been used to produce nanosecond-scale pulses from a 3 μs, 110 GHz gyrotron at the megawatt power level. Photoconductivity was induced in the wafers using a 532 nm Nd:YAG laser, which produces 6 ns, 230 mJ pulses. Irradiation of a single Si wafer by the laser produced 110 GHz RF pulses with 9 ns width and reflectance of $>$70%. Under the same conditions, a single GaAs wafer produced 24 ns 110 GHz RF pulses with $>$78% reflectance. For both semiconductor materials, a higher value of reflectance was observed with increasing 110 GHz beam intensity. In dual-wafer operation, which uses two active wafers, pulses of variable length down to 3 ns duration could be created at power levels up to 300 kW. The switch was successfully tested at incident 110 GHz RF power levels up to 600 kW. To complement experimental results, a 1-D reaction-diffusion model is presented that agrees well with experimentally observed temporal pulse shapes obtained with a single Si wafer. The LDSS has many potential uses in high power millimeter-wave research, including pulsed EPR spectroscopy and testing of high-gradient accelerator structures.

THZ WAKEFIELD SOURCE POWERED BY NONRELATIVISTIC ELECTRON BEAM

Mitchell Schneider[1], Stanislav Baturin[2], Sergey Baryshev[3]
1. 1Department of Electrical and Computer Engineering, Michigan State University
2. PSD Enrico Fermi Institute, University of Chicago
3. Department of Electrical and Computer Engineering, Michigan State University

High peak power tunable THz sources are enabling tools for medicine and materials science, non-destructive evaluation, space exploration. There is a special class of military and defense applications that includes THz communication, atmosphere monitoring, stand-off weapon and contraband detection, crowd screening. All applications require highest possible power to increase the detection distance, signal-to-noise ratio, or the penetration depth for transmission applications. More specifically, development of sources providing the output power from 1 W to 1 kW at frequencies $>$0.3 THz would be a remarkable advancement. Up to now, this metrics can be obtained only at large scale facilities such as ultrarelativistic MeV synchrotrons and linear accelerators. This is, of course, might not be a practical solution for most applications.

It is possible to generate intense (few W peak power) THz radiation using nonrelativistic ($\gamma\sim2$) beam of $\sim$200 keV via shock wave Cherenkov radiation. For this purpose, a long electron pulse is transmitted through a multimode dielectric lined slow wave cylindrical waveguide. A $\sim$30 ps long uniform electron bunch with a charge of 1 nC (peak current of 10 A) can be considered. With the listed parameters, the Cherenkov condition is satisfied. Therefore, the electron bunch will start to radiate and produce a wakefield that will result in energy modulation of the bunch. The energy modulation will, in turn, cause different parts of the bunch to travel with different velocities, and so-called ballistic longitudinal compression and consequent microbunching should emerge if the bunch is to travel few cm in free space downstream the dielectric waveguide. It can be shown that the micro bunch train spectrum contains THz harmonics up to 2 THz. In our presentation, we will outline analytical estimations and detailed PIC simulations. Experimental verification and designs of the proposed source will be presented.

THZ STRUCTURES FOR MEV ELECTRON BUNCH COMPRESSION

Mohamed Othman[1], Emma Snively[1], Michael Kozina[1], Benjamin Ofori-Okai[1], Suji Park[1], Xiaozhe Shen[1], Stephen Weathersby[1], Charles Yoneda[1], Xijie Wang[1], Matthias Hoffmann[1], Renkai Li[1], Emilio Nanni[1]
1. SLAC National Accelerator Laboratory

Probing structural dynamics at atomic spatial and ultrashort temporal scales reveals unprecedented details of nature's fundamental behavior, allowing for better understanding of intricate energy-matter interaction occurring at such scales. Ultrafast electron diffraction (UED), is the ideal choice to capture information from atomic-scale initiated by a pump laser and probed by MeV electrons. Moreover, injecting such multi-MeV electron beams from an RF gun with pulse durations and timing jitter both significantly smaller than pump optical pulse width opens new avenues for discovering unprecedented ultrafast phenomena. Laser-generated THz pulses through a titled-pulse-front scheme is a reliable technique to produce THz single cycle pulses of high field intensity. Here, we demonstrate a new design of a dispersion-free parallel-plate standing wave compressor structure that provides focusing of THz pulses to the interaction point therefore strongly modulates the incoming electron bunch energy. The compressor structure is characterized by THz electro-optical sampling (EOS) which provides both the THz spectrum and peak field amplitude at the interaction point. The experimental setup utilizes a compact THz single cycle sources; one is coupled to the structure through a series of parabolic mirrors and another source for the streaking deflector stage. There, the THz is intrinsically time-synchronized with the injected MeV electrons from the RF gun. We show that timing-jitter in the relative time-of-arrival of the compressed MeV electron bunches is reduced compared to uncompressed (elongated) bunches, which enables new frontiers in accessing femtosecond dynamics with UED.

A COLD-CATHODE MAGNETRON GUN IN PLASMA MODE AS DRIVER FOR A THZ GENERATOR

Sergiy Cherenshchykov, Sergiy Cherenshchykov

Increasing of electron beam current density is important problem in development of a THz generator. Howeever a conventional thermionic cathode have limited current density. Experiments with magnetron gun with transaction on plasma mode are described. The gun has a metall cathode with a diameter of 6 mm and a length nearly 70 mm. The cathode was coaxially mounted inside a stainless tube with a diameter of 54 mm and a length nearly 500 mm. The tube was used simulteniosly as anode and drift tube. The electodes may were immersed in magnetic field of coils. A direction of the magnetic field was paralel of common axis of the electrodes. The electrodes were coaxially mounted inside a ceramic wacuum chember. The electrodes were connected with a storage capasitor 0.2 mmF. A discharge was controlled by switch on current in the magntic coils. An electron beam up 500 A along the anode tube was observed. A start air pressure was 0.12 Pa. A start voltge was nearly 10 kV. A pulse of the electron beam had exelent repeatability with duration of several mikroseconds. A beam track on a collector was observed as a light spot with a diameter of 10 mm on a collector. So beam current density more then several times higher then from best thermionic cathode. Amplitude of the magnetic field was nearly 50 mT. At so low pressure is applicable vacuum scale law. According the law current density must increase as square of the magnetic field. Conventionaly in a portable THz clynotron a magnetic field are used with strens nearly 20 times higher. That gives us possibility of increasing of current density in several hundreds times with corresponding decreasing of gun dimention and nearly the same total beam current. Nature of superdense emission as self-supported electron secondary emission is discussed.

NO PLIF FLOW VISUALIZATION AND TIME-RESOLVED TEMPERATURE DISTRIBUTION MEASUREMENTS IN LASER INDUCED BREAKDOWN PLUMES

Dirk van den Bekerom[1], Elijah Jans[1], Igor Adamovich[1]
1. The Ohio State University

Achieving higher fuel efficiency and reducing NO_x emissions from internal combustion engines and gas turbine requires operation at lower equivalence ratios, when ignition and flameholding may become unstable. A similar problem occurs during ignition of supersonic flows, when ignition delay time may become comparable with the flow residence time and fuel-air mixing time in the combustor. Laser Induced Breakdown (LIB) is being studied as a promising non-intrusive approach to initiate combustion and enhance fuel-air mixing at these conditions. The objective of the present work is to characterize the flow induced by laser breakdown at near atmospheric pressure, and to measure the temperature distribution in the breakdown-induced plume.

The time evolution of the temperature profile of a laser breakdown plume was studied by Planar Laser Induced Fluorescence (PLIF) at 226 nm. The 2^{nd}-harmonic output of an Nd:YAG laser (47 mJ/pulse) produced optical breakdown in a slow flow at near atmospheric pressure. The delay time between the LIB and PLIF laser pulses was varied to monitor the time evolution of the breakdown-induced plume.

For characterization of the induced flow, the laser-induced depletion of NO in a 1000 ppm NO-N_2 mixture at 600 Torr was imaged for ensembles of laser shots at varying LIB-PLIF time delays up to 500 μs. Statistical analysis of the plume boundary for the individual laser shots reveals stochastic behavior at time delays longer than 100 μs, with little or no shot-to-shot reproducibility.

Time resolved, two-dimensional temperature profiles in dry air at 600 Torr were inferred from the intensity ratio of PLIF images of two rotational lines obtained by exciting NO generated in the laser breakdown plasma. Images of the two rotational transitions of the NO($X^2\Pi, v' = 0 \rightarrow A^2\Sigma^+, v'' = 0$) ${}^{Q}R_{12} + Q_2$ band, $J'' = 6.5$ and $J'' = 12.5$, are averaged over 600-1200 laser shots. Peak temperatures over 1200 K are detected in the plume at time delays up to 500 μs.

PHYSICAL EXPERIMENTS ON THE HEAVEN-I KRF LASER FACILITY

ZHAO WANG[1]
1. China Institute of Atomic Energy

The HEAVEN-I KrF excimer laser facility is the Chinese largest krypton fluoride laser facility, housed at the China Institute of Atomic Energy, Beijing, China. There were 6 laser beams at this facility, combined energy up to 100 J with a pulse width of 28 ns at a wavelength of 248 nm. The uniformity distribution of laser intensity is less than 2

Heaven-I's capability to provide extremely uniform focal profiles and its deep UV wavelength facilitate the conducting of experiments with laser-produced shocks with negligible effects from laser imperfections and laser plasma instability. Thus the laser facility was used in the research of high energy density physics and other related field physical experiments, such as the Shock Dynamics and the equation of state at high-pressure, simulation of space debris, and direct laser-driven quasi-isentropic compression. Side light shadow photography and imaging VISAR (Velocity Interferometer System for Any Reflector) were developed for the purpose of active diagnostic for physical experiments.

FEATURES OF LASER PRODUCED ANNULAR PLASMAS USING DIFFERENT TARGET MATERIALS AND AMBIENT CONDITIONS

Mario Favre[1], Fabián Velásquez[1], Diego Oportus[1], Heman Bhuyan[1], Felipe Veloso[1], Julio Valenzuela[1], Edmund Wyndham[1]

1. Instituto de Física, Pontificia Universidad Católica de Chile

We have been studying the dynamics and overall features of laser produced annular plasma expanding in background gases. The initial plasma is produced by focusing a Nd:YAG laser beam (1064 nm, 3.5 ns FWHM, $\sim 10^{10}$W/cm^2) onto a flat target employing a combination of a 10 mrad axicon prism and a converging lens, which results in an initial ring-like shape plasma of 1 mm radius and ∼150 μm thickness. Previous observations using 3.5 ns shadowgraphy imaging at background pressures up to 1.0 atm Argon background indicate that the plasma propagates inwards with characteristic velocities $\sim 10^4 - 10^5$ m/s, depending on pressure. This is then followed by on axis stagnation and formation of a jet-like column. The resulting plasma expands both, radial and axially, being the expansion dynamic very well described by the drag model. As a result of on-axis stagnation, initial axial velocity is higher than initial radial velocity. Subsequent plasma axial plasma expansion leads to the formation of a blast wave with a non-spherically symmetric shock, with a bubble-like feature on-axis. 3.5 ns Mach-Zhender interferometric observations indicate that at all observed times and pressures the innermost region behind the shock is always filled with plasma. In order to get further insight into the overall plasma features we have investigated the plasma dynamics using different target materials, carbon, aluminium and copper. We have also used Faraday cups to characterize ion beams emitted along the initial stages of the annular plasmas. Based on these observations, a quantitative description of the dynamics of laser produced annular plasmas, over a wide set of parameters, will be presented.

Work funded by FONDECYT grant 1180100.

HIGH-BRIGHTNESS X-RAY UNDULATOR RADIATION FROM ULTRA-SHORT ELECTRON BEAMS

David Bruhwiler[1], Boaz Nash[2], Oleg Chubar[3], Nicholas Goldring[1], Paul Moeller[1], Maksim Rakitin[3], Robert Nagler[1]
1. RadiaSoft LLC
2. European Synchrotron Radiation Facility
3. Brookhaven National Laboratory

Ultra-short (fs-scale) high-brightness electron beams from plasma accelerators could provide a bright partially-coherent synchrotron X-ray source. The open source Synchrotron Radiation Workshop (SRW) provides physical optics based algorithms for correctly simulating such sources and the subsequent X-ray beamline [1]. We present SRW capabilities to calculate source brightness and related quantities for undulators [2]. The Sirepo cloud computing framework includes a browser-based GUI for SRW [3], including analytical calculations for flux, photon beam size, divergence and photon brightness. We have included the effects of detuning from resonance and electron beam energy spread. Differences between published brightness calculations are explained in detail, clarifying the implicit assumptions, conventions and ranges of validity. These state-of-the-art simulation capabilities are available to the community in a free scientific gateway [4].

This material is based upon work supported in part by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0011237.

[1] O. Chubar and P. Elleaume, “Accurate and efficient computation of synchrotron radiation in the near field region,” Proc. of EPAC, 1177 (1998).

[2] B. Nash, O. Chubar, N. Goldring, D.L. Bruhwiler, P. Moeller, R. Nagler and M. Rakitin, “Detailed X-ray Brightness Calculations in the Sirepo GUI for SRW,” AIP Conf. Proc. 2054, 060080 (2019); https://doi.org/10.1063/1.5084711

[3] M.S. Rakitin, P. Moeller, R. Nagler, B. Nash, D.L. Bruhwiler, D. Smalyuk, M. Zhernenkov and O. Chubar, “Sirepo: an open-source cloud-based software interface for X-ray source and optics simulations,” Journal of Synchrotron Radiation 25, 1877 (2018).

[4] The Sirepo Scientific Gateway for particle accelerators and x-ray optics, https://sirepo.com

TIME EVOLUTION OF HARD X-RAY CHARACTERISTIC EMISSION FROM TUNGSTEN PULSED-POWER PLASMAS

Alla Safronova[1], Victor Kantsyrev[1], Austin Stafford[1], Ishor Shrestha[1], Veronica Shlyaptseva[1], Ryan Childers[1], Christopher Butcher[1], Nicholas Ouart[2], John Giuliani[2]
1. University of Nevada, Reno
2. Naval Research Laboratory

Recently, hard x-ray characteristic lines from high Z materials produced from pulsed power plasmas have been studied: as signatures of hot electrons using Mo K-alpha emission from Mo nested wire arrays on SNL-Z [1], Cu and Zn K-alpha emission from brass planar wire arrays on UNR's Zebra generator [2], and as a new hard x-ray spectroscopic diagnostic for the direct measurement of the ionization distribution in warm dense plasmas using W L emission generated by the NRL's Gamble II pulsed power machine [3]. Characteristic x-ray W L-shell lines occupy the energy range from 8 to 12 keV and in pulsed power plasmas their studies were focused mainly on the spatially resolved hard x-ray spectroscopy. However, investigation of time evolution of hard x-rays is very important for understanding the mechanisms of hard x-ray and electron beam generations [4]. Here we present the analysis of experiments with W Compact and Nested Cylindrical Wire Arrays (CCWA and NCWA, respectively) produced on the Zebra generator. A comprehensive set of diagnostics including x-ray detectors, a bolometer, a Faraday cup, a time-gated spatially resolved x-ray pinhole camera, and a time-gated spatially integrated x-ray spectrometer were implemented. The time history of relative intensities of characteristic x-ray W L lines from W NCWA in a broad time interval before and after stagnation is presented and compared with W CCWA. Correlation with measurements of electron beams and possible mechanisms of W L lines formation are considered. Future work on x-ray line polarization of these lines is discussed. This research was supported by NNSA under DOE grant DE-NA0003877 and in part by DE-NA0002075.

1. S.B. Hansen et al, Phys. Plasmas 21, 031202 (2014).

2. N.D. Ouart et al, HEDP 8, 247 (2012).

3. J.F. Seely et al, HEDP 9, 354 (2013).

4. I.K. Shrestha et al, HEDP 6, 113 (2010).

THE HED INSTRUMENT AT THE EUROPEAN XFEL

Toma Toncian[1], Wolfgang Morgenroth[2], Alexander Pelka[1], Ian Thorpe[3], Cornelius Strohm[4], Andreas Berghäuser[1], Jan-Patrick Schwinkendorf[3], Hanns-Peter Liermann[4], Samuele Di Dio Cafiso[1], Dominik Möller[1], Sebastian Göde[3], Thomas Preston[3], Monika Toncian[1], Andreas Schmidt[3], Zuzana Konopkova[3], Thomas Feldmann[3], Konstantin Sukharnikov[3], Mikako Makita[3], Motoaki Nakatsutsumi[3], Ulf Zastrau[3], Carsten Baehtz[1], Lennart Wollenweber[3], Valerio Cerantola[3], Mohamed Hassan[1], Karen Appel[3], Hauke Höppner[1], Eike-Christian Martens[3]

1. Helmholtz-Zentrum Dresden Rossendorf
2. Goethe-Universität Frankfurt
3. European XFEL GmbH
4. Deutsches Elektronen-Synchrotron DESY

The European XFEL is a superconducting, radio-frequency free-electron laser simultaneously operating three variable-gap undulator SASE beamlines. Each beamline supplies two instruments with X-rays of up to 25 keV photon energy. One of them, the High Energy Density (HED) scientific instrument, will be a unique platform to generate and investigate matter under extreme conditions of pressure, temperature or electro-magnetic fields. For this purpose, in addition to the XFEL, there will be high energy/intensity optical lasers, pulsed magnets and a diamond anvil cell (DAC) setup available. In the first half of the year X-ray commissioning is ongoing before first user operation starts. In the second half of the year optical laser operation is foreseen to begin to be available for users next year. Here the current status of the instrument will be presented.

BREAKDOWN CHARACTERISTICS OF NATURAL AND SYNTHETIC ESTER LIQUIDS WHEN CONTAINING VARYING LEVELS OF MOISTURE

Chris Williamson[1], Igor Timoshkin[1], Scott MacGregor[1], Mark Wilson[1], Martin Given[1]
1. Strathclyde University

Natural and synthetic ester liquids offer numerous benefits when compared with conventional naphthenic oils, such as improved biodegradability, low toxicity, high flash and fire points and increased ability to accommodate moisture. It is for these reasons that the power and pulsed power industries are adopting ester liquids as a long term replacement for naphthenic oils. One barrier to the acceptance of esters as a suitable alternative to naphthenic oils is the lack of data on their performance in highly divergent electric fields, and on how they react under these field conditions when high levels of moisture are present within the liquids.

This study is focused on how moisture content can affect the impulsive breakdown characteristics of ester liquids, and on how variations in their breakdown performance compare with changes in the breakdown characteristics observed in naphthenic oils with elevated moisture contents. The chosen liquids (MIDEL 7131, Cargill FR3 and Shell Diala S4 ZX) were exposed to standard lightning impulses of both positive and negative polarity, following the methodology outlined in IEC 60897. Three liquid states were evaluated, specifically: "as received", which refers to liquid taken from a newly opened container provided by a manufacturer; "naturally aged", where the liquid was left in an open container in ambient laboratory conditions, to allow the moisture content to increase slowly; and "accelerated aged", where liquid samples were exposed to humidification to increase their moisture content significantly, over a short time period.

This paper will present and discuss experimental results on the relative breakdown characteristics (breakdown voltage and time to breakdown) of the liquid samples, with the aim of identifying operational dissimilarities between ester fluids and naphthenic liquids. The obtained results will help to understand how both the means of ageing and the ageing time can affect the dielectrics properties of the tested liquids.

CHARGE CARRIER MOBILITIES IN DIELECTRIC LIQUIDS

Qingjiang Xue[1], Igor Timoshkin[1], Martin Given[1], Mark Wilson[1], Scott MacGregor[1]
1. University of Strathclyde

In order to satisfy the growing need of the power and pulsed power industries for environmentally-friendly dielectric liquids, natural and synthetic esters have been introduced as liquid insulators. In order to optimise the use of these liquids in practical applications, better understanding of their dielectric behaviour is required.

The main focus of this paper is on the charge carrier mobility in dielectric liquids, directly linked with their breakdown performance. Furthermore, understanding of the charge carrier mobility in these liquids will help in the development of, and finding of practical applications for, novel liquids seeded with nano-particles - so called Nano Fluids. The space charge accumulation in the host liquid, which is governed by the charge carrier mobilities, will control charging of these particles and their dynamic behaviour in the host liquid.

The liquids studied in this paper were a mineral oil, a natural ester, and a synthetic ester. The pre breakdown conduction current was obtained by exposing the tested liquids to a highly-divergent electrical field, produced using a needle-plane electrode system. The I-V curves for all tested liquids were measured to analyse the charge carrier mobility of the tested liquids, when their pre breakdown current was mainly controlled by space charge.

The obtained results from the tests show that the charge carrier mobility varies for different dielectric liquids. This may result in noticeable differences in the breakdown voltages of these liquids, and this information is critical for their adoption in practical applications.

INVESTIGATION OF INSULATED WIRE BREAKDOWN UNDER DC AND LIGHTNING IMPULSE CONDITIONS

Landon Collier[1], William Brooks[1], David Barnett[1], James Dickens[1], John Mankowski[1], David Hattz[2], W. A. Harrison[2], Andreas Neuber[1]
1. Texas Tech University
2. CNS Pantex

An investigation into the breakdown characteristics of a dielectric-coated wire-plane electrode system in atmospheric air is presented. Simulating the scenario in which standard utility wiring in close proximity to a grounded conductor is excited by a lightning strike, the wire is insulated while the plane electrode is a bare metal surface. At sufficiently high fields, greater than ∼30 kV/cm, ionization of the air in the gap results in charge accumulation on the wire dielectric surface. The combination of this pre-breakdown ionization and redistribution of charge effectively collapses the field in the air gap region. Thus, as observed, and supported by 3D field simulations, the size of the air gap plays a minor role in determining the overall breakdown threshold of the system. For instance, for 12 AWG solid-core THHN copper wire (600 V manufacturer rating), the breakdown threshold voltage increases only slightly from ∼81 kV with a small air gap of 5 mm to ∼94 kV with an air gap of 50 mm. Hence, the breakdown threshold is primarily dependent upon the dielectric strength of the wire coatings.

Overall, tests were conducted with air gaps ranging from 0 to 50 mm between the grounded, bare conductor and standard THHN copper wire of varying gauge (coated with PVC and covered with a nylon sheath) under both lightning impulse and direct voltage excitation. A 4-stage, 40 kJ, 400 kV open-circuit output Marx generator is used to generate lightning currents in the range of interest, with risetimes from 500 ns to 5 μs and peak currents from 2 – 5 kA. A smaller 750 J capacitor bank, with a peak voltage of 200 kV, is used to perform DC tests with a slow voltage ramp of ∼20 kV/s. Results elucidating polarity, wire defects, and waveform dependence will be discussed.

INCEPTION VOLTAGE FOR ELECTRICAL DISCHARGES IN THE PRESENCE OF TRIPLE JUNCTIONS

Michael Kirkpatrick[1], Giacomo Galli[2], Emmanuel Odic[1], Philippe Dessante[1], Philippe Molinié[1], Hassen Hamrita[3]

1. GeePs — Group of electrical engineering - Paris, UMR CNRS 8507, CentraleSupélec, Univ. Paris-Sud, Université Paris-Saclay, Sorbonne Université

2. Centralesupelec

3. CEA, LIST, Sensors and Electronic Architectures Laboratory

The prevention of electrical discharges is a classic problem in the design of electrical equipment, which is only becoming more important with the evolution of various technologies (electrification of airliners, increased voltage levels in various other applications). While the physics of discharge development is well described by Paschen's Law for the case of a gas gap between planar electrodes, deviations from this behavior may occur at high temperature[1] or in the case of a triple junction[2] (metal/solid insulator/gas).

In order to investigate discharge inception under these conditions, a customized system, which can operate at pressure up to 1MPa and temperature of 400°C, was used to test various electrode geometries with and without ceramic insulators.

Experimental results on the deviation from Paschen's law for different geometries of triple junction electrodes are presented compared with each other and with Paschen's law between two spherical electrodes without solid insulator.

In addition to the observed effects of the different conditions (geometry of triple junction electrodes or gas type) on electrical discharge inception voltage, the resulting impulsions have been examined and compared in terms of total charge, rise time, and other parameters.

1. G. Galli et al., "Characterization and localization of partial-discharge-induced pulses in fission chambers designed for sodium-cooled fast reactors," IEEE Transactions on Nuclear Science, 65 (2018) 2412.

2. C. Tran Duy et al., "Partial discharges at triple junction metal/solid insulator/gas and simulation of inception voltage", Journal of electrostatics, 66 (2008) 319.

Work supported by the CEA (Alternative Energy and Atomic Energy Commission) in France and by the GeePs (Group of electrical engineering) laboratory in France.

INVESTIGATION OF ELECTRICAL BREAKDOWN IN HIGH PRESSURE (0.1 TO 1 MPA) CARBON DIOXIDE AND ITS MIXTURES UNDER PULSED FIELDS

Siddharth Kumar[1], Tom Huiskamp, Guus Pemen[2]
1. TU Eindhoven
2. Eindhoven University of Technology

Sulphur Hexafluoride (SF_6) is an insulating gas which is used in high-voltage circuit breakers due to its unique insulating properties. However, it is an extremely potent greenhouse gas with a global warming potential (GWP) of 23900! Also, it produces toxic byproducts during electrical arcing. Hence, environment friendly and easier to handle alternative insulating gases are being investigated.

Carbon dioxide (CO_2) is a promising alternative insulating gas and is the focus of this research. The electrical breakdown strength of CO_2 and its mixtures under lightning impulses are investigated. The voltage pulses are generated using a 500 kV Marx generator and have a rise time of 700 ns. A rod-plane electrode geometry is used in the experiments to study the electrical breakdown phenomena under non-homogeneous electric fields. The rod has a hemispherical tip with a diameter of 20 mm and the gap distance between the electrodes is 30 mm.

The electrical breakdown strength of CO_2 is measured experimentally from 0.1 to 1 MPa under both positive and negative polarities. The results show that breakdown strength of CO_2 is greater under positive polarity and shows higher scatter in the breakdown voltage when compared to negative polarity. The polarity effect is inverse to that of air and currently, experiments are under way to understand this phenomena by using additional diagnostics such as high speed imaging and measurement of the pre-discharge currents.

It is reported in literature that addition of oxygen (O_2) can improve the dielectric strength of CO_2, due to its electronegative properties. Therefore, the effect of adding 10-30% O_2 to CO_2, on breakdown strength is being investigated at various pressures in order to find the optimum gas mixture ratio.

INFLUENCE OF THE CONCENTRATION ON SURFACE FLASHOVER OF THE EPOXY INSULATOR UNDER LIGHTENING IMPULSE VOLTAGE IN C4F7N-CO2 MIXTURES

Zhongbo Zheng[1], Weidong Ding[1], Zhichuang Li[1], Yishu Liu, Yue Li[1], Shuhan Liu[1], Lanxi Li[1], Yinan Zhu[1]

1. Xi'an Jiaotong University

In recent years, alternative insulating gas of SF6 becomes a research hotspot in electric power system. The insulation performance of C4F7N is 2.2 times more than that of SF6, and its global warming potential is low. Its mixture gas with CO2 has the potential to replace SF6 gas. As a medium for gas-insulated equipment, it is of great engineering significance to study the surface flashover characteristics at different types of voltages. However, the flashover performance in this mixture gas is rarely studied.

In this paper, the surface flashover experiment platform is built and PR equation and Antoine equation are used to establish the mixing method and calculates the liquefaction temperature. The influence of C4F7N concentration under positive and negative lightning impulse voltage in uniform electrical filed is studied with the gas pressure changes from 0.1MPa to 0.3MPa. The creepage distance of the tested epoxy insulators is 10mm. The results are also compared with the data of the sureface flashover characteristics in C4F7N-CO2 mixtures under ac voltage.

Results show that small quantities of C4F7N mixed in CO2 can obviously promote the surface flashover voltage but, as the fraction of C4F7N increases, the surface flashover voltage saturates. When the molar fraction of C4F7N is 13%, the surface flashover voltage of C4F7N/CO2 gas mixture can reach more than 90% of that of pure SF6 under the same conditions. Moreover, the flashover voltages of insulators under different types of voltages are arranged as follows: positive lightning impulse voltage(LI+) > power frequency voltage(AC) > negative lightning impulse voltage(LI-).

RESEARCHES ON SPECTRUMS AND MACROSCOPIC FORMS OF DC ARC IN A SHORT AIR GAP

Ruiyang Guan[1], Zhidong Jia[2]
1. Graduate School at Shenzhen, Tsinghua University
2. Graduate School at Shenzhen, Tsinghua University, Shenzhen

Arc accidents may cause serious problems in power grid. Yet, the progress of arc evolution is very complicated and rapidly changed, which can be easily disturbed by external factors. Here, in order better describe DC arc mechanism and exclude external influence factors, a testing platform, which can produce a small DC arc in the condition of gap length less than 15mm and current less than 60mA, was built. Arc evolution and macroscopic forms were captured by a high-speed camera. Spectrums of various states of arc were measured by a multichannel spectrometer and the arc temperatures were calculated based on the spectral lines. The relationships between DC arc resistance and gap length and current were studied. The experimental results show that DC arc develops from the positive electrode rather than negative electrode. With the current increasing, the macroscopic forms of arc evolution progress are mainly consisted of 4 periods: spark, purple-arc, yellow-arc and flame-arc. The arc spectrogram reflects the wavelengths of 4 maximum relative intensities are 315.865 nm, 337.107 nm, 357.649 nm and 391.421 nm, respectively. The relationship between arc resistance and current is a power function, while it is a linear function of gap length. The work in this paper is helpful to understand the progress of DC arc evolution.

PLASMA APPLICATION FOR EMISSION CONTROL

Dae Hoon Lee[1], KWAN TAE KIM, Young-Hoon Song[1], Sungkwon Jo[1], Hongjae Kang[1]
1. Korea Institute of Machinery and Materials

Applications of plasma for the after treatment of exhaust gas are introduced. Recently, environmental pollution such as fine dust generated in East Asia countries is known to be generated mostly by PM, NOx, SOx, VOC, etc. emitted from combustors process such as inside internal combustion engines and boilers. For the removal of these contaminants, plasma can be utilized for the supply of oxidants or reducing agents and the thermal management of post-treatment catalyst systems. In this paper, we present the commercial programs where plasma is applied in the after treatment system and introduce the technical principles.

DISINFECTION AND SENSITIZATION OF EAR INFECTION RELATED BACTERIAL BIOFILMS BY MICROPLASMA JET ARRAY

Sun Peter P.[1], Jungeun Won[1], Gabrielle Choo-Kang[1], Wenyuan Chen[1], Stephen A. Boppart[1], Thanh H.(Helen) Nguyen[1], J. Gary Eden[1]
1. University of Illinois urbana Champaign

Ear infections affect more than 80% of all children in the United States, and the common treatment for an acute middle ear infection is to use antibiotics. However, antibiotic treatment has been shown to be ineffective in over 30% of the cases with acute middle ear infections [1]. Chronic ear infections have been associated with the development of a bacterial biofilm in the middle ear space, and the bacteria within these biofilms commonly develop antibiotic resistance and seed recurrent ear infections. Surgical treatment to place a small drainage tube in the ear drum is often the only way to stop a chronic ear infection.

Portable and replaceable microplasma jet arrays have been designed at the University of Illinois and fabricated by 3D printing. The antibiotic susceptibility of Pseudomonas aeruginosa, a common bacterial strain associated with ear infections, was measured as the minimal inhibitory concentration (MIC50) that causes 50% growth inhibition, and found to fall by a factor of 5 after 10 mins of plasma treatment, and more than three orders-of-magnitude after 12 mins of plasma treatment. The number of living cells remaining in the cultured bacterial biofilm before and after microplasma jet array treatment has been investigated through confocal laser scanning microscopy. Reactive species, such as OH and 1O2 produced by the microplasma jet array and evaluated quantitatively through liquid chromatography are believed to play an important role during disinfection. Operational parameters for effective disinfection are being determined and will provide feedback for device optimization. This work demonstrates the potential of microplasma jet arrays as an alternative to antibiotic treatment for bacterial infections in the ear.

[1] Pichichero, Michael E. ”Acute ottis media: Part II. Treatment in an era of increasing antibiotic resistance.” American Family Physician 61, no. 8 (2000): 2410-2418.

CONTROL OF LARGE ELECTRIC SPARK THROUGH LASER FILAMENTATION IN AIR

Pierre WALCH[1], Benoit Mahieu[1], Leonid Arantchouk[1], André Mysyrowicz[2], Aurélien Houard[1]

1. Laboratoire d'Optique Appliquée, ENSTA ParisTech, Ecole Polytechnique, CNRS, Institut Polytechnique de Paris, 91128 Palaiseau, France

2. André Mysyrowicz Consultants, 6 Rue Gabriel, 78000 Versailles, France

Controlling lightning is a long time dream of mankind. As a part of the Laser Lightning Rod (LLR) project, we investigate the feasibility of a new type of lightning protection based on the use of upward lightning discharge initiated through a high-repetition-rate multi-terawatt femtosecond laser [1].

When such high intensity laser pulse propagates in the atmosphere, a process called filamentation happens. The laser pulse undergoes Kerr self-focusing until creating a long column of weakly ionized plasma. Energy deposition through photoionization will result in a low density channel over a microsecond timescale [2]. This channel acts as a preferential path for discharge propagation, providing a way to trigger and guide electric discharge [3].

To prepare for the real scale experiment on lightning, we study the impact of the laser parameters over the discharge control by analyzing the propagation of a laser guided meter scale electric discharge from a compact Tesla coil (output voltage: 360 kV) using a fast camera. Furthermore, we characterize by means of transverse interferometry the spatial and temporal evolutions of the underdense channel, with a particular attention to the hydrodynamics effects appearing with high-repetition-rate laser.

[1] http://llr-fet.eu/

[2] G. Point, et al., "Generation of long-lived underdense channels using femtosecond filamentation in air," J. Phys. B 48, 094009 (2015).

[3] B. Forestier et al., "Triggering, guiding and deviation of long air spark discharges with femtosecond laser filament," AIP Advances 2, 012151 (2012).

NITRIC OXIDE SCAVENGING OF HYDROXYL RADICALS IN A NANOSECOND PULSED PLASMA DISCHARGE GAS-LIQUID REACTOR

Radha Krishna Murthy Bulusu[1], Robert Wandell[1], Rachel Gallan[1], Bruce Locke[1]
1. Department of Chemical and Biomedical Engineering, Florida State University

Plasma discharges generated by moderate frequency, low energy pulses in a flowing gas-liquid (argon-water) reactor produce hydrogen peroxide (H_2O_2) at moderately high energy yields. The leading hypothesis is that the H_2O_2 is generated from the recombination of hydroxyl radicals (ΔOH) which are formed by the plasma electrons reacting with vaporized water. Experiments with carbon monoxide as an ΔOH scavenger have shown that the primary yield of ΔOH far exceeds what can be accounted for in H_2O_2. Similar to CO, NO can also be used as a gas phase ΔOH scavenger leading to the formation of water soluble HNO_2 and HNO_3. Gas phase NO_2 can also be formed from reaction of NO and atomic oxygen, however because the atomic oxygen must ultimately come from H_2O in the $Ar/NO/H_2O$ mixtures, this provides further insight into both the primary ΔOH yield and reaction pathways for nitrogen fixation with plasma. The main objective of this work is to utilize NO/Ar mixtures (0-20000 ppm NO) to assess both the primary yield of ΔOH and the roles of ΔOH and atomic oxygen in the reaction pathways leading to NO_2^- and NO_3^-. A continuous gas-liquid film reactor with deionized water is utilized and the liquid phase (NO_2^- and NO_3^-) and gas phase (NO and NO_2) are analyzed using ion chromatography and FTIR, respectively. A variable nanosecond power supply is utilized to determine the effects of pulse width, frequency, and input voltage on the efficiency of ΔOH generation. The plasma properties including gas temperature and electron density are also assessed using Optical Emission Spectroscopy. (This work was supported by the National Science Foundation, CBET 1702166 and Florida State University.)

OPTIMIZING POWER DELIVERY USING IMPENDENCE MATCHING NETWORKS WITH SET-POINT AND FREQUENCY TUNING FOR PULSED INDUCTIVELY COUPLED PLASMAS

Chenhui Qu[1], Joel Brandon[2], Carl Smith[2], Steven C. Shannon, David Coumou[3], Mark J. Kushner[1]
1. University of Michigan
2. North Carolina State University
3. MKS Instruments

Radio frequency (RF) power delivery to plasma processing reactors for microelectronics fabrication use impedance matching networks to minimize reflected power. During pulsing, the plasma impedance can significantly change, thereby requiring real-time-adjustment of the components of the network to maintain efficient power transfer. The pulses are typically too short for these components to be adjusted during the pulse. Other strategies are needed to maximum impedance matching during pulsing. One strategy is to select network components to match the power at a single time to optimize power delivery either early or late in the pulse. This also enables tailoring of the power during the pulse. Matching pulsed inductively coupled plasmas (ICPs) by this method is challenged by the capacitive-to-inductive transition at the beginning of the pulse. Another strategy varies the RF frequency, an adjustment that can be done rapidly. The network components and plasma impedance are frequency dependent, enabling real-time matching by adjusting RF frequency. Implementation requires a feed forward frequency trajectory instead of a reflected power driven feedback loop employed in frequency tune generators.

Impedance matching of pulsed ICPs was computationally investigated using the Hybrid Plasma Equipment Model and compared to experiments . Pulsed ICPs were operated in 20 mTorr Ar/Cl2. Set point matching at different times can suppress or enhance the capacitive portion of the E-H transition, thereby controlling oscillations in plasma potential. Impedance matching by frequency tuning over a few MHz for a base frequency of 10 MHz achieves matching over a limited range of change in plasma conditions, depending on the network components and termination capacitance of the antenna. Frequency tuning is then a more robust form of set-point-matching, broadening the time during the pulse that matching can be achieved.

Work was supported by Samsung Electronics Co. Ltd., National Science Foundation, DOE Office of Fusion Energy Sciences.

PLASMA UNIFORMITY CONTROL TECHNOLOGY OF ICP DRY ETCHER EQUIPMENT FOR MEDIUM AND LARGE DISPLAY

Hosik Yang, Honggoo Jeon, Sungjae Hong, Sinpyoung Kim, Ilho Noh

The current display technology trends to be highly integrated with high resolution, the element size is gradually downsized, and the structure becomes complicated. Inductively coupled plasma (ICP) dry etcher of various types of etching equipment is a structure that places a large multi-divisional antenna source on the top lid, passes current to the antenna, and generates plasma using the induced magnetic field generated at this time. However, in the case of a device of a large area size, a support that can withstand a load structurally is necessary, and when these support portions are applied, arrangement of antenna becomes difficult, which causes reduction in uniformity. As described above, the development of Antenna source of a large area having a uniform plasma density on the whole surface is difficult to restrict hardware (H/W). As a solution to this problem, we confirmed the change in uniformity of Plasma by applying two kinds of specific shape faraday shield to the lower part of the large area upper lid antenna of 6 and 8th generation size. In this thesis, we verify the faraday shield effect which can improve plasma uniformity control of ICP dry etcher equipment applied to medium and large displays, which enables us to the world's biggest ICP dry etcher equipment at a later date i try to present a direction.

CHARACTERISTICS OF NANOSECOND PULSED DISCHARGE TYPE OZONIZER WITH A TUBE TO CYLINDER REACTOR

Hiroki Hidaka[1], Daichi Ikoma[1], Kanji Sasaki[1], Douyan Wang[2], Takao Namihira[2]
1. Graduate School of Science and Technology, Kumamoto University – Japan
2. Institute of Pulsed Power Science, Kumamoto University – Japan

Ozone characteristics such as strong oxidation power and no-residual toxicity makes it highly expected as a next-generation oxidant. Ozone has been used mainly in clarification of drinking water and industrial wastewater treatments. In recent years, ozone generation by pulsed power technique has been studied. In our laboratory, nanosecond (ns) pulse generator which produces non-thermal plasma has been developed to generate ozone. It has been demonstrated that ns pulsed discharge is effective for high efficiency ozone generation. However, there is still a problem that the maximum ozone concentration saturates at approximately 40 g/m3. The ozone concentration required for water purification application is typically 100 – 120 g/m3. Therefore, improvement of ozone concentration using ns discharge method is necessary. It is assumed that one of the main cause of ozone concentration saturation is ozone thermal decomposition due to gas temperature rise. In our previous studies, gas temperature rise was observed in the vicinity of the high voltage applied wire electrode in a wire to cylinder electrode geometry. Therefore, a new electrode has been developed in the present study by employing a tube to cylinder electrode geometry. Thus, the high voltage applied tube electrode enables to pass through cooling medium inside of the tube. Characteristics of ozone generation using the tube to cylinder electrode will be presented in this paper. Furthermore, the effect of helium gas addition to the seeding gas is investigated. As a result, it was deduced that tube to cylinder electrode system and helium gas addition are effective for increasing ozone concentration.

INTEGRATED PHOTONICS FOR LOW TRANSVERSE EMITTANCE, ULTRAFAST NEGATIVE ELECTRON AFFINITY GAAS PHOTOEMITTERS

Rehan Kapadia[1], Louis Blankemeier[1], Fatemeh Rezaeifar[1]
1. University of Southern California

Photocathodes exhibiting simultaneous high quantum efficiency, low mean transverse energy, and fast temporal response are critical for next generation electron sources. Currently, caesiated negative electron affinity GaAs photocathodes have demonstrated good overall results. However, due to the nature of the photoemission process and the details of the Cs surface structure, a tradeoff exists. A low mean transverse energy of ∼25 meV can be obtained by using photons with near bandgap energy, at the cost of an unacceptably high response time, or higher energy photons can be used with mean transverse energy of ∼60 meV with acceptable response times of 2-5 ps. Here, it is shown through a calibrated Monte-Carlo Boltzmann Transport Equation simulation that a thin layer of ceasiated GaAs on a waveguide can potentially exhibit photoemission with MTEs ∼30 meV, ultrafast response times of ∼0.2-1 ps, and QE of 1-10%, breaking the traditional tradeoffs associated with bulk negative electron affinity photoemitters.

COUPLED OPTICAL AND ELECTRONIC SIMULATION OF INTEGRATED PHOTONICS BASED HOT-ELECTRON GRAPHENE PHOTOEMITTERS USING A 2-D ENSEMBLE MONTE CARLO BOLTZMANN TRANSPORT EQUATION SOLVER AND A FINITE-DIFFERENCE TIME-DOMAIN MAXWELL'S EQUATION SOLVER

Ragib Ahsan[1], Fatemeh Rezaeifar[1], Rehan Kapadia[1]
1. University of Southern California

Recently, we have shown that a waveguide integrated graphene photocathode excited with sub-workfunction energy photons can emit electrons at optical power densities significantly lower than traditional multi-photon or strong-field emission cathodes using metallic tips. Initial modeling efforts indicated that the behavior was due to non-equilibrium heating of electrons in graphene beyond the lattice temperature, and direct field-emission of excited electrons before scattering. Here, we develop a rigorous optical and electronic simulation to study the behavior by considering the fundamental generation, scattering, and emission rates. This is enabled via a 2-D ensemble Monte Carlo Boltzmann Transport Equation solver coupled to an optical simulation.

Using this simulation, we have studied the ultrafast relaxation of the electrons considering both K and K' valleys close to the Dirac point. The uniqueness of our model lies in the dynamic calculation of the scattering rates rather than using a precalculated net scattering rate. The dynamic scattering rates are particularly important due to Pauli blocking, which modifies the scattering phenomena as the system evolves. We have considered the major scattering mechanisms: coulomb scattering including auger processes, optical phonons, and supercollision acoustic phonons. Using the dynamically calculated electron lifetimes, we have determined the tunneling rates of electrons into the vacuum following Bardeen's tunneling Hamiltonian approach within WKB approximation. To calibrate our scattering models, we have reproduced published pump-probe spectroscopic data on graphene. The calibrated tool is then used to model our own experimental devices, showing good fits to our experimental results. The tool is then used to predict the potential performance of the integrated photonics based hot electron emitters.

ELECTRON EMISSION FROM A METAL ELECTRODE SUBJECT TO A HIGH INTENSITY LASER IN THE PRESENCE OF DC ELECTRIC FIELDS*

Sayeed Nafis Sami[1], Dong Guo[1], Ravi Joshi[1]
1. Texas Tech University

Laser-driven ultrafast electron emission offers the possibility of manipulation and control of coherent electron motion in ultrashort spatiotemporal scales. Superposition of a high DC field will enable the generation of high electron emission currents. The process would be facilitated by quantum tunneling across the potential barrier at the surface [1], aided by the absorption of energy which would alter the electronic energies and create a nonequilibrium distribution at elevated temperatures.

In this contribution, the process of electron emission from a dc biased metal surface illuminated by a single frequency laser is assessed. The time-dependent evolution of the electron distribution function and its equivalent temperature are obtained through energy balance rate equations. The results are found to simplify to and yield the Fowler-Nordheim characteristic in the absence of an external laser under equilibrium conditions. However, with the laser excitation, the currents are predicted to be much higher, and dependent on the incident intensity. The role of possible electric field enhancement at the emitting tip will also be discussed.

[1]. W. S. Truscott, Wave functions in the presence of a time-dependent field: Exact solutions and their application to tunneling. Phys. Rev. Lett., vol. 70, pp. 1900–1903 (1993).

*This work was supported by Grant # N00014-18-1-2382 from the Office of Naval Research, and by Grant #A19-0103-001 from the Air Force Office of Scientific Research.

FABRICATION AND CHARACTERIZATION OF DIAMOND FIELD EMITTER ARRAY CATHODES

Dongsung Kim[1], Heather Andrews[1], Bo Choi[2], Ryan Fleming[1], Evgenya Simakov[1]
1. Los Alamos National Laboratory
2. Cheju Halla University

This abstract reports on the status of the diamond field emitter array (DFEA) cathode project at Los Alamos National Laboratory (LANL). DFEA pyramids have nanometer scale tips and produce high currents with small emittance, making them a promising candidate for use in compact dielectric laser accelerators. At LANL, we recently established the capability to fabricate DFEA cathodes by using a mold-transfer method. First, we make a photomask with array patterns on the oxidized Si wafer. Then we transfer the pattern onto (100) Si wafer through anisotropic etching. Then we oxidize the wafer and perform diamond deposition. We braze the diamond film to a polished molybdenum substrate with the TiCuSil brazing material. Finally, the Si and SiO2 layers are removed by an etching process using KOH and buffered oxide etch (BOE). The arrays are finally imaged under a scanning electron microscope. We condition the arrays under a DC electric field to determine the emission uniformity and the number of emitting tips. Typically the number of emitting tips and emission current increase with time while operating at a constant electric field. We demonstrate that the pyramids produce high per-tip current (> 15 μA per-tip). We will present the details of the fabrication process and conditioning results of DFEA cathodes.

SHAPED BEAMS FROM DIAMOND FIELD-EMITTER ARRAY CATHODES

Heather Andrews[1], Dongsung Kim[1], Kimberley Nichols[1], Evgenya Simakov[1], Manoel Conde[2], Darrell Doran[3], Gwanghui Ha, Wanming Liu[3], John Power, Jiahang Shao[4], Charles Whiteford[3], Eric Wisniewski[2], Sergey Antipov[5], Gongxiaohui Chen

1. Los Alamos National Laboratory

2. Argonne National Laboratory

3. ANL

4. Tsinghua University and Argonne National Laboratory

5. Euclid Beamlabs LLC

We present the first experimental demonstration of production and transport of a shaped electron beam from a diamond field emitter array (DFEA) cathodes in an RF gun. DFEAs are arrays of diamond pyramids with exquisitely sharp tips and micron-scale bases that produce high current densities. These arrays can be fabricated in arbitrary shapes, ranging from single tips to many millions of tips, so that they produce an inherently shaped electron beam. Each tip emits a modest current, but large dense arrays can produce many Amps. These cathodes are currently being studied for use in dielectric wakefield accelerators, however they may also be applicable to vacuum microwave tubes. Recently, shaped beam production and transport has been demonstrated in the 1.3 GHz RF gun at the Advanced Cathode Test Stand at Argonne. Current was measured on a faraday cup, and the beam imaged on a YAG screen with various peak electric field gradients on the cathode from 12 – 35 Mv/m. Three cathode geometries were tested, one sparse 5x5 square array with 20 micron base and 400 micron pitch, a 1 mm equilateral triangle with 7 micron base pyramids and 10 micron pitch, and a 1 mm equilateral triangle with 10 micron base and 25 micron pitch. The two dense arrays emitted 35 nC bunch charge at 35 MV/m and 13 nC bunch charge at 27 MV/m field respectively, while the sparse array emitted 0.36 nC bunch charge at 15 MV/m.

FIELD EMISSION PROPERTIES OF VERTICAL AND LOOPED CARBON NANOTUBE FIBERS

Steven Fairchild[1], Jeongho Park[1], Peng Zhang[2], Taha Posos[2], Sergey Baryshev[2]
1. Air Force Research Laboratory
2. Michigan State University

Carbon Nanotube Fibers (CNFs) have demonstrated excellent field emission (FE) properties and thus hold significant potential for use as electron sources for vacuum electronic devices (VEDs). CNFs were fabricated from pre-made carbon nanotubes (CNTs) mixed with chlorosulfonic acid resulting in a dopant with CNTs composing 2-6% of the solution mass. This dopant was extruded through a small diameter spinerette to make CNFs with a diameter of $\sim$20 $\neq$m. The CNFs were then cut into segments and arranged in various emitter geometries and their field FE performance was measured. The CNF cathode samples were mounted in a vacuum chamber with a simple DC diode configuration for measuring I-V curves up to a maximum voltage of 3 kV. Both free standing and looped configurations were measured for their emission current and temperature. The free standing CNF was 4 mm tall and the looped CNF was 4 mm tall at the loop apex. Direct IR imaging during FE showed that the maximum temperature of the looped CNF was half that of the vertical CNF at the same emission current of.. The lower temperature operation is due to improved thermal management resulting from having both ends of the looped fiber connected to the substrate. Field emission microscopy was used to examine the looped CNF. Results indicated that initial emission is confined to isolated stray single CNT bundles that comprise the CNFs, with the total output current on the order of 100's μA to a few mA. Initial stray emitters condition away via a series of micro-breakdowns caused by extreme thermal loads due to high current density. The looped CNF produced high output current and directed emission after undergoing the initial conditioning process. This work demonstrates the CNFs offer significant potential for use as high current density, low temperature FE cathodes for use in VEDs.

A STUDY ON ATTENUATION CHARACTERISTICS OF EXPLOSIVE EMISSION CATHODE PLASMA BASED ON ULTRA HIGH SPEED CAMERA TECHNOLOGY

tengfang wang[1], hua huang[2], xiao jin[2], zhenbang liu[2], yu bai[2], zhiwei dang[2], shuming peng[2]

1. Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Fudan University. Shanghai 200433, China

2. Science and Technology on High Power Microwave Laboratory, Institute of Applied Electronics, CAEP.Mianyang 621900, China

Explode emission cathodes can be used to generate intense-current relativistic electron beams(IREBs) required for high-power microwave(HPM) systems, its characteristics affect the performance of HPM system. This type of cathode forms a plasma on the surface of the cathode during the emission process, and the electron beam is mainly obtained from the plasma. Therefore, the characteristics of the plasma are directly related to the beam characteristics, including the uniformity of plasma generation, the rate of expansion and attenuation. The attenuation characteristics are related to the repetitive performance of the cathode. In this paper, a ultra-high-speed framing camera is used to construct a diagnostic system to take pictures of cathode plasma luminescence. The camera has 12 channels and can perform up to 24 frames. By setting the exposure time and delay timing of different channels, high-speed photography can be performed over a long time to obtain state information of cathode plasma at different time points during the attenuation process after the explosion emission, the result is very intuitive. The intense-current emission experiment was carried out by using a ring-shaped stainless steel cathode. The camera photographed the plasma luminescence on the front the cathode. The image processing and analysis showed that the attenuation time of the explosion emission cathode plasma was about 55μs, and the plasma gradually expanded from the cathode surface to the anode during the attenuation process. The expansion rate is on the order of several cm/μs and is affected by the guiding magnetic field, and the distribution is very uneven. This result has important reference significance for studying the characteristics of explode emission cathode plasma.

VALIDATION OF A CONFIGURABLE ION SOURCE FOR TESTING SPACEFLIGHT-BASED THERMAL PLASMA MEASUREMENT INSTRUMENTS

Ellen Robertson[1], Gregory Earle[1], Jonathan Green[1]
1. Virginia Tech

Governments and corporations around the world have billions of dollars of assets in Low Earth Orbit (LEO). It is, therefore, valuable to analyze the environment, including the thermal ions, in LEO. These thermal ions are critically important to establishing the “ground” potential for all elements of the spacecraft electrical system. Before instruments are launched to make such measurements, they are typically tested, validated, and calibrated in vacuum chambers. We have designed a thermal ion source to emulate the LEO environment and facilitate testing of such instruments. This paper describes the ion source and presents both simulations of its capabilities and empirical test results. Comparing these simulations and test results leads to characterization and understanding of the ion source. With this understanding, we can properly configure the source and better interpret the data from instruments under test.

PARTICLE-IN-CELL MODELING OF THE SATURN ACCELERATOR VACUUM SECTION

Ben Ulmen[1], Ken Struve[1]
1. Sandia National Laboratories

X-ray and particle beam source designs at the Saturn accelerator would greatly benefit from a better understanding of the power flow in the center vacuum section. The Chicago particle-in-cell (PIC) code has been used to create a model of the insulator stack-MITL-diode system to attempt to match simulations to experimental B-dot current data. The stack voltage waveforms for the different MITL (magnetically-insulated transmission line) levels were first simulated using the Bertha circuit code, which was tuned to match experimental machine diagnostics, and these waveforms were used to drive the PIC simulation. One parameter of interest that is difficult to measure experimentally is the diode voltage. The simulation gives plausible results that correlate to indirect measurements of the voltage made via examining the end-point energy of x-ray spectral unfolds.

HOLLOW CATHODE RADIAL PLASMA SOURCE BASED ON CLOSED DRIFT ANODE LAYER THRUSTER

Vasilii Gushenets[1], Efim Oks[2], Alexey Bugaev[3]
1. High Current Electronics Institute
2. Tomsk State University of Control Systems and Radioelectronics
3. High Curent Electronics Insritute

Two conceptual designs of plasma sources for materials modification are investigated. The sources presented in this publication are based on plasma thrusters (plasma accelerators), that were developed by Prof. Goncharov group in Institute of Physics (Kiev, Ukraine). This kind of system can be classified as plasma optic device in crossed electric and magnetic fields. These devices are a well-explored tool for focusing high-current, large area, energetic, heavy ion beams. In our plasma devices the magnetic field is produced by permanent magnets. The first device is based on ring-shaped closed drift anode layer thruster with hollow cathode. It is known the anode-layer thruster has two operating modes. The first mode is low-current with narrow anode layer and clear-cut plasma flow, where as the second mode operates with high-current and plasma fills the entire volume of the accelerator. This mode of the anode-layer thruster was used in a wide-aperture plasma optical system for producing and transporting intense electron beams. In low current mode of the thruster operation, the axially converged ion beam formed and, as follow from experiment, the energy of the ions could reach some kV. The second device is circular anode layer plasma thruster. For effective operation of devices, it is important to know their usage parameters, therefore the current-voltage and discharge characteristics of the anode-layer thrusters in different modes were investigated

This work was supported by the grants of Russian Foundation for Basic Research 18-08-00113-a in plasma source development and 19-08-00315-a in electron beam transport.

MONTE CARLO SIMULATION OF SECONDARY ELECTRON YIELD FROM A MICROPOROUS SURFACE

Asif Iqbal[1], J. Ludwick[2], S. Fairchild[3], M. Cahay[2], D. Gortat[4], M. Sparkes[4], W. O'Neill[4], Peng Zhang[1]

1. Department of Electrical and Computer Engineering, Michigan State University, East Lansing, Michigan 48824-1226, USA

2. Spintronics and Vacuum Nanoelectronics Laboratory, University of Cincinnati, Cincinnati, OH 45221, USA

3. Materials and Manufacturing Directorate, Air Force Research Laboratory,Wright Patterson Air Force Base, OH 45433

4. Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, Cambridge CB3 0FS, UK

We study secondary electron yield (SEY) suppression in a metal surface with microporous array. We propose an empirical fitting to the experimentally measured SEY of a flat gold surface for both normal and oblique incidence of primary electrons. Using this empirical model of SEY, we perform two-dimensional Monte Carlo (MC) simulation [1] of the electron trajectory in a single rectangular well and determine the SEY of a microporous array.

We find that the SEY of the porous surface is significantly lower than that of the flat surface and is a function of the aspect ratio of the micro-pores and the surface porosity of the metal plate. The results are compared to an existing analytical model [2], which is found to underestimate the effective surface SEY for large values of aspect ratio of the micro-pores. This is attributed to the fact that the analytical model accounts only for the first generation of secondary electrons, whereas MC simulation takes into account the subsequent generations of secondary electrons generated inside the well. The MC results are in very good agreement with the experimental data [3], indicating the subsequent generations of secondary electrons inside the well contribute significantly to the effective SEY of a porous surface for large aspect ratio of the micro-pores.

[1] M. Ye, Y.N. He, S.G. Hu, R. Wang, T.C. Hu, J. Yang, and W.Z. Cui, J. Appl. Phys. 113, 074904 (2013).

[2] J.M. Sattler, R.A. Coutu, R. Lake, T. Laurvick, T. Back, and S. Fairchild, J. Appl. Phys. 122, 055304 (2017).

[3] J. Ludwick and S. Fairchild, private communication.

Work supported by AFOSR MURI Grant No. FA9550-18-1-0062.

FEATURES OF THE MILLISECOND ARC DISCHARGE GENERATING EMISSION PLASMA IN THE FOREVACUUM PLASMA-CATHODE SOURCE OF LARGE-RADIUS ELECTRON BEAM

Andrey Kazakov[1], Aleksander Medovnik[2], Efim Oks[1]
1. Tomsk State University of Control Systems and Radioelectronics
2. Tomsk State University of Control System and Radioelectronics

The pulsed low-energy (up to 15 keV) forevacuum plasma-cathode electron sources, operating at pressures 3-30 Pa, provide direct processing of dielectric materials (ceramics and polymers) due to compensation of negative charge on the dielectric surface by beam-produced plasma and by non-self-maintained discharge between charged surface of the dielectric and a grounded vacuum chamber. In addition, the beam-produced plasma also can be used for surface modification. For some applications of the large-radius electron beam and beam-produced plasma (e.g. surface modification of high temperature materials), it is necessary to increase the pulse energy (energy density). While at current up to 100 A and gas pressure of 3-30 Pa maximal accelerating voltage is limited by breakdown of accelerating gap, one of the ways to obtain the required beam energy per pulse is to increase pulse duration up to several milliseconds. For stable generation of emission plasma with millisecond pulse duration, we have used an arc discharge with cathode spot. A copper cathode with diameter of 5 mm, and a hollow anode with height of 90 mm and diameter of 110 mm, have been used. Our study has demonstrated that gas type and gas pressure strongly affect on the arc parameters in 3-30 Pa pressure range. Increase of pressure and the use of gas with greater ionization cross section results in decrease of arc discharge voltage. At distances more than 40 mm from the cathode, increase of gas pressure leads to plasma density growth. Depending on the gas and its pressure, significant increase in plasma density can occur only up to 1 ms. Thus, at the pulse duration of more than 1 ms, the arc discharge operates in quasi-stationary mode in the forevacuum pressure range.

The work was supported by Russian Foundation for Basic Research, grant No. 18-38-20044.

PLASMA SOURCE WITH MULTI-APERTURE EXTRACTION SYSTEM FOR GENERATING A RIBBON ELECTRON BEAM

Denis Zolotukhin[1], Aleksander Klimov[2], Alexey Zenin[3]
1. The George Washington University
2. Tomsk State University of Control Systems and Radioelectronics
3. Tomsk State University of Control System and Radioelectronics

A plasma source of a ribbon electron beam for electron beam generating with a cross section of 10*250 mm in the fore-vacuum region of pressure was created. The cathode was a rectangular cavity with an extended slit. To increase the uniformity of the electron beam current distribution, a multi-aperture extraction system was used. A part of the anode, facing the extractor, contained 60 holes with a diameter of 3 mm, located along the line. In the extractor, holes with a diameter of 5 mm were made coaxially to the holes in the anode. The emission of electrons was carried out from a variety of holes when an accelerating voltage was applied between the anode and the extractor. At a distance of 10 cm from the electronic source, the electrons emitted by each hole were formed into one electron beam. This configuration of the accelerating gap made it possible to obtain an electron beam of the ribbon configuration with stable parameters in the forevacuum pressure range. The beam is formed by the emission of electrons from the hollow cathode discharge in the residual atmosphere of the vacuum chamber without the use of a gas inlet and a differential pumping system. On the basis of the developed source, the so-called plasma-beam discharge is implemented, and the possibility of using such a plasma generator in coating deposition technology is shown.

The work was supported by the grant of the Russian Foundation for Basic Research № 18-48-700015.

MONTE-CARLO MODELLING OF PARALLEL ELECTRON TRANSPORT IN THE PROTO-MPEX LINEAR PLASMA DEVICE

Juan Caneses[1], Donald Spong[1], Cornwall Lau[1], Theodore Biewer[1], Tim Bigelow[1], John Caughman[1], Rick Goulding[1], Nischal Kafle[2], Juergen Rapp[1]
1. Oak Ridge National Laboratory
2. The University of Tennessee, Knoxville

The Prototype Material Plasma Exposure eXperiment (Proto-MPEX) is a linear plasma device located at Oak Ridge National Laboratory which serves as a test-stand to develop the plasma source concept for the Materials Plasma Exposure eXperiment (MPEX). Recent experiments have demonstrated the heating of electrons via Electron Bernstein Waves (EBW) in this linear configuration using 28 GHz microwaves. Moreover, experimental observations suggest that the magnetic ripple adversely affects the parallel transport of the heated electrons toward the target where material samples are to be exposed to the plasma. To understand the transport process during microwave application, a test-particle Monte-Carlo (MC) code has been developed that incorporates the effects of Coulomb collisions, magnetic mirror kinetic trapping and electron cyclotron interaction via a quasilinear RF operator.

In this work, we describe the MC code and its application to Proto-MPEX. We observe that test electrons relax to a Maxwell-Boltzmann distribution when interacting with the low-temperature (4 eV) high-density (4e19 m^{-3}) helicon-generated background plasma. Upon injection of microwaves, electron cyclotron interactions produce high energy electrons. Depending on the conditions, such as the shape of the magnetic ripple and the location of the cyclotron resonance, anisotropic distributions characteristic of kinetic trapping are observed. We find that injecting microwaves in magnetic wells with significant asymmetry assists in releasing kinetically-trapped heated electrons. This reduces the adverse effects of magnetic ripple on parallel electron transport. Moreover, we observe that the location of the cyclotron resonance affects whether a particle experiences multiple RF "kicks" and becomes trapped or it experiences a single RF "kick" and exits the magnetic well towards the target section. Results are compared with experimental measurements. Finally, the implications of the results are discussed in the context of the upcoming MPEX device.

STUDIES ON POWER TRANSFER EFFICIENCY IN THE DRIVERS OF THE SPIDER INDUCTIVELY COUPLED RF ION SOURCE

Mauro Recchia[1], Palak Jain[2], Elena Gaio[1], Alberto Maistrello[1], Gianluigi Serianni[1], Andrea Zamengo[1]

1. Consorzio RFX

2. University of Padova and Consorzio RFX

SPIDER is the full-size prototype of ITER Neutral Beam Injector ion source, in operation since June 2018 as a project of the ITER Neutral Beam Test Facility located at Padova, Italy. It consists of an inductively coupled plasma source and an extraction system to accelerate the produced negative ions up to 100 keV energy. The plasma source is composed of 8 drivers, operated in low hydrogen gas pressure ($\sim$ 0.3 Pa) and maximum radio frequency (RF) power of 100 kW per driver at 1 MHz frequency.

A key parameter to qualify performances of the driver is the power transfer efficiency (PTE) which is defined as the ratio between the power absorbed by the plasma and the total RF input power. Experimentally it is not possible to measure the power absorbed by the plasma, which is found to depend on various parameters coupled together. Therefore a model is needed which can account for all the mechanisms to provide an estimation of this PTE.

A methodology was developed in this regard based on the integration of two main models: analytical, to account for different mechanisms of plasma particle dynamic; and electrical, accounting for coil, plasma and passive metallic structures present within the driver region. The methodology was then applied to two different ion sources.

This work highlights a further development of this methodology. Two main additions in analytical model are discussed: the estimation of average electron density as a function of RF power and gas pressure; and the influence of the magnetic field on the input parameters for the electrical model (for instance, plasma conductivity). The methodology is then applied to SPIDER drivers and the results in terms of equivalent electrical parameters and PTE are presented.

EXPERIMENTAL INVESTIGATION OF PSEUDOSPARK DISCHARGE BASED PLASMA CATHODE ELECTRON SOURCE FOR THE GENERATION AND PROPAGATION OF HIGH DENSITY AND ENERGETIC ELECTRON BEAMS

Varun .[1], Mahesh Kumar[2], Udit Narayan Pal[3]
1. CSIR- CEERI, Pilani, India and AcSIR, Ghaziabad, India
2. Microwave Devices Area, CSIR- Central Electronics Engineering Research Institute (CEERI), Pilani, Rajasthan-333031, India
3. CSIR-Central Electronics Engineering Research Institute, Pilani, India

Pseudospark discharge has attracted significant attention for the generation of high density, energetic and high brightness electron beams with fast current rise for the growing applications on extreme ultraviolet and X-ray radiation source, microwave and THz radiation generation, surface modification, etc. [1-2]. In this work, the investigation has been carried out for the generation and propagation of high density and energetic electron beams from the triggered multi-gap pseudospark discharged based plasma cathode electron (PD-PCE) source [3-5]. The proposed multi-gap PD-PCE source mainly consists of hollow cathode, trigger unit, multi-gap floating electrodes, anode and multi-ring annular collector. The properties of generated electron beams are mainly influenced by trigger location and energy, gases (Argon, Helium, Nitrogen) and pressures, electrode apertures and anode voltages (up to 40kV) [5]. The generated focused electron beam has been propagated $>$ 100 mm in the ion focused regime without using any external magnetic field. The radial and axial profile of generated electron beam at different locations have been analyzed for different operating and circuit conditions. The electron beam of $\sim$30kV and $\sim$103 A/cm2 has been generated and propagated in the PD-PCE source. The design and characterization issues of the multi-gap PD-PCE source has also been presented.

[1] D. Bowes, et.al. Nucl. Inst. Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, vol. 335, pp. 74–77, 2014.

[2] Y. Fu, et.al, Nucl. Inst. Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, vol. 434, pp. 88-92, 2018.

[3] Varun et. al, IEEE Trans. Electron Devices, vol. 65, no. 4 pp. 1542-1549, 2018.

[4] Varun, et. al, IEEE Trans. Electron Devices, vol. 65, no. 10, pp. 4607–4613, 2018.

[5] Varun et. al, IEEE Trans. on Plasma Sci., vol. 46, no. 6, pp. 2003-2008, 2018.

STATISTICAL QUANTIZATION AND OPTIMIZATION OF COLD ATMOSPHERIC PRESSURE PLASMA SOURCE FOR DESTROYING BACTERIA AND BIOFILMS THROUGH DESIGN OF EXPERIMENTS METHOD

Jim Browning[1], Adam Croteau[2]
1. Professor
2. Boise State

Cold atmospheric pressure (CAP) plasma has been shown to kill bacteria and destroy biofilms through reactive etch and sputter activity and could be used on industrial surfaces in the food processing industry where microbial contaminants are a source of food-borne illness. Our group has developed a parallel plate plasma source using embedded electrodes. Results have demonstrated that our source, operating at 20 kHz and 2-5 kV, can kill bacteria on various substrates with a Colony Forming Unit (CFU) reduction of 50% in <10 s. However, the operating mechanisms to achieve the most effective bacterial reduction have yet to be optimized. A 2-stage Design of Experiments (DoE) is being employed. A fractional factorial Factor Screening Experiment (FSE) is used to detect the statistical significance of seven experimental factors. The remaining factors will be put through a Central Composite Design capable of detecting non-linear interactions between factors within the design space. Experimental factors and variance ranges are as follows: discharge gap (0.1-3mm), covering electrode dielectric thickness (.2-1.8mm), AC voltage (2.5-5kV), proximity to substrate (0.3-5mm), exposure duration (2-18s), Argon gas flowrate (5-25 lpm) and Oxygen gas flowrate (0.35-5.64 lpm). We will measure the discharge current and the remaining CFU count as numeric responses and the bacteria removal as a binary response. These responses will show the optimal configuration of experimental factors to achieve the lowest CFU counts possible. These results will be presented.

PROPERTIES OF THE ENERGY-CONTROLLED ATMOSPHERIC PRESSURE PLASMA DRIVEN BY MULTI-STEP EXTERNAL BALLAST CAPACITORS

Chang-Seung Ha[1], Yun Sik Jin[1], Seong-Tae Han[1], Chae-Hwa Shon[1], Dae-Jong Kim[1], Ho-Jun Lee[2]
1. Korea Electrotechnology Research Institute
2. Pusan National University

Atmospheric-pressure plasma sources have been intensively studied because of their various industrial applications. Especially atmospheric pressure plasma has a strong potential for biomedical and surface treatment applications. In this paper, we report properties of the energy-controlled atmospheric pressure plasma. The independent control of the voltage and the discharge current is suggested to make high degree of process selectivity and competitiveness of a functional atmospheric pressure plasma source.

The developed plasma has external ballast capacitors. Energy of the external ballast capacitor is injected directly into plasma region. Therefore, the discharge current and voltage can be controlled independently through the capacitance and the charging voltage. In this study, two external ballast capacitors are used. The capacitors are connected in parallel during the charging period, and the capacitors are connected in series during the discharge one. The connections of the capacitors are controlled by an Insulated Gate Bipolar Transistor(IGBT)s as switching devices.

Plasma formation process is observed by the synchronized Intensified Charge Coupled Device(ICCD) image along with monitors, such as optical emission line, voltage and discharge current. Characteristics of two different plasma modes are compared at the same discharge energy. One is low capacitance with high voltage and the other is high capacitance with low voltage. Light intensity, optical emissions, gas temperature, discharge current, plasma duration are controlled, depending on discharge current and voltage. For this reason, the developed plasma source is expected to be used for promising applications, such as, plasma activated water (PAW), surface treatment and biomedical applications.

RADIO FREQUENCY PLASMA GENERATION WITHOUT 50 OHM MATCHING

Tim Ziemba, James Prager[1], Kenneth E. Miller[2]
1. Eagle Harbor Technologies, Inc.
2. Eagle Harbor Technologies, Inc

Eagle Harbor Technologies (EHT), Inc. is developing radio-frequency (RF) solid-state switching power supplies without the need for a 50-ohm matching network. The ability to remove the 50-ohm matching network from RF plasma generation systems significantly simplifies the design while allowing for a faster response time to changing plasma conditions. This system takes advantage of EHT's previously developed full-bridge circuit to drive a resonant load. These systems can be designed to operate from 100 kHz to tens of megahertz. This power system has applications in semiconductor processing, fusion energy science, material science, and basic plasma physics. EHT will present circuit modeling, diagrams, and waveforms.

CNT FIELD EMISSION CATHODES EVALUATED FOR A PORTABLE X-RAY GENERATOR FOR ROOT IMAGING

Enbo Yang[1], Scott Kovaleski[1], Jacob Williams[1]
1. University of Missouri

A portable X-ray generator for plant root imaging is being developed. The generator mainly includes a Cockcroft-Walton DC high voltage generator, which provides a high voltage DC bias to an x-ray diode, and a metallic target to convert the electron beam into X-rays. A backscatter imaging technique is used, where X-rays are projected onto the plant target (the roots buried in soil), and Compton scattered photons are collected to reconstruct an image. To reduce the size and complexity of the X-ray generator, cold cathodes are desired to avoid the need for cathode heating. Ex-situ fabricated carbon-nanotubes (CNT) deposited on silicon wafers have been chosen as a potential cathode considering their high field emission efficiency and physical and chemical stability. Preliminary tests of CNT field emission cathodes for use as the electron beam emitter in the X-ray diode are presented. CNT cathodes have been shown to produce a current with a magnitude of 100 μA with a relatively low turn-on voltage. Compared to thermionic sources of electrons, field emission-based carbon nanotube cathodes appear to be a very good candidate electron source for our X-ray generator.
Work supported by the Advanced Research Projects Agency-Energy.

THE INCREASING EFFICIENCY OF PENNING ION SOURCE

Sergey Korenev[1], Anton Korenev[1]
1. Kore-ip, LLC

The tantal has good accumulation for hydrogen and this property we can use for hybridization in hydrogen plasma in Penning Ion Source for decreasing of work function and increase the autoemission electron current from tantal cathodes in the Penning Ion Source. In this paper shown the increasing of electrons current emitted from tantal cathodes can be explained by effect of hybridization in hydrogen plasma in compare with thermionic emission which used for increasing of negative hydrogen ions in Penning Ion Source. The critical analysis of experimental data of Penning Ion Source is considered in this paper.

CHARACTERISTICS OF CATHODE SPOTS IN VACUUM ARC DISCHARGE WITH HYDROGENATED CATHODE

Pan Dong, Jie Li[1], Jidong Long[1]
1. Institute of fluid physics

Hydrogenated metal used as the cathode of vacuum arc ion source could produce strong hydrogen ion current. Compared with pure metals, the cathode spot characteristics of hydrogenated cathode have special features due to hydrogen release. High speed photograph was used to observe the luminous spot during discharge, and microscopy was used to observe the cathode surface appearance after a single discharge. The results showed the plasma aggregated together during discharge and there was only one luminous spot. There were multiple luminous spots due to droplets occasionally. The surface of hydrogenated cathode had common molten craters and distinctive flocculent pores. The cathode spots were continuous distributions around the microcracks on the cathode surface, which was consistent with the aggregated plasma. These results are helpful to understand the process of vacuum arc discharge with hydrogenated electrode, and to promote the applications of such ion source.

INVESTIGATION OF A PULSED PINCH PLASMA FOR THE APPLICATION AS FAIR PLASMA STRIPPER

Marcus Iberler[1], Thilo Ackermann[2], Bernhard Bohlender[2], Konstantin Cistakov[2], Hock Christian[2], Alexander Müller-Münster[2], Xu Ge[2], Joachim Jacoby[2]
1. Goethe Universität Frankfurt
2. Goethe University Frankfurt

The accelerator laboratory for Antiproton and Ion Research (FAIR) is under development at GSI in Darmstadt, Germany. The main topic at this facility is aimed to heavy ion research. The FAIR project in comparison to the existing facility GSI extends the research area by raising the energy of heavy ion beams. The demand for acceleration of the beam to the highest possible energy is a highly ionized charge state of the Ion beam. For beam stripping to get higher charge state, the traditional tools are foil stripper and gas stripper. For this reasons Plasmas are suggested to use as stripper medium. In Frankfurt a Theta Pinch is under investigation for this application. The experimental set up consists of a linear theta pinch coil and pulse forming network. For switching the pulsed current a thyratron was used. The constricting effect on the plasma or conductor is produced by the magnetic field pressure resulting from the magnetic field of the linear current and magnetic field of the coil. The device operates at a frequency of approximate 10 kHz with a capacity of 150 μF and voltages up to 40kV. This contribution gives the first results of the transfer efficiency and optical investigations of the pulsed theta pinch. In addition first measurements of beam time experiments at GSI will be presented.

Work is supported by BMBF

ELECTRON BEAM STUDIES AND X-RAY SPECTROSCOPY OF DENSE PLASMA FOCUS EXPERIMENTS

Emil Petkov[1], Stuart Jackson[1], Andrey Beresnyak[2], Nicholas Ouart[1], Arati Dasgupta[1], John Giuliani[1]
1. Naval Research Laboratory
2. Consultant to NRL through RSI

The study of electron beam generation in a dense plasma focus (DPF) can yield insight into the physical mechanisms that lead to the formation of electron beams in pinched plasmas. A detailed understanding of these mechanisms may enable the production of a high-intensity x-ray source for various applications. Plasma polarization spectroscopy (PPS) is a novel diagnostic tool that will be employed in this proposed work to investigate the electron distribution function and fields within a DPF plasma. We plan to use PPS to measure the degree of polarization of several x-ray spectral lines emitted by a DPF driven by NRL's Hawk pulsed-power generator. Preliminary experiments will focus on diagnosing the plasma electron temperature in DPF experiments doped with Ar gas. This data will be used to validate a finite volume MHD code that calculated the plasma temperature and density of a Hawk shot doped with Ar gas. These parameters are used as input in non-local thermodynamic equilibrium (non-LTE) kinetic models to identify possible line emission candidates that have appreciable degrees of polarization. To measure the degree of polarization experimentally, two spectrometers will be configured with identical crystals that yield a nominal Bragg angle as close to 45 ° as possible for the selected optimal lines. The two crystals will be oriented such that the separate spectrometers simultaneously record x-rays polarized parallel and perpendicular to the axial direction of propagation of the electron beam. The measured polarization will then be compared with atomic and radiation calculations for different electron distribution functions in order to determine the beam energy and infer the strength of the accelerating fields in the DPF. The development of a magnetic sublevel kinetics code, which will complement future spectropolarimetry studies, is also discussed.

*This work was supported by NRL/ONR/Karle Fellowship.

DETERMINATION OF THE PARTICLES INVOLVED IN ANODE INITIATED VACUUM BREAKDOWN USING A 1-MV, 50-NANOSECOND PULSE GENERATOR*

Raymond Allen[1], David Hinshelwood[1], Stuart Jackson[1], Paul Ottinger[2], Ian Rittersdorf[1], Joseph Schumer[1]

1. Naval Research Laboratory

2. Consultant to NRL through Syntek Technologies, Fairfax, VA 22031

Several experiments have shown that the anode initiates breakdown of vacuum gaps in cases where the anode and cathode field enhancements are approximately equal.1 The previous understanding was that only explosive emission at the cathode initiates breakdown between metal electrodes in vacuum with nanosecond pulses. Past experiments have shown clear evidence of particles from the anode initiating breakdown when the cathode was not specially roughened or treated to increase field enhancement. However, the type of particles coming from the anode was not known. Now, we have measurements from a specially designed anode-cathode structure that has allowed us to capture these particles. CR-39 film was used as a particle detector. A Thomson parabola and also a Kimfoil filter allowed us to determine the particle species.

1. R. J. Allen, et al., "Effects of Anode and Cathode Surface Treatments on Vacuum Breakdown Between Metal Electrodes with 50-ns High Voltage Pulses", 21st International Pulsed Power Conference, June 18 - 22, 2017.

----

* Work supported by the Naval Research Laboratory Base Program

EFFECTS OF THE ELECTRON BEAM PARAMETERS ON HYDRODYNAMIC RESPONSE OF ALUMINUM: MEASUREMENTS AND SIMULATIONS.

Béatrice Bicrel[1], Bruno Cassany[1], Alain Galtié[1], Jacques Gardelle[1], David Hébert[1], Nicolas Szalek[1]
1. CEA

Effects of the electron beam parameters on hydrodynamic response of aluminum: measurements and simulations.

J. Gardelle, B. Bicrel, B. Cassany, A. Galtié, D. Hébert and N. Szalek.

CEA/CESTA, 15 avenue des Sablières, CS 60001, 33116, Le Barp, France

The study of the dynamical response of material under shocks produced by electrons requires a good knowledge of these when they interact with solid targets. The CESAR generator is used at CESTA to feed a field emission diode which delivers single-shot and very intense electron pulses ($\approx$ 800 keV, $\approx$ 300 kA, 60 ns). The electrons emitted by the cathode propagate in a gas-filled chamber where they are focused by a magnetic coil onto an aluminum target. The analysis of the beam characteristics at the target position gives the initial conditions required for precise hydrodynamics simulations. In this paper, we present the measurements of the main beam characteristics at the position where the target is installed. We paid particular attention to voltage, current, spatial homogeneity, dose rate onto the target, as well as Photon Doppler Velocimetry (PDV) of the target back face. The angles of incidence of the electrons are estimated by using the PIC code MAGIC with a strong approximation. Indeed, our simulations tools do not work in gases at 1 mbar and we are currently assuming perfect space charge and current neutralization. We are trying to address this issue by adapting the code CALDER developed at CEA/DIF and within a Basic Science collaboration with SNL. Nonetheless, we obtained very nice agreement between the measurement and the simulation of the shock, as computed by the CEA codes Diane and Hesione.

PROPAGATION OF ELECTRON BEAMS IN GAS CELLS

Bruno Cassany[1], David Hébert[1], Jacques Gardelle[1], Patrick Modin[1], Nicolas Szalek[1], Kate Bell[2], Chris Moore[2], B Medina[2], Matt Bettencourt[2]
1. CEA
2. Sandia National Laboratories

PROPAGATION OF ELECTRON BEAMS IN GAS CELLS

B. Cassany, D. Hebert, J. Gardelle, P. Modin, N. Szalek,

CEA/CESTA, CS 60001, 33116 Le Barp, France

K. Bell, C. H. Moore, B. Medina, M. Bettencourt

Sandia National Laboratories

Albuquerque, NM 87185 USA

In this work, we present the first results of joint Sandia National Laboratories (SNL) and CESTA experiments where electron beams are produced by field-emission diodes and propagate in Argon-filled gas cells. We are presently using the RKA generator (500 keV, up to 30 kA, 100 ns) at CESTA [1] and future experiments will include the SPHINX facility (0.5-2MeV, 30 kA, 10 ns) at SNL [2]. Two similar experimental chambers, containing a large number of diagnostics, are being built at each institution for this fundamental science program. Diagnostics include a Cerenkov imaging line for spatial-temporal electron beam homogeneity analysis, PDV systems for plasma electron density measurements, and a grating for measurements of kinetic energy. These diagnostics are supported by standard electrical measurements such as B-dot probes and Faraday cups. The experimental data are used to compare to the EMPIRE code developed at SNL [3] as well as the CALDER code at CEA [4].

[1] K. Pepitone, J. Gardelle and P. Modin, Journal of Applied Physics 117, 183301 (2015);

[2] N. R. Joseph, M. E. Savage, J. C. Stephens, J. A. Lott, B. A. Lewis, R. D. Thomas, M. A. Torres, and E. G. Holman, in 2015 IEEE Pulsed Power Conference (PPC), (2015), pp. 1–5.

[3] A. Markosyan, C. H. Moore, M. T. Bettencourt, J. C. Bennett, J. J. Lifflander, D. S. Hollman, J. J. Wilke, K. Hemanth, Particle in Cell Algorithms and Codes Towards Next Generation Architectures, 70th GEC, 2017.

[4] F. Pérez, L. Gremillet, A. Decoster, M. Drouin and E. Lefebvre, Phys . Plasmas 19, 083104 (2012)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

PROPAGATION OF AN INTENSE RELATIVISTIC ELECTRON BEAM THROUGH PLASMA.

claude fourment[1], Thomas Lahens[1], Rémi Maisonny[2], Fabien Dorchies[3]
1. CEA-CESTA, Le Barp, F-33116 France
2. CEA, DAM, GRAMAT, F-46500 Gramat, France
3. Universite de Bordeaux-CNRS-CEA, CELIA, Talence F-33405 France

In the framework of X-Ray Flash Radiography, we investigate the propagation of an intense (2 kA), pulsed (60 ns) relativistic (4 MeV) electron beam (REB) through a cold plasma. The REB electrons interact with the plasma through binary collisions and collective response, whose importance depends on the ratio of plasma over beam density. Under some conditions, the collective response induces partial or total charge and/or current neutralization of the beam, breaking the near-perfect cancellation of self-forces and leading to a noticeable modification of its propagation. We present a simple model of this phenomenon based on an axisymmetric envelope equation. According to this calculation, a significant gain in the focusing of the REB can be achieved in a broad range of plasma density (10^{10} to $10^{13}\,cm^{-3}$), but special care should be taken regarding the plasma current diffusion and the ionization of the residual gas. We will also present some detailed Particle In Cell simulations as well as a dedicated experiment designed to validate our understanding of the physical situation.

COMPARISONS OF A QUANTUM PHOTOEMISSION MODEL WITH THREE-STEP MODEL AND FOWLER-DUBRIDGE MODEL

Yang Zhou[1], Peng Zhang[1]
1. Michigan State University

Photoemission is one of the fundamental processes to produce electron beams and is important to particle accelerators, electron microscopy, and vacuum electronics [1]. Recently, an analytical model for photoelectron emission from metal surface illuminated by a laser field was developed, by solving the time-dependent Schrödinger equation exactly [2, 3]. The model includes the effects of dc electric field and laser electric field (of arbitrary frequency and strength), as well as metal properties (Fermi energy, work function). The model shows good agreement with experiments [3]. In this study, we compare this quantum model with existing classical models for photoemission, including the three-step model and Fowler-Dubridge model [4-7]. The validity and limitations of each model will be examined.

[1] P. Zhang, and Y. Y. Lau, J. Plasma Phys., Vol. 82. 595820505, 2016.

[2] P. Zhang, and Y. Y. Lau, Sci. Rep., Vol. 6, 19894, 2016.

[3] Y. Luo, and P. Zhang, Phys. Rev. B, Vol. 98, 165442, 2018.

[4] R. H. Fowler, Phys. Rev., Vol. 38, pp. 45-56, 1931.

[5] L. A. DuBridge, Phys. Rev., Vol. 43, pp. 727-741, 1933.

[6] J. H. Bechtel, W. Lee Smith, and N. Bloembergen, Phys. Rev. B, Vol. 15, pp. 4557-4563, 1977.

[7] D. H. Dowell, and J. F. Schmerge, Phys. Rev. Special Topics-Accelerators and Beams, Vol. 12, 074201, 2009.

Work supported by the Air Force Office of Scientific Research (AFOSR) YIP Award No. FA9550-18-1-0061.

DESIGN AND DEVELOPMENT OF 1 MV GRADED INSULATOR ELECTRON BEAM DIODE FOR KALI 30 GW SYSTEM

Rakhee Menon[1], Senthil K[1], Romesh Chandra[1], Amitava Roy[1], Archana Sharma[1]
1. BARC

KALI 30 GW (1 MV, 30 kA, 80 ns) system in APPD, BARC has been operational for pulsed high power relativistic electron beam generation and it's applications like Flash X-rays (FXR) and High Power Microwave (HPM) generation. A MARX generator and Blumlein (BL) pulse forming line (oil dielectric) based topology provides the high voltage pulse ($\sim$ 1 MV) to the cathode/anode. The present radial insulator based electron beam diode has been upgraded to metal insulator staked graded electron beam diode mainly for the FXR applications. The vacuum insulator consists of a stack of solid dielectric insulating rings (cut at an angle of 450 to the diode axis) alternated with annular metal disks. The insulator stack consists of 18 each alternated Perspex (25 mm) and Aluminium (3 mm) ring assembly of 526 mm length for withstanding surface flashover on oil side. On the vacuum side, the insulator is at 45 degree angle with respect to the high voltage electrode to prevent secondary electron emission initiated flashover. Field stress analysis was carried out using CST EM Studio Software and the estimated field values are $<$ 150 kV/cm. The HV electrode is an SS tube (250 mm diameter and 917 mm length) at the end of which suitable connections are made for diode mounting. The electron beam diode has been fabricated and installed in KALI 30 GW system and operated upto 330 kV peak voltages. A Tungsten (W) Anode (4 mm diameter) & graphite disc cathode forms the FXR diode. At a vacuum level of 8 x 10-5 mbar and 4 mm A-K gap, a dose of 128 mR was measured at 1 m distance.from the window. The typical peak diode voltage and current measured was 330 kV, 7 kA respectively. Experiments are under way to increase the diode voltage upto 1 MV.

SATURN ACCELERATOR BREMS DIODE SINGLE CATHODE CURRENT SCALING

Nathan Joseph[1], Chris Grabowski[1], Ken Struve[1], Ben Ulmen[1], Andrew Biller[1], Debrah Kirschner[1]
1. Sandia National Laboratories

The Saturn accelerator was commissioned in 1987 as a 5.4 MJ, 2.7 MV flash x-ray machine that delivers 750 kJ at 2.1 MV to a three-ring Bremsstrahlung (BREMS) diode with a peak power of 25 TW and FWHM pulse width of 40 ns. In December of 2017 and June of 2018 experiments were conducted using varying numbers of Saturn pulsed power modules connected to one of the three Saturn parallel BREMS diodes. In this paper, we will describe the measured effect of current scaling on a single cathode BREMS diode, with metrics on total current and calculated voltage to a single BREMS diode, compared with radiation production from a single BREMS diode (total dose and pulsed width) on the Saturn accelerator.

----

* Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

DESIGN AND TESTING OF S-BAND RBWO FOR GIGAWATT LEVEL OUTPUT MICROWAVE POWER AND COBRA LENS FOR DIRECTIVE OUTPUT

Romesh Chandra[1], Sandeep Singh[1], Amitava Roy[2], Rakhee Menon, Vishnu Sharma[2], Ankur Patel, Senthil Kalyanasundaram, Sabyasachi Mitra, Jayanta Mondal, Archana Sharma

1. Bhabha Atomic Research Centre

2. BARC

A relativistic backward wave oscillator (RBWO) has been designed in S-band frequency for 600 kV and 6 kA beam current. A five cell uniform slow wave structure (SWS) has been used for electron beam to microwave interaction and a resonant reflector (RR) is used to reflect the generated microwave power in the forward direction. The dispersion curve of the SWS is obtained numerically and hot dispersion shows electron beam to SWS interaction at 3.3 GHz frequency. PIC simulations were performed for optimization of SWS-RR separation and for 90.0 mm separation maximum efficiency of 25% was achieved. The complete structure is installed at KALI 30 GW system for microwave generation. A magnetic field coil with maximum 0.7 T magnetic flux density is used for guiding electron beam through SWS. Maximum output power achieved was 1.2 GW for 600 kV, 7 kA electron beam current at 3.28 GHz frequency for 0.55 T magnetic flux density. Output power is measured in the farfield region as well as by B-dot probes placed in the antenna. The output microwave pattern in the farfield was impinged upon a Neon bulb array. An annular illumination pattern is obtained with a null in the centre. To make the output pattern directive, a Coaxial Beam Rotating Antenna (CoBRA) has been designed which converts the annular pattern into a TE11 like mode having maximum intensity in the centre of the profile. The directed imprint of 300 MW radiation profile is taken at Neon array which shows illumination in centre.

EMPIRE SIMULATION OF THE RKA DIODE INTO THE GAS CELL

Brandon Medina[1], Chris Moore[1], Matt Bettencourt[2], Keith Cartwright[2], Troy Powell[2], Kate Bell[2], Timothy Pointon[2], Edward Phillips[2], Jacques Gardelle[3], David Hebert[3]

1. Sandia National Labs

2. Sandia National Laboratories

3. CEA

As part of a continued validation effort for Sandia's new plasma code, EMPIRE, we have modeled and are simulating the RKA beam experiment. Specifically, we have improved previous simulations of the RKA diode by using input parameters that more closely match the experiment and implementing Space Charge Limited (SCL) emission from the cathode velvet into EMPIRE. Moreover, we have begun simulations of the diode into the gas cell. The current EMPIRE (informal) validation effort is ultimately concerned with the electron-beam transport (e.g. electron-neutral chemistry) through an Ar-filled gas cell at various pressures from vacuum to $\sim$1 Torr. Two collisional models are investigated in the present work: Monte Carlo Collisions (MCC) that assume a uniform, unperturbed background gas and the Direct Simulation Monte Carlo Method (DSMC) that models the background gas evolution self-consistently. In the current work, we will compare to CEA results and investigate the performance and accuracy of the two collision schemes across a range of pressures.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

EFFECTS OF VACUUM IMPEDANCE CHANGES ON MITL FLOW USING 3D ELECTROMAGNETIC PIC SIMULATIONS

Troy Powell[1], Andrew Biller[1], Keith Cartwright[1], Timothy Pointon [1]
1. Sandia National Labs

Vacuum impedance changes in Magnetically Insulated Transmission Line (MITL) flow has been shown via simulation to have profound impact on MITL flow patterns. Using EMPHASIS, a 3D Unstructured Time Domain Electromagnetics Particle-In-Cell (PIC) code, it was shown that the HERMES III extended MITL exhibits significant power loss due to changes in vacuum impedance.

Results are compared with those using QUICKSILVER, a structured EM PIC code and EMPIRE, another unstructured EM PIC code. All codes agree with each other, and, more importantly, with experimental current measurements. Further evidence of electron loss in the MITL is given by strong thermoluminescent dosimeter (TLD) readings along the outer surface of the MITL anode.

The MITL has recently been redesigned with constant impedance and now shows virtually no current loss. It is expected that this will increase the dose output of HERMES III by at least a factor of 2. Geometry choice as well as comparison between simulation and experimental performance of the redesigned MITL is reported and discussed. Predictions of current shunt and B-dot data from EMPHASIS are also discussed.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

PIC SIMULATION OF ION BEAM EXPANSION IN A DRIFT CONE CONFIGURATION FOR RFEA MEASUREMENTS.

Yao Du[1], Matthew Talley[1], Steven C. Shannon, Alok Ranjan[2], Peter Ventzek[2]
1. North Carolina State University
2. Tokyo Electron Limited

Ion energy distribution function (IEDF) plays a significant role in numerous plasma enhanced manufacturing processes in the semiconductor industry. To measure the IEDF, retarding field energy analyzers (RFEA) have been widely used. To extend the capability of measuring higher ion energies and minimize impact on manufacturing processes, a traditional RFEA was redesigned and embedded in the bias cathode of a plasma reactor. One design element is a differentially pumped drift cone between the cathode surface and RFEA that allows for recessed placement of the probe and uniform delivery of facilities such as water cooling and He backside cooling for manufacturing processes.

Significant ion current reduction was observed in this design due to Coulomb expansion of the beam and ion collisions with background gas. A 2D particle-in-cell (PIC) code, XOOPIC1, was used to quantify the impact.

For the collisionless case, the trajectory of ion beam was solved analytically assuming single-energy flux. The solution used Dawson function to implicitly give the outer radius of ion beam as a function of distance. The solution matched the results obtained from XOOPIC.

For the collisional case, to accurately model small-angle scattering, angular differential cross section was derived by incorporating polarization scattering into collision integral based on impulse approximation, which was then used to replace the isotropic cross section in XOOPIC. The updated model performed better by reducing the large-angle scattering, especially at high pressure regime. However, at small pressure regime ($\sim$0.12mTorr), Coulomb expansion dominates the significant current reduction.

This work presents a pathway to compensate the RFEA measurements in a drift cone configuration, enabling measurement with minimal process perturbation. In addition, the derived angular differential cross section can be used in Monte Carlo simulation of elastic scattering between ions and neutral particles to give a better result for cases where small-angle collisions can be significant.

IMPROVEMENT OF HEAVEN-I HIGH POWER EXCIMER LASER FACILITY FOR ICF STUDY

Zhixing Gao[1], Jing Li[1], Zhao Wang[1]
1. China Institute of atomic energy

Improvement of Heaven-I high power excimer laser facility for ICF study

Zhixing Gao, Jing .Li, Zhao Wang, Fengming Hu, Baoxian Tian, Ze Lu

China Institute of Atomic Energy, Beijing 102413, China

The recent works on Heaven-I KrF laser facility was introduced to improve the performance of E-beam pumped laser for ICF study. The technique of EFISI had been used to improve the irradiation uniformity on target and the uniformity with six beam irradiation is near to 2% in our facility. To eliminate the dependence on uniform discharging of the front-end, it was attempted to homogenize the amplified self-emission from the discharge pumping KrF Laser with a light pipe. Meanwhile, the efforts have been made to compress the pulse with from 21ns to less than 10 ns with gain switch. A scheme to generate the shaped pulses for shock ignition was developed, which based on gain depletion and pulse overlapping. The ability for spatial and temporal shaping was taken into account in the future upgrade of Heaven-I at tens Kilo-Joule level for fusion study.

AUTO-COLLIMATION AND MONITORING OF KRF LASER BEAM IN THE E-BEAM PUMPED HIGH POWER EXCIMER LASER FACILITY

Jing Li[1], Fengming Hu[1], Zhixing Gao[2], zhao wang[2]
1. China Institute of atomic energy
2. China institue of atomic energy

Auto-collimation and monitoring of KrF laser beam in the E-beam pumped high power excimer laser facility

Jing li, Fengming Hu, Zhixing Gao, Zhao wang, Baoxian,Tian

(China Institute of Atomic Energy, Beijing, 102413)

Abstract:

The characters of the laser beam, such as the aiming precision and irradiation intensity on target, are important for the laser-matter interaction study. To ensure the aiming precision of the KrF laser in planar target experiment,an auto-aiming device with computer control has been set up in the target field of Heaven-I facility and some auto-collimating devices has been used to precise align the multiple laser beams in angular multiplexing system. These devices have greatly improved the aligning efficiency and aiming precision. Meanwhile, an on-line monitor system has been set up to acquire the beam energy and uniformity of the laser system.

PARAMETRIC STUDY OF A CYLINDRICAL INERTIAL ELECTROSTATIC CONFINEMENT FUSION DEVICE AND ITS APPLICATION

Smruti Ranjan Mohanty[1], Neelanjan Buzarbaruah[2], Darpan Bhattacharjee[2], Donney Jigdung[2], Eiki Hotta[3]
1. Centre of Plasma Physics- Institute for Plasma Research, Sonapu
2. Centre of Plasma Physics-Institute for Plasma Research
3. Tokyo Institute of Technology

Portable and cheap neutron sources are in demand for various applications such as cancer therapy, fusion material study, explosive materials etc. Among various neutron sources, inertial electrostatic confinement fusion (IECF) is an extremely simple device that produces neutron yield typically $\sim 10^8$ DD n/s. IECF is basically a fusion concept where the lighter fuel ions (deuterium, tritium) are trapped in a converging electrostatic field inside a cylindrical or spherical geometry.

A compact cylindrical IECF device is under operation at Centre of Plasma Physics-Institute for Plasma Research. This device mainly comprises of a cylindrical grid assembly housed inside a cylindrical vacuum chamber, a vacuum pumping system, a gas injection system, a high voltage feedthrough and a high voltage negative polarity power supply. Deuterium plasma is produced in it by the filamentary glow discharge as well as cold cathode discharge. The plasma is characterized using electrostatic probes. Plasma parameters such as the electron temperature (T_e), plasma potential (V_p) and plasma density (n_i) are evaluated. The plasma temperature and density are estimated at optimum experimental conditions and it is noted that the plasma temperature is 3 eV in the case of hot cathode discharge whereas 10 eV in the case of the cold cathode discharge. The plasma density as determined is two orders more in the case of the hot cathode discharge ($10^{15} m^{-3}$) than the other. Neutron Production Rate of the order 10^6 n/s is measured in this device by applying 80 kV to the cathode grid. The neutrons produced from the device have been characterized using various detectors such as neutron area monitor, He-3 proportional counter, bubble detector etc. The X-rays and neutrons emitted from the device were utilized for demonstrating the radiography and detection of explosives, respectively. A detailed of the recent results will be presented.

DEVELOPMENT OF HIGH-VOLTAGE POWER SUPPLY SYSTEM FOR UPGRADING ECH SYSTEM OF THE KSTAR

Sunggug Kim[1], Sonjong Wang[2], jongwon Han[2], Mi Joung[2], Inhyuk Rhee[2], Jong gu Kwak[2]
1. NFRI (Natinal Fusion Research Institute)
2. NFRI

Electron cyclotron heating (ECH) is used as one of the most important auxiliary heating method for plasma heating in modern fusion research. In addition to plasma heating, EC system is used for plasma current drive and control of plasma instabilities such as NTM (Neoclassical Tearing Modes). ECH (Electron Cyclotron Heating) system for KSTAR (Korea Superconducting Tokamak Advanced Research) is composed of two dual-frequency gyrotrons, each generating 950kW of RF power at 140 GHz and 800kW of RF power at 105 GHz. In KSTAR, Gyrotron upgrade is planned up to 6MW RF power for steady-state operation. Gyrotron is the most sensitive and expensive equipment in the ECH system. In addition, high voltage power supplies (HVPS) are as important as gyrotron. HVPS must protected the gyrotron in emergency situation. In addition, the performance of the HVPS should be verified because It affects the quality of the RF beam. Generally, gyrotron requires two high-voltage power supplies (HVPS), referred to as the cathode power supply (CPS) and body power supply (BPS). EC systems of the KSTAR use the HVPS of PSM (Pulse Step Modulation) technology and the chopper type, respectively. The storing energy of the PSM type power supply is much lower than other power supply. It is very important factor to gyrotron protection. The protection time and energy are less than 5us and 10J. Output voltage stability and ripple are less than 1% ($<1\%$). The output voltage is adjustable in 0.5kV increments. PSM type HVPSs are under development for four gyrotron system to be added from 2019. In addition, a control system for gyrotron and all power supply is under development. This control system is designed for power control in real time. In this paper, we will describe the EC system currently installed in KSTAR and explain its future plans.

ECH/EBW HEATING SYSTEM IMPROVEMENTS FOR THE PROTO-MPEX EXPERIMENT AT ORNL

Tim Bigelow[1], John Caughman[1], Rick Goulding[1], Mike Kaufman[1], Ted Biewer[1], Cornwall Lau[1], Jeff Bryan[1], Juan Caneses[1], Juergen Rapp[1]
1. Oak Ridge National Laboratory

The Proto-MPEX (Material Plasma Exposure eXperiment) experiment at Oak Ridge National Laboratory has been developed as a prototype high density, medium temperature plasma source for a future MPEX facility for fusion relevant energy material sample testing [1]. On Proto-MPEX, an RF generated helicon plasma is further heated by electron cyclotron (ECH) and/or electron Bernstein wave (EBW) heating with microwave power generated by either a 28 GHz or 105 GHz gyrotron system. The 28 GHz system has been improved recently in the launcher configuration to more efficiently couple to the plasma. A new 105 GHz system has recently been installed and operated. Efforts are underway to increase the gyrotron output power available for experiments. Both systems utilize a mode converter and corrugated waveguide for power delivery. Two styles of launchers have been developed and tested: 1) a focused beam launcher for providing the optimum polarization and launch angle for efficient 28 GHz EBW coupling, and 2) a multi-bounce cylindrical mirror system has been developed for 2nd harmonic 105 GHz ECH experiments where low single-pass absorption is expected. Measurements and analysis of the waveguide transmission system performance, overall system efficiency and coupled power calibrations will be presented. Details of launcher design will be discussed and high power performance and coupling efficiency to the plasma for several launcher configurations compared based on experimental results[2].

[1] J. Rapp et al., Nucl. Fusion 57 (2017) 116001

[2] Biewer, T.M., et al. "Utilization of O-X-B mode conversion of 28 GHz microwaves to heat core electrons in the upgraded Proto-MPEX," submitted to Physics of Plasmas.

DEVELOPMENT OF AN ELECTRON-BEAM PUMPED, ARGON FLUORIDE LASER FOR INERTIAL CONFINEMENT FUSION*

Matthew Myers[1], Matthew Wolford[1], Andy Schmitt[1], Tzvetelina Petrova[1], George Petrov[1], John Giuliani[1], Malcom McGeoch[2], Stephen Obenschain[1]
1. Naval Research Laboratory
2. Plex, LLC

The U.S. Naval Research Laboratory has converted the repetitively pulsed Electra krypton fluoride (KrF) laser system to an electron-beam (e-beam) pumped argon fluoride (ArF) laser. Operating at 193 nm, ArF has the potential of being the most efficient excimer laser and is a good candidate for an inertial confinement fusion (ICF) driver. The shorter ultraviolet wavelength increases energy coupling to the target due to increased absorption at higher density and reduction of laser-plasma instabilities (from both smaller wavelength and a cooler plasma). The shorter wavelength also increases hydrodynamic efficiency due to the higher ablative pressure.

Measurements of the small signal gain, non-saturable absorption, and saturation intensity of ArF as a function of laser gas pressure were made in an e-beam pumped amplifier experiment. A gated, intensified camera was used to study the time-resolved e-beam deposition in the laser gas as a function of gas pressure. These measurements allow an evaluation of the intrinsic efficiency as function of energy deposition in the gas. Converting to an oscillator configuration with a 10 cm x 10 cm aperture, the laser yield, time-dependent laser intensity, and amplified spontaneous emission (ASE) were measured as a function of laser gas pressure. Data from the amplifier experiments as well as the oscillator measurements provide a rigorous evaluation of the NRL-developed, ArF kinetics code Orestes. The program goals are to evaluate the laser performance as a function of pressure, e-beam deposition, and gas composition; advance the NRL Orestes code to be a reliable and predictive tool for designing large scale e-beam pumped ArF lasers for optimal output; and develop the required e-beam technologies to fabricate large scale ArF lasers for fusion applications.

*This work was supported by the Naval Research Laboratory 6.1 Base Program and by the U.S. Department of Energy, National Nuclear Security Administration.

EFFECT OF VISCOSITY ON PROPAGATION OF MHD WAVES IN ASTROPHYSICAL PLASMA

Alemayehu Cherkos[1]
1. Addis Ababa University

We determine the general dispersion relation for the propagation of magnetohydrodynamic (MHD) waves in an astrophysical plasma by considering the effect of viscosity with an anisotropic pressure tensor. Basic MHD equations have been derived and linearized by the method of perturbation to develop the general form of the dispersion relation equation. Our result indicates that an astrophysical plasma with an anisotropic pressure tensor is stable in the presence of viscosity and a strong magnetic field at considerable wavelength.

PLASMA FORMATION PECULIARITIES ON DENCE PLASMA FOCUS DEVICES

Anuar Zhukeshov[1], Assem Amrenova [2], Zhangaly Moldabekov[3], Erlan Baltabay[3]
1. al-Farabi Kazakh national university
2. KazNU al-Farabi
3. Kazakh national university named after al-Farabi

One of the alternative fusion method is a plasma focus (PF) devices, based on the focusing of the plasma beam in a small area with high density. But today there are problems with plasma parameters and understanding of kind of neutron appear phenomena. We compared several PF devices with similar storage energy for the neutron and x-radiation generation peculiarities. Both methods theoretical estimates and experimental diagnostics were used to understand of native and conditions of plasma radiation. It can be conclude, that plasma particles radiation depended from device geometry but not from current or voltage. Thus, the radiations will efficiency then plasma formed and structured at same geometry or conditions.

Next, we have considered the features of the interaction of materials with plasma, which also sheds light on the dynamics of plasma formation. Experiments were conducted on the pulsed plasma accelerator “CPA-30” using different electrodes geometry. The results indicate that the efficiency of plasma compression became much higher with a short electrode. However, as the length of the electrode decreases, no increase in the plasma temperature is observed. The reason for this is the too long discharge time (14 μs), so the accelerated particles in the plasma can be thermalized. To start the synthesis and emission of X-rays from the focus region, calculations show that discharge times on the order of picoseconds are necessary. It is almost impossible to achieve this with existing equipment. Therefore, one should look for ways without using arresters and ignition devices, so as not to reduce the reaction time.

HYBRID FLUID/KINETIC MODELING OF DENSE PLASMA FOCUS DEVICES USING USIM AND VSIM

Christine Roark, Peter Stoltz[1], John W. Luginsland[2], Stuart Jackson[3], Andrey Beresnyak[3]
1. Tech-X Corp.
2. Confluent Sciences
3. Naval Research Laboratory

The Dense Plasma Focus (DPF) is a compact coaxial pulsed plasma source of radiation, especially neutrons. Researchers have known for some time that a DPF will produce more neutrons than one would expect from a purely thermal fluid prediction [S. Lee and S. H. Saw, Appl. Phys. Lett. 92, 021503 (2008)], and therefore the most accurate DPF simulations take into account kinetic effects [A. Schmidt, et al., Phys. Rev. E 89, 061101 (2014)]. Therefore, we are investigating how to leverage and integrate fluid and kinetic tools to study the DPF. We use the codes USim and VSim for this work. USim is a 3D capable, fluid plasma modeling framework that simulates the dynamics of charged fluids using any of a range of fluid models (for example, ideal MHD, extended MHD, or multi-fluid) on an unstructured grid. VSim is a 3D capable, kinetic particle-in-cell, FDTD modeling framework that can model fields with either Maxwell or Poisson equations. We present the results of varying initial conditions in the fluid code, such as density and background gas fill, on the formation of the pinch. We also present the results of varying the fluid model from ideal to extended MHD, including in particular Hall terms, to determine the effect of the electric field. We compare results with similar studies done in Athena [A. Beresnyak, et al., "Current disruption and electric field in dense plasma focus", 2018 APS DPP meeting, Portland OR; NO6.00002]. Finally we show the results of transitioning from fluid to full kinetic models and discuss the tools and algorithms we used for that. For all of this work, we use parameters relevant to the Hawk DPF at Naval Research Lab [S. Jackson, "Charged particle acceleration experiments in a dense plasma focus driven by a high-inductance generator", 2018 APS DPP meeting, Portland OR].

THE DESIGN, PROPERTIES, OPERATION AND MODELING OF THE STPX PLASMA DEVICE

R. Williams[1], J. Clark, M. Richardson, S. Evans, D. Ologunogba, A. Aghedo, J. Titus, C. Weatherford
1. Florida A. & M. University

The Spheromak Turbulence Physics Experiment (STPX), a new large diameter (1.5 m) gun injected spheromak confinement system, has been constructed recently at FAMU for use originally in studying equilibrium, reconnection, turbulence, dust transport, and astrophysical phenomena, and for diagnostic probe development. We present details on its design, construction, operation, performance parameters and on its suite of diagnostic devices. Diagnostics to measure plasma parameters, electric and magnetic fields, particle flux and optical emission will be described in detail. STPX has many access ports which, along with its large volume, makes possible many new flexible experimental configurations. Ongoing results of a new computation model we developed to study particle dynamics in the injector gun will be discussed. Studies are underway to design a research campaign to adapt this laboratory device to study topics related to high energy density science. This university facility is being used to train students in the basics of plasma physics that can be useful to them in larger fusion, high energy density science, and astrophysically-related laboratories.

Supported by Consortium for High Energy Density Physics.

ELEMENTS OF THREE DIMENSIONAL MODELING OF A PULSED FISSION FUSION HYBRID Z-PINCH TARGET FOR ADVANCED PROPULSION

Jason Cassibry[1], Robert Adams[2], Nathan Schilling[1], Kevin Schillo[1], Bryan Winterling[1], Brian Taylor[2], Steve Howe[3]
1. University of Alabama in Huntsville
2. NASA Marshall Space Flight Center
3. Howe Industries

The Pulsed Fission-Fusion Engine (PuFF) propulsion concept combines utilizes targets of fission and fusion fuel layers compressed and heated by a pulsed z-pinch driver. Fusion may provide the neutron seed to ignite the fission fuel, which in turn provides fission fragment heating to sustain the fusion reactions. The propulsion system utilizes a z-pinch to compress PUFF targets. Thermal expansion of the fission/fusion fuel and inert propellant against a magnetic nozzle produces thrust. The concept is expected to have a thrust range of of 0.5 to 10 kN and specific impulse from 10000 to 30,000 s. In this talk, modeling efforts supporting PuFF will be discussed, with emphasis placed on 3D modeling. We will present some notional implosion modeling of high Z materials in cylindrical geometries and rapid expansion against pulsed magnetic nozzles.

OVERVIEW OF THE C-2W FORMATION SECTION PULSED POWER

Ian Allfrey[1], Andrey Korepanov[1], Yuanxu Song[1], Erik Trask[1], Travis Valentine[1], Will Waggoner[1], Evan Bomgardner[1], Mark Morehouse[1], Kurt Walters[1]
1. TAE Technologies, Inc.

To achieve the goal of fusion TAE Technologies developed the C-2W experiment, an advanced beam-driven field-reversed configuration (FRC), which is the world's largest compact toroid device. It is a linear system which consists of two theta-pinch formed FRCs, translated and merged in a confinement vessel. Each of C-2W's Formation sections consists of two sets of magnets. First, a rotating magnetic field (RMF) which consists of a set of saddle coils triggered in phase such that the radial magnetic field rotates azimuthally. The RMF provides the initial plasma ionization. Secondly, a set of axial coils, fired sequentially with sub-microsecond precision, form and accelerate the FRC by means of a Bias and Main Reversal (MR) circuits. A wide range of charge and timing settings are possible, allowing for flexibility in the generated target.

The pulsed power consist of 190 capacitors with more than 2MJ of stored energy transferred by 516 switches into the load through $\sim$30km of high voltage coaxial cable. The MR circuit provides peak power in excess of 100GW. Current rise times range from 5μs to 130μs, where peak current in each of the axial coils exceeds 300kA. Total system current is measured by 380 rogowski probes.

With 440 pseudo-spark switches requiring heaters to control breakdown characteristics, we have developed heater control system, with remote monitoring and setpoint adjustment.

Details of the various systems will be presented.

MONOENERGETIC ION ACCELERATION FROM SHOCK WAVES DURING SELF-CHANNELING OF LASER PULSE

Amritpal Singh[1]
1. Lyallpur Khalsa College Jalandhar

The dynamics of a low density plasma following the charge-displacement self-channeling of a relativistically intense laser pulse is investigated by 2D- particle-in-cell (PIC) simulation. Long-lived, quasi-periodic multi-dimensional coherent field structures along the plasma channel are observed. Their dynamics is characterized with high spatial and temporal resolution in electromagnetic PIC simulations. An axially symmetrical pattern of electric and magnetic fields, resembling both soliton- and vortex-like structures is studied and a theoretical analysis of their generation is presented[1,2].

Mono-energetic ion acceleration along the channel radius is also studied by an electrostatic, ponderomotive model. Various issues such as the threshold between the ponderomotive acceleration [3] and the Coulomb explosion regimes, the effect of hydro-dynamical plasma wall breaking in the ion density and a related ”echo” effect in the electrostatic field have been unfolded.

1. T. V. Liseikina et al., Applied Physics Letters, 91, 171502 (2007).

2. Andrea Macchi et al., Plasma Physics and Controlled Fusion, 49, B71-B78 (2007).

3. Andrea Maccchi et al., Physical Review Letters 94, 165003 (2005).

HIGH INTENSITY SOURCE OF XUV RADIATION BASED ON FERRITE SURFACE BREAKDOWN

Ivan Tilikin[1], Sergey Tzhai[1], Sergey Savinov[1], Tatiana Shelkovenko[1], Alexey Agafonov[1], Sergey Pikuz[1]
1. P. N. Lebedev Physical Institute

High-current discharges along a ferrite surface have been studied on BIN pulsed power facility (270 kA current amplitude; 80 ns risetime, and 300 kV output voltage). It was found that the initial discharge pattern could be predefined by drawing on the surface with a graphite pencil. Each discharge generated an intense, reproducible pulse of optical and XUV radiation in the direction orthogonal to the ferrite surface. Time-integrated optical and XUV images of the discharge channel were similar for $\sim$5 consecutive shots.

Short, bright, strongly collimated XUV radiation was registered along the ferrite surface in a pre-breakdown stage of the discharge. Angular distribution and energetic characteristics of this radiation were studied. Possible mechanisms of the radiation are discussed.

ANALYSIS FOR THE GENERATION OF EXTREME ULTRAVIOLET (EUV)/SOFT X-RAY RADIATIONS BASED ON SHORT PULSE ELECTRON BEAMS

NAVIN KUMAR SHARMA[1], Varun .[2], Udit Narayan Pal[3], Y. Choyal[1]
1. School of Physics, Devi Ahilya University, Indore-452001, India
2. CSIR- CEERI, Pilani, India and AcSIR, Ghaziabad, India
3. CSIR-Central Electronics Engineering Research Institute, Pilani, India

Extreme ultraviolet (EUV)/soft X-ray radiations are highly important in the growing areas of surface modification of polymers for biocompatibility improvements, radiography of small objects for potential biological applications, etc. [1-2]. In this work, theoretical and plasma simulation studies have been presented for the generation of EUV/soft X-ray radiations from the pseudospark discharge (PSD) based short pulse, high density and energetic electron beams. Recently, PSD electron beam based devices are found to be most suitable for the generation of EUV/soft X-ray radiations [2-4]. The energetic PSD based electron beam is responsible for the electron impact excitation/de-excitation of background gas atoms for the emission in the range of EUV/soft X-ray. The investigation is presented for the electron impact excitation/de-excitation of background gas atoms due to scattering of propagated short pulse and energetic electron beams at different operating conditions. The transitions of gas atom/ions have also been explored for the emission of EUV/Soft X-ray radiation. It has been observed that the EUV/soft X-ray radiations are strongly influenced by the beam parameters, gas and pressures.

[1] J. Vieker et al., J. Phys. D, Appl. Phys., vol. 50, no. 34, p. 345601, 2017.

[2] D. Bowes, et al., Nucl. Inst. Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, vol. 335, pp. 74–77, 2014.

[3] Varun, et. al, IEEE Trans. Electron Devices, vol. 65, no. 10, pp. 4607–4613, 2018.

[4] Varun et. al, IEEE Trans. on Plasma Sci., vol. 46, no. 6, pp. 2003-2008, 2018.

COMBUSTION OF ELECTRICAL UNDERWATER EXPLODED ALUMINUM WIRE

Sergey Efimov[1], Alexander Rososhek[1], Anatoly Goldman[1], Somesh V. Tewari[1], Yakov E. Krasik[1]
1. Physics Department, Technion

Experimental observation of aluminum (Al) combustion realized in microsecond timescale under-damped underwater electrical explosion of Al wire is presented. Experiments were carried out using pulse power generator with peak current $\sim$220 kA and rise time of $\sim$1.6 μs. Using time-resolved spectroscopy, absorption bands of AlO oxide was obtained in the case of Al wire explosion with diameter <0.6 mm when underdamped discharge was realized. The temporal evolution of the temperature, calculated using time-dependent vibrational lines intensity, shows a minor increase from $\sim$6000 K at 35 μs (with respect to the beginning of the discharge current) towards the maximum of $\sim$7000 K at 65 μs and cooling thereafter. This range of temperature of AlO oxides satisfactory coincides with the temperature obtained from the Plank's radiation of the plasma channel, $\sim$5700 K. Also, it was shown that in the case of overdamped discharge realized during the explosion of 0.8 mm in diameter Al wire, only a weak continuous light spectrum was registered during $\sim$30$\neq\mu$s with respect to the beginning of the discharge current.

FINE LIQUID-METAL LOAD FOR REPEATABLE APPLICATIONS OF PULSED-POWER DISCHARGE

Toru Sasaki[1], Ryota Mabe[1], Kazumasa Takahashi[1], Takashi Kikuchi[1]
1. Nagaoka University of Technology

We have demonstrated a thin liquid-metal load for repeatable applications using pulsed-power discharge. To understand the liquid-metal behavior, we measured the liquid-metal diameter as a function of hydrodynamical normalized number. We found that the length and diameter of liquid-metal can use the hybrid X-pinch system. To demonstrate the thin liquid-metal load, we used a pulsed-power system using a magnetic switch. From the optical emission spectroscopy, the components of liquid were observed during the discharge. It indicates that the liquid-metal is the load for the pulsed-power discharge. We also demonstrated the repeatable discharge using pulsed-power system. The results show that the time-evolution of optical emission is reproduced within the experiments. It reveals that our proposed liquid-metal load is well repeatable applications for pulsed-power discharge.

STUDY OF FLAT FOIL EXPLOSION AT (0.1-5) GA/CM.SQ CURRENT DENSITIES

Tatiana Shelkovenko[1], Sergey Pikuz[1], Ivan Tilikin[1], Egor Parkevich[1], Albert Mingaleev[1], William Potter[2], Levon Atoyan[2], David Hammer[2]
1. P. N. Lebedev Physical Institute
2. Cornell University

The experiments with exploded flat foils will help one to reveal common features and differences in the processes of wire, flat foil and cylindrical liner explosion. Electric explosions of flat Al, Ti, Ni, Cu, and Ta foils with thicknesses of $1-16$ μm, widths of $1-8$ mm, and lengths of $5-11$ mm were studied experimentally on the GVP (8 kA, 15-20 kV, 350 ns), BIN (270 kA, 300 kV, 100 ns), KING (200 kA, 45 kV, 190 ns), XP (400 kA, 350 kV, 100 ns) and COBRA (1000 kA, 600 kV, 100 ns) pulsed power generators. The characteristic features of foils explosion in time have been studied using x-ray, UV and optical diagnostics in different experimental conditions. The dynamics of foil explosion in different experimental conditions was investigated. In the course of foil explosion, rapidly expanding core and corona were observed. It was shown that the core of the exploded foil has a complicated time-varying structure. Characteristic features of the structure of the exploded foils such as gaps and bubbles have been observed.

This work was supported by RFBR № 18-02-00631 and DE-NA0003764 grants

EFFECT OF ENERGY DEPOSITION ON STUCTURES OF EXPLODING AL WIRES IN ARGON GAS

Haoyu Liu[1], Junping Zhao, Qianlong Zhang, Qiaogen Zhang
1. Xi'an Jiaotong University

The experiments demonstrate a strong dependence of structures of exploding large-sized Al wires (100-400μm in diameter) in argon gas on energy deposition. Based on current and voltage waveforms, the specific energy deposition before voltage collapse is calculated. Spatial-temporal distribution characteristics of luminous plasmas and high-density cores are analyzed through multi-frame photographs and laser shadowgraphs, respectively. When exploding 100μm wires, stratification structures along the wire axis is observed and discussed. The axial inhomogeneity becomes significant when applying larger wires, due to inhomogeneous Joule heating and phase transition. Large-scale bubble-like structures are also observed. Furthermore, expansion velocities of metal cores are found to increase significantly with increased energy deposition.

TARGET MACHINING USING DATUM POINT TOOLING FOR PRECISION HIGH ENERGY-DENSITY LINER IMPLOSION EXPERIMENT (PHELIX) MAGNETIC IMPLOSION SYSTEM

Franklin Fierro[1], christopher rousculp[1]
1. Los Alamos National Laboratory

Target machining using datum point tooling for

Precision High Energy-Density Liner Implosion Experiment (PHELIX) magnetic implosion system

Franklin Fierro, Patrick M. Donovan, John C. Lamar, Jeff Griego, Randall B. Randolph, Christopher L. Rousculp

Los Alamos National Laboratory

Los Alamos NM, 87545

Cylindrical driven shock experiments examining damaged surface hydrodynamics and Richtmyer-Meshkov instabilities require targets and assemblies to have precision-machined surfaces and made to exacting tolerances. The objective is to ensure that the impactor shocks the target wall cylindrically and not asymmetrically requires a well thought out design and precision placement of the targets. Our solution was the use of palletized datum point tooling which helped us achieve the work piece precision with a high degree of repeatability and flexibility throughout several machining and inspection processes. I will explain how this tooling was key to success in a series of three different fielded experiments for the Phelix pulsed power program.

Method of Presentation: Poster

LA-UR-19-21555

Franklin Fierro ffierro@lanl.gov

Cell: 505-500-5477

MST-7 Target Engineering

OPTIMIZING MICROPINCHES PRODUCED BY HYBRID X-PINCHES FOR HIGH TIME RESOLUTION X-RAY SPECTROSCOPY

Ahmed Elshafiey[1], Jeffrey Musk[1], Sergey Pikuz[2], Tatiana Shelkovenko[2], Dave Hammer[1]

1. Cornell University

2. P. N. Lebedev Physical Institute

We are planning detailed spectroscopic studies of the X-ray bursts produced by hybrid X-pinches using ∼20 ps time resolution X-ray streak cameras. The purpose is to investigate whether radiative collapse occurs in the micropinches that produce the X-ray bursts. In order to do that, we want 1 strong X-ray burst from the hybrid X-pinch at a time that is reproducible within ± 1 ns. As a first step, we have optimized Hybrid X-Pinches made of Al, Ag, Mo, and Ti by changing the gap distance between the two conical electrodes, keeping the mass per unit length constant across all the different materials. For all materials, 0.5-1.5 mm gap appears to be satisfactory to assure a single micropinch from a 250-300 kA, 50 ns rise time current pulse on the XP pulsed power generator. In addition, time resolved, and time-integrated X-ray spectroscopy was carried out on molybdenum wires coated with aluminum. General parameters were obtained such as; hotspot source size, radiated energy, x-rays energy spectrum and plasma density and temperature.

Funding Acknowledgment: This research is sponsored by DE-SC0018088, as well as by NNSA/SSAP under DOE Cooperative Agreement DE-NA0003764.

DIAGNOSTICS TO STUDY ELECTROTHERMAL INSTABILITIES ON MYKONOS

M.W. Hatch[1], T.J. Awe[2], E.P. Yu[2], K.C. Yates[3], T.M. Hutchinson[4], B.S. Bauer[5], K. Tomlinson[6], M. Gilmore[1]

1. University of New Mexico

2. Sandia National Laboratories

3. Los Alamos National Laboratories

4. University of Nevado, Reno

5. University of Nevada, Reno

6. General Atomics

The electrothermal instability (ETI) is a Joule heating-driven instability that can initiate in the solid state in solid liner-driven fusion. In the solid state, the ETI generates azimuthally correlated (striated) temperature and density perturbations. These striations may seed the magneto Rayleigh-Taylor (MRT) instability, which has been shown to limit stagnation pressure and fusion yield. These experiments will observe ETI growth from diamond-turned, 99.999% pure aluminum rods in a z-pinch configuration by monitoring characterized "engineered" defects machined into the rod surface. Experiments will be conducted on the $\sim$ 1 MA MYKONOS driver at Sandia National Laboratories. A multi-camera splitter system will be used to simultaneously image these scaled defect patterns, located on the front and back sides of the target, in order to examine visible-light emission from the surface. Laser shadowgraphy and interferometry diagnostics are also being developed to characterize ETI evolution. Experimental results will be compared to 3D-MHD simulations. Here, diagnostic developments and ongoing experimental results will be presented.

EXPERIMENTAL MEASUREMENT OF THERMAL AND ELECTRICAL CONDUCTIVITIES IN WARM DENSE STATE GENERATED BY PULSED-POWER DISCHARGE FOR EFFICIENT ENERGY CONVERSION OF FAST IGNITION

Shingo Kusano[1], Kazumasa Takahashi[1], Toru Sasaki[1], Takashi Kikuchi[1]
1. Nagaoka university of technology

Physical properties of a guiding cone for fast ignition in an inertial confinement fusion system are one of the key issues to understand the behavior of laser-generated fast electrons. The guiding cone will be changed from a solid state to a region of warm dense matter (WDM) irradiated by an intense-laser. The conversion efficiency, which is defined by the ratio of the energy of fast electrons to the heated implosion core, relies on the thermal and electrical conductivities of the cone. However, the thermal and electrical conductivities are not explained in WDM. To evaluate the behavior of fast electrons in the guiding cone, the thermal and electrical conductivities in WDM region are required.

To measure the thermal and electrical conductivities of fusion materials in WDM region, we have developed a simultaneous measurement method of both conductivities. The method is an isochoric heating using pulsed-power discharge with a ruby capillary. The electrical conductivity is estimated from the shape of WDM and the measured voltage-current waveform. The thermal conductivity is estimated by measurement of the thermal conduction from WDM to ruby capillary based on the temperature dependences with laser-induced ruby fluorescence. The WDM of gold was generated, and the temperature and density dependences of the thermal and electrical conductivities were measured. As a result, the electrical conductivity of WDM had about 4×10^4 to 9×10^4 S/m with the temperature from 1.5×10^4 to 1.5×10^5 K. The electrical conductivity dependence on the temperature has an inflection point as a metal-non-metal transition.

2D SIMULATIONS OF THE NS-LASER SHOCK PEENING

Vasily Pozdnyakov[1], Jens Oberrath[1]
1. Institute of Product and Process Innovation, Leuphana University of Lueneburg, Germany

Laser shock peening (LSP) is a widely known technique, which is used in industry to improve the properties and performance of metallic components. Laser induced compressive residual stresses (RS) allow to enhance the fatigue life of aircraft structures [1]. Due to deeper depth and higher magnitude of RS in the target material, this technique is a potential substitute of the conventional methods applied in industry, e.g. shot peening. In LSP short laser pulses (fs-, ps- and ns-ranges) with high intensity (usually $> 1\,\mathrm{GW/cm^2}$) are used to vaporize and ionize the thin surface layer of the target material. The fast expansion of this plasma plume induces a mechanical shock wave propagation, which causes microstructure changes and results in compressive RS generation.

Plasma formation and shock wave propagation are non-linear processes with extremely short time scales. Due to that, it is very difficult to optimize the LSP only based on experiments. Thus, simulation models are required. In our research, a 2D laser peening model is implemented in MULTI2D [2]. The temporal and spatial distributions of plasma parameters are determined for different laser intensities. Plasma behavior and a shock wave propagation are analyzed in order to understand the influence of different parameters on the occurred processes.

[1] R. Fabbro, P. Peyre, L. Berthe, X. Scherpereel, J. Laser Appl. **10** (6), 265–279 (1998)

[2] R. Ramis, J. Meyer-ter-Vehn, J. Ramírez, Comput. Phys. Commun. **180**, 977–994 (2009)

CIRCUIT SIMULATION WITH NONLINEAR MAGNETIC CORE OF A NEW LINEAR TRANSFORMER DRIVER STAGE

Wei Zhenyu[1], Wang Yu[1]
1. Xi'an Jiaotong University

A single stage of a new Fast Linear Transformer Driver (FLTD) has been built and tested in Xi'an Jiaotong University. In order to analyze the performance of new device in different states, the author develops a circuit model of nonlinear magnetic core, which contains a changeable initial magnetic flux and time-dependent loss resistance. Afterwards, the core model is added into the integrate circuit simulation of the single stage of FLTD, and the result fits the experimental result very well under both saturated and unsaturated situations, the experimental result with different load resistance is also given in this paper by the author. Moreover, this circuit model also lay the foundation of the future malfunction analysis and fault diagnosis, which will be beneficial to assess the equipment limit.

SIMULATIONS OF NOZZLE GAS FLOW AND GAS-PUFF Z-PINCH IMPLOSIONS WITH MAGNETIC FIELDS IN THE WEIZMANN Z-PINCH*

Varun Tangri[1], John Giuliani[2], Guy Rosenzweig[3], Tal Queller[4], Yitzhak Maron[4]
1. Research Support Instruments
2. Naval Research Laboratory
3. Massachusetts Institute of Technology
4. Weizmann Institute of Science

Till recently, measurements of the magnetic field in gas-puff z-pinch implosions were limited to low density and temperatures typically found at very early times and outside the pinch radius ($r \geq 9$ mm and $t \leq -90$ ns). However, recent, more accurate measurements at higher densities and temperatures at various R and Z-locations on the generator at the Weizmann Institute of Science (WIS) have yielded information close to stagnation and beyond. These measurements seem to be inconsistent with earlier 2D radiation-magneto-hydrodynamics simulations using MACH2-TCRE as well as simple snowplow models when using the inductive current notch, pinch length the pinch radius.

In this presentation, it will be shown that some of these inconsistencies can be resolved by simulating the entire Anode-Cathode gap of 18mm. Simulations of magnetic field evolution using the 2D radiation-magneto-hydrodynamic code, MACH2-TCRE are presented in two steps as follows. In the first step, simulations of the initial density profile by modeling the neutral gas-flow of subsonic oxygen through De-Laval nozzles are made and compared to measurements. In the second step, the density profile from the previous step is used as initial condition for investigating the radial profile and evolution of the magnetic field during the gas-puff implosions. Comparisons are made with the measured data of magnetic field and radius. It is shown that simulating the nozzle geometry and outflow significantly improves the comparison between the measurements and the pinch simulations.

* Work supported by DOE/NNSA

STUDY ON FAULT CONDITIONS OF A SINGLE STAGE OF FAST LINEAR TRANSFORMER DRIVERS

Zhenyu Wei[1], Yu Wang [1], Xu He[1], Qi Shi [1], Qiangfeng Luo[1]
1. Xi'an Jiaotong University

Fast linear transformer drivers (FLTDs) are a rapidly developing field of pulsed-power technology in recent years, which is used to output high-power, high-current pulses. However, an FLTD on terawatt level usually contains more than thousands of switches. As a result, the fault of self-discharge of switches is common in FLTDs. This brings a. important problem that when self-discharge occurs, whether it is necessary or not for researchers to stop the whole process and demagnetize the core again. In this paper, we will analysis how it will affect the output of a single stage of FLTD and give the answer to the question above.

To begin with, a circuit model of a single stage of FLTD with a nonlinear magnetic core, which contains 23 discharge branch based on real FLTD is developed in this paper. On top of that, in order to simulate the fault condition under different working coefficients, one or more switches is set to discharge itself abnormally before the coming of trigger signal. According to this simulation, the output of the current flowing the load and magnetic cores is given when the number of the fault switch increases from 1 to 5, which can provide the prediction of the needs of demagnetization.

ABLATION BEHAVIORS AND IMPLOSION DYNAMICS OF PRECONDITIONED TWO-WIRE Z-PINCH

Yihan Lu[1], Jian Wu[1], Huantong Shi[1], Daoyuan Zhang[1], Ziwei Chen[1], Xingwen Li[1], Shenli Jia[1], Aici Qiu[1]
1. Xi'an Jiaotong University

Experiments of two-wire Z-pinches are carried out, in which an adjustable current prepulse is introduced to preheat the wires before the main current start. Experimental results show that the time delay (Tdelay) between the prepulse and the main pulse has a fatal effect on the ablation behavior and the dynamic of implosion.

The two-wire load is heated to a core-corona state by the prepulse current, and a two-layer structure of mass distribution is formed. The mass expands freely during the interval Tdelay. Thus the mass distribution of the load at the instant when the main current start can be controlled by changing Tdelay, which was adjusted from $\sim$200 ns to $\sim$1 μs. It is observed that under a short Tdelay ($\sim$200 ns), the preconditioned load shows an ablation stage as the typical wire array Z-pinch. And the ablation stage was nearly suppressed as the Tdelay increases to 1 μs. The changing of the ablation behaviors of the preconditioned load can be related to the interaction of the imploding plasma shell and the expanding dense core.

The imploding trajectories of the preconditioned load under different Tdelay are obtained from optical diagnostics. The stagnation instant would be postponed with a longer Tdelay, showing the potential of increasing energy conversion efficiency in wire array Z-pinch using an adjustable prepulse. In addition, a circuit model coupled with 0D load model is developed to describe the imploding of the preconditioned load, and the calculation result has a good agreement with the experimental trajectories.

This research shows the effect of the prepulse parameter on the dynamics of two-wire Z-pinches, the results of which are valuable as the reference to the future multi-wire experiments. And the prepulse approach is hopeful in the suppression of instability of wire array Z-pinch according to the research.

UNDERSTANDING ELECTROTHERMAL INSTABILITY GROWTH BY COMPARING Z-PINCHES WITH ENGINEERED DEFECTS TO 3D-MHD SIMULATIONS

Thomas Awe[1], Edmund Yu[1], Trevor Hutchinson[2], Bruno Bauer[2], Kurt Tomlinson[3], David Yager-Elorriaga[1], Maren Hatch[4], Gabriel Shipley[1], Brian Hutsel[1]
1. Sandia National Laboratories
2. University of Nevada, Reno
3. General Atomics
4. University of New Mexico

The electrothermal instability (ETI) is driven by Joule heating and arises from the dependence of resistivity on temperature. When a metal is Joule heated through the boiling point, ETI may drive azimuthally correlated surface density variations or "strata" which provide the dominant seed for subsequent growth of the magneto Rayleigh-Taylor (MRT) instability. Simulations of z-pinch experiments are generally too coarsely resolved to adequately capture ETI physics, resulting in large discrepancies between experiment and simulation. Data on ETI can be difficult to interpret due to the complexity of inhomogeneities present in the metal (inclusions, surface defects, grain boundaries, etc.). To reduce such complexities, experiments will examine ETI growth from 99.999% pure aluminum 800-micron-diameter z-pinch rods driven to 800 kA in 100 ns. Rod surfaces are diamond turned to extreme smoothness, and then further machined to include carefully characterized "engineered" defects—designed lattices of micron-scale pits. Highly reproducible pit fabrication has been achieved using a 5-axis diamond turning lathe in slow tool servo mode. Engineered pits will divert current density and drive local overheating. Visible-light emissions from the rod surface will be captured with multi-frame high-resolution gated imagers. Laser shadowgraphy and interferometry may provide information on expansion dynamics at the pit location. Experiments will generate data to constrain 3D-MHD simulations, accelerating the development of an advanced computational model of instability growth during magnetically driven implosions.

*Supported in part by the LDRD Program at Sandia National Laboratories (Projects 178661/200269). Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under Contract No. DE-NA-0003525.

INVESTIGATING THE ELECTROTHERMAL INSTABILITY IN PULSED POWER SOLID LINER IMPLOSIONS USING EXTENDED MAGNETOHYDRODYNAMICS

Robert Masti, Bhuvana Srinivasan[1], Jacob King[2], Peter Stoltz[3], David Hansen[4], Eric Held[4]

1. Virginia Tech
2. Tech-X Corporation
3. Tech-X Coporation
4. Utah State University

Recent results from experiments of magnetically-driven pulsed power solid liners have exhibited electrothermal instability (ETI) growth early during the phase transitions of the conductor. Understanding the development of these instabilities and potential stabilization mechanisms could play a significant role in the success of fusion concepts such as MagLIF (Magnetized Liner Inertial Fusion). For MagLIF, the magneto Rayleigh-Taylor (MRT)instability is the most detrimental instability toward achieving fusion energy production, so understanding any and all seeding mechanisms can help delay or control the MRT instability growth. The solid liner implosions undergo exotic phase transitions that make ideal magnetohydrodynamics inadequate resulting in the need for more advanced physics models such as extended-MHD. The overall focus of this project is on using a multi-fluid extended-MHD model with kinetic closures for thermal conductivity, resistivity, and viscosity to study moderately-to-highly coupled high energy density plasmas. Thus far extended-MHD simulations have been conducted using SESAME equation-of-state tables along with semi-implicit time-stepping schemes for the parabolic terms of resistivity and thermal conductivity. Simulations of early time ETI growth will be presented using tabulated Lee-More-Desjarlais electrical and thermal conductivities in various configurations and for different pulse profiles.

MILLIMETER-WAVE RADIOMETRY AND COHERENT THOMSON SCATTERING FOR STUDIES OF POWER BALANCE IN COBRA*

Thomas Schmidt[1], M.W. Hatch[1], M. Gilmore[1], E. Schamiloglu[1]
1. University of New Mexico

Millimeter-wave radiometer and coherent Thomson scattering diagnostics are being developed in order to characterize radiated power and turbulent density fluctuations in pinch plasmas in the COBRA accelerator at Cornell University. The purpose of these measurements will be to study the overall power balance in COBRA plasmas under various conditions. An initial radiometer channel will operate in the 94 GHz range. It is envisioned that this will be expanded to a number of channels covering the 10-300 GHz range in order to characterize emission vs. frequency in the mm-wave band. The coherent Thomson scattering system will operate at 1064 nm in the Bragg scattering limit, with detection at several scattering angles in order to characterize the evolution of the density fluctuation spectrum in terms of amplitude and wavenumber. Diagnostic system designs and preliminary results will be presented.

* This research is supported by the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764.

MAGNETIC FIELD DIFFUSION INTO AL-6061 ROD UNDER MEGAAMPERE CURRENT DRIVE

Seth Kreher[1], Bruno Bauer[1], Chris Rousculp[2], Trevor Hutchinson[1], Irv Lindemuth[2]
1. University of Nevada, Reno
2. Los Alamos National Laboratory

The magnetic field diffusion into a conductor driven by intense pulsed power is of interest for current-driven instabilities such as the electrothermal instability (ETI). ETI is thought to develop on the surface of a conductor due to uneven ohmic heating and variation in resistivity that follows the spatial distribution of the current density as impacted by surface roughness and inclusions. The magnetic field also diffuses radially inward to the center of a cylindrical rod in a nonlinear magnetic diffusion wave (NDW)—diffusing more rapidly into the conductor interior because of resistivity increases driven by rising temperatures. The NDW interplays with the inward shock wave caused by the Lorentz force and ejection of low-density material from the conductor surface. The ASC Magnetohydrodynamic (MHD) code FLAG developed by Los Alamos National Lab was used to numerically calculate the radial magnetic field diffusion within an exploding rod, in the skinned current regime, including hydrodynamic effects. A 100-ns, 1-MA current pulse modeled after that from the Zebra pulsed power generator was passed through a 1-mm diameter Al-6061 wire tamped with 70 μm of Teflon. Results were compared with experimental data.

ELECTROSTATIC GYROKINETIC SIMULATIONS OF SHEARED Z-PINCH

Vasily Geyko[1], Mikhail Dorf[1], Justin Angus[1]
1. Lawrence Livermore National Laboratory

Z-pinch is known to be unstable due to MHD kink ($m = 1$) and sausage ($m = 0$) modes [1]. Recent experiments demonstrated that these modes can be stabilized by a radially sheared axial flow [2]. Typical MHD models are usually unable to adequately describe evolution of short wave length modes as they ignore finite ion gyroradius ρ_i effects. Gyrokinetic simulations of the $m = 0$ mode performed in the present paper provide a growth rate as a function of the shear amplitude and axial mode number k. The mode stabilization by a sheared flow is observed in the simulations. The simulations are carried out with high order finite volume COGENT code and are analyzed for the parameters characteristic of the FuZE experiment [2]. For the case of a Bennett equilibrium, high k modes are shown to require less shear amplitude for stabilization than $k\rho_i \approx 1$ modes. In addition, a local analytical linear analysis is performed and shown to be in agreement with simulation results.

*Prepared by LLNL for USDOE SC-FES under Contract DE-AC52-07NA27344.

1. B. B. Kadomtsev, Sov. Phys. JETP 10, 780 (1960).

2. H. McLean, U. Shumlak, and B. Nelson, 2016 Exploratory Plasma and Fusion Workshop, Aubunr, Alabama, 2016.

MEASUREMENTS OF THE MAGNETIC RAYLEIGH TAYLOR INSTABILITY IN CENTIMETER-SCALE MAGNETIZED PLASMA BUBBLES*

R. H. Dwyer[1], D. M. Fisher[1], M. Gilmore[1]
1. University of New Mexico

The PBEX (Plasma Bubble Expansion eXperiment), being conducted on the University of New Mexico's HelCat (Helicon-Cathode) basic plasma science device, utilizes a coaxial plasma gun to launch plasma jets and bubbles (spheromaks) into lower density magnetized plasmas. The goal of these experiments is to study the dynamics of magnetic relaxation processes in the presence of background plasma. Gun-produced plasma bubbles, which exist on cm spatial scales and tens of microsecond time scales, exhibit much more complicated dynamics when injected into background plasma, as compared to vacuum. These dynamics include a double shock structure at the bubble leading edge, magnetic reconnection upon bubble detachment from the gun, trailing edge turbulence, and finger-like structures that have been identified as Magneto-Rayleigh-Taylor (MRT) instability. The relatively large spatial and time scales of this experiment provide an opportunity to investigate MRT physics in a regime much different than typical high-energy-density cases. Here we report on studies of the MRT with varying background magnetic field, gas fill, and background plasma using fast imaging and magnetic and Langmuir probes.

*Work supported by the U.S. Army Research Office, award W911NF1510480

ZEEMAN SPECTROSCOPE STUDIES IN AR GAS PUFF Z-PINCHES ON 1-MA COBRA*

Niansheng Qi[1], Jacob Banasek[1], Sophia Rocco[1], E. Sander Lavine[1], William Potter[1], John Greenly[1], Dave Hammer[1], Bruce Kusse[1]
1. Cornell University

The Zeeman splitting of visible spectral lines is measured to infer the magnetic field and current profiles in gas puff z-pinches. In high current (>1MA) z-pinches, the plasmas are highly ionized and most of the emitted photos are in XUV or x-ray region. It is difficult to apply the Zeeman splitting spectroscopy there because there are not many detectable visible lines. We have identified several spectral lines for the Zeeman splitting measurements in Ar gas puff z-pinches. These are 5174 and 5193Å from Ar VIII 4d-4f transition, 5801.3 and 5812.0Å lines from C IV 3s-3p transitions, and 5696.6 and 5722.7Å line from Al III 4s-4p transitions. Using a triple-nozzle gas puff z-pinch on COBRA, we observed Zeeman splitting of the Ar VIII and C IV lines about 15 ns before the pinch time. Gas puff z-pinches imploding onto an Al wire will be also investigated. Using the Zeeman spectroscopy, the radial current distribution between the wire and gas puff can be inferred.

In the experiments, the emitted light from the plasma is focused on to arrays of optical fibers. Each fiber views a different chord in the plasma. The emission vs. chord light is disbursed by a 0.75M imaging spectrometer and the spectra are recorded by an ICCD camera. The spatially resolved doublet line-profiles of Ar, C or Al are captured for each shot. A de-convolute model for the spectrum is used to deduce the Zeeman shifts and the current in the plasma.

Using suitable polarization optics, the spectrum of the right σ+ and left σ- circularly polarized Zeeman components are separately recorded and the π component are removed. At a field of 10T, Zeeman splitting between the red and blue shifted spectral features is about 5Å, while the instrument resolution is $<$0.5Å. Details of the experiments will be presented.

X-RAY SPECTROSCOPY AND TOTAL YIELD MEASUREMENTS ON A MICROSECOND X-PINCH

G.S. Jaar[1], R.K. Appartaim[1]
1. Florida A&M University

Emission spectra from a microsecond x-pinch were studied in the soft x-ray region which give information about the radiating hot spot plasma. The spectra were collected using a flat crystal spectrometer from aluminum and molybdenum in a 2x25 μm wire x-pinch configuration. We present results that show aluminum reaching the hydrogen-like state and molybdenum reaching the neon-like charge state, from which relevant plasma parameters are determined. We also present the results of a load optimization study for an x-pinch driven by a 350-kA microsecond generator. A scan of the configuration space across material, thickness, and number of wires was performed to determine which parameter combination creates the best total x-ray yield for use in radiography and backlighting. The configuration assessment was conducted using x-ray imaging, Si photodiodes, and diamond radiation detectors.

INITIAL CONDITIONS & PLASMA EVOLUTION IN THE HAWK DENSE PLASMA FOCUS

Joseph Engelbrecht[1], Stuart Jackson[1], Bruce Weber[2], Joseph Schumer[1], Aliaksandr Mamonau[3], Daniel Klir[4], Karel Rezac[4], Jakub Cikhardt[4]

1. Naval Research Laboratory

2. U.S. Naval Research Laboratory

3. RSI

4. CTU

The 650 kA Hawk pulsed power generator at NRL has been configured as a fast (1.2 μs), high inductance (607 nH) driver for a dynamic dense plasma focus load. The current pulse is initiated in a deuterium plasma that is injected radially by three Marshall guns. This plasma is accelerated through a coaxial region, and pinches onto neutral deuterium injected axially by a gas-puff valve. Promising experimental results along with recent tweaks to the Marshall gun design have prompted efforts to better characterize the density profiles produced by the guns. A multi-channel heterodyne interferometer focused into a ribbon beam is used to provide time-resolved measurements of the Marshall gun plasma density in a separate test chamber, allowing parameters to be varied and mass distributions to be established for a wide range of initial conditions. The same instrument is fielded in situ during Hawk DPF shots, with the ribbon beam probing the plasma as a function of radial position across the A-K gap, measuring the density pileup as the plasma is driven downstream. These density measurements are presented alongside electrical data and radiation measurements, to infer the time-evolution of the plasma through the pinch.

----

* This work was supported by the Naval Research Laboratory Base Program, the Office of Naval Research under Grant # N62929-16-1-2192, and the Ministry of Education, Youth, and Sports of the Czech Republic under grant no. LTAUSA-17084.

EXTENDING EXPERIMENTAL AND DIAGNOSTICS CAPABILITIES ON THE 1-MA, 100-NS MAIZE PULSED POWER FACILITY

Akash Shah, Paul Campbell[1], Stephanie Miller[1], Jeff Woolstrum[1], Brendan Sporer[1], Nick Jordan[1], Ryan McBride[1]
1. University of Michigan

The Z-machine housed at Sandia National Laboratories is instrumental in plasma physics research across a range of applications. University-scale z-pinch experiments, such as gas-puff z-pinches, can inform the high-value experiments conducted at Sandia. A gas puff z-pinch requires gas to be puffed into the region between two electrodes, which is then pulsed with a high voltage [1]. The gas is ionized and compressed as the current flows across the electrodes, allowing for a systematic study of pinch phenomena. It involves a rapid plasma acceleration and compression resulting in fusion reactions [2]. These are largely the result of micro-pinch instabilities, which are regions of extreme pressures and temperatures within the plasma and are poorly understood. We report on the progress made in developing this system for MAIZE.

Additionally, we have revamped switch diagnostics on MAIZE, which consists of a set of 40 capacitor-switch-capacitor “bricks”. Discharging these capacitors is carried out by the breakdown of the spark-gap switch, resulting in the emission of light. Monitoring this light provides information on switch performance– whether a switch fired early or synchronously with the other switches. Examination of 40 switches during each shot with a dedicated photomultiplier tube (PMT) and oscilloscope channel is a resource-intensive process. A circuit can be set up that reduces a PMT to a computer bit and with such a circuit, six PMTs can uniquely identify a single pre-firing switch out of 40.

1. J. Giuliani, “A Review of the Gas-Puff Z-Pinch as an X-Ray and Neutron Source”, IEEE Trans. Plasma Sci. 43, 2385 (2015).

2. M. Krishnan, “The Dense Plasma Focus: A Versatile Dense Pinch for Diverse Applications”, IEEE Trans. Plasma Sci. 40, 3189 (2012).

*Work supported by a seed grant from the Michigan Memorial Phoenix Project and the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764.

FARADAY-ROTATION FIBER-BASED GAUGE FOR CURRENT MEASUREMENT IN PULSE-POWER SYSTEMS

Kobi Cohen[1], Yahel Horowitz[1], Gal Goldstein[1], Itay Gissis[1]
1. Rafael Advanced Defense Systems LTD.

Diagnostics of pulse-power systems is a challenging experimental task. The high electric and magnetic fields that are usually involved in their operation can interfere the measurement, and moreover, can damage sensitive electronic data acquisition systems. Optical fibers, being almost immune to electric noise pick-up, are thus favorable as gauges or transmission lines in noisy systems.

In the following contribution we introduce a novel technique to measure absolute current, based on the Faraday-rotation of light in a magnetic field. Using this method, we measure Mega-Amps current in a pulsed power machine in the final stage of a vacuum transmission line and in close proximity to a z-pinch plasma. The gauging system design is based on off-the-shelf 1550nm fiber components, it does not require alignment and can be used easily anywhere current measurement is required and a thin optical fiber can be inserted.

We will show here the design of the measuring system, calibration, and experimental results from our gas-puff z-pinch experiments.

CHARACTERIZATION OF NEUTRON PRODUCTION IN DEUTERIUM Z-PINCH EXPERIMENTS AT CURRENT OF 3 MA

Jakub Cikhardt[1], Daniel Klir[2], Karel Rezac[2], Alexander V. Shishlov[3], Rustam K. Cherdizov[3], Balzhima Cikhardtova[2], Gennady N. Dudkin[4], Vladimir A. Kokshenev[3], Kravarik Jozef[2], Pavel Kubes[2], Vojtech Munzar[2], Vladimir N. Padalko[4], Nikolai A. Ratakhin[3], Karel Turek[5], Valery A. Varlachev[4]

1. Czech Technical University in Prague

2. Czech Tehcnical University in Prague

3. Institute of High Current Electronics, SB RAS

4. National Research Tomsk Polytechnic University

5. Nuclear Physics Institute, Czech Academy of Sciences

In order to study the mechanisms of deuteron acceleration and neutron production, deuterium gas-puff z-pinch experiments are performed at the terawatt-class GIT-12 generator. In these experiments, during the stagnation of z-pinch implosion at a time of about 700 ns, the generator current achieves approximately 3 MA. After a relatively stable implosion, the disruption of the z-pinch by instabilities occurs during a moment shorter than 1 ns. The fast plasma column disruption causes a high time derivative of the z-pinch current. It leads to generation of a high electric field which accelerates hydrogen ions up to the energies of 40 MeV. By collisions of the accelerated deuterons, a 20 ns pulse of more than 10^{12} neutrons is generated. In the radial direction, the neutron energies exceed 20 MeV. Due to the high deuteron energies, in dependence on the experimental set-up, approximately 15% of the total neutron yield could be produced by non-DD reactions of deuterons with materials inside the vacuum chamber, especially stainless steel and aluminum alloy. The high deuteron energies and non-DD reactions cause a relatively anisotropic neutron emission which is measured using indium activation samples.

POTENTIAL OF DIELECTRICS AT ELECTRON BEAM IRRADIATION IN MEDIUM VACUUM

Denis Zolotukhin[1], Victor Burdovitsin[2], Efim Oks[2]
1. The George Washington University
2. Tomsk State University of Control Systems and Radioelectronics

Electron beam irradiation can be used to modify the surface properties of various materials, including dielectrics. The inevitable factor, accompanying such exposure, is the accumulation of charge and the formation of the potential on the dielectric, which can alter the incident electron beam energy. Measuring and predicting this potential is a non-trivial task. In the pressure range of 1-50 Pa, when the electron beam energy is 2-10 keV and the current density is 1-10 mA/cm^2, the dielectric target usually acquires a negative potential, which is manifested in the formation of a space charge sheath between the beam plasma and the target. This sheath is not fundamentally different from the sheath, separating the positive plasma column from the cathode in a glow discharge, and can be considered to be an ionic.

The main results are the following. Under the same irradiation conditions, the surface potentials of different (alumina ceramics, quartz) dielectrics differ markedly. The most likely reason for this is the difference in the secondary emission properties of materials. This consideration has become an incentive for the development of a mathematical model, based on charge balance equations on the dielectric surface and in beam plasma. The use of this model makes it possible to estimate the secondary emission properties of dielectrics based on a comparison of the surface potentials when irradiated with an electron beam in medium vacuum.

The work was supported by RFBR, grant 19-08-00170.

BEAM-PLASMA DISCHARGE FOR DEPOSITION OF CARBON-CONTAINING COATINGS INSIDE DIELECTRIC CAVITY

Denis Zolotukhin[1], Yury Yushkov[2], Andrey Tyunkov[2], Efim Oks[2]
1. The George Washington University
2. Tomsk State University of Control Systems and Radioelectronics

Recently we have demonstrated that injection of continuous electron beam into dielectric cavity without any charge-compensating electrodes, placed inside, is possible due to dense beam-produced plasma, generated as a result of gas ionization by accelerated to 1-10 keV electron beam, extracted from a fore-vacuum plasma-cathode electron source at medium (1-15 Pa) vacuum pressures. Such beam plasma, produced in dielectric cavity, typically has higher density and electron temperature, and it provides the ion flow, sufficient for electron beam charge neutralization.

In this work we demonstrate that by providing special conditions for better beam-plasma interaction (higher beam current, lower gas pressure and e-beam energy), it is possible to increase the efficiency of electron beam energy transfer to plasma by ignition of a so-called beam-plasma discharge (BPD). Supplying a hydrocarbon (acetylene) inside the cavity during BPD, an amorphous carbon-containing coating will be deposited onto the inner surface of the cavity. Significant adhesion of the mentioned coatings will be provided by the intensive bombardment of the cavity surface by the ions, accelerated both in near-wall sheath and electromagnetic field of the BPD.

The work was supported by the Russian Foundation for Basic Research, grant 18-38-00009 mol_a.

CORROSSION RESISTANCE OF CARBON STEEL COATED WITH A SIOX-ORGANOSILICON LAYER

Rita de Cássia Cipriano Rangel[1], Elidiane Cipriano Rangel[1], Nilson Cruz[1]

1. Technological Plasma Laboratory, Paulista State University - UNESP, Science and Technology Faculty, Sorocaba, SP, Brazil

Carbon steel is the most commonly used material in mechanical metallurgy and construction industry. However, the susceptibility of carbon steel to oxidation under real conditions of use turns preventive and corrective repairs mandatory. A way to avoid this phenomenon is to coat the metal with a layer, which inhibits permeation of corrosive agents to the metal interface. Some works suggest the development of protective coatings using the plasma deposition technique based on hexamethyldisiloxane, HMDSO, compound. Altering the plasma excitation parameters, enables to deposit organosilicon (SiOxCyHz) to oxide (SiOx) films. Literature works use this flexibility to prepare multilayered films. However most of these works does not study the interference of the order of the layers application on the corrosion resistance of the system. Considering that, the present work aims to study the corrosion resistance of the carbon steel coated with multilayers constituted of SiOx and SiOxCyHz films in different sequences. SiOx-organosilicon multilayers were deposited by low pressure radiofrequency (13.56 MHz) plasmas using HMDSO, Ar and O2 mixtures. The change of an organosilicon to inorganic coating or vice versa was made only by adjusting the plasma conditions without interrupting the process. It was investigated what sequence of monolayers leads to better barrier properties. EIS was used to evaluate the corrosion resistance provided by the multilayer to the carbon steel. FTIR, was applied to analyze the chemical composition and molecular structure of the layers. The thickness of the films was measured by profilometry while the morphology and roughness were determined by AFM. The surface wettability was evaluated by contact angle measurements. The best results of corrosion resistance, Rt, of the multilayer system have been obtained with an outermost organosilicon layer. The coating of carbon steel with the multilayered film resulted in an increase of 6 orders of magnitude in Rt.

Financial support: FAPESP.

EFFECT OF ELECTRON BEAM IRRADIATION ON THE SURFACE FLASHOVER OF POLYMERIC MATERIALS IN VACUUM

Chengyan Ren[1], Duo Hu[1], Yangwei Li[1], Hao Sun[1], Tao Shao[2], Ping Yan[1]
1. Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciences
2. Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciencesmy of Sciences

The polymeric materials will degrade due to the electron collision, photo-irradiation and heat effect following with the surface flashover in vacuum. In order to study the effect of electron collision on the insulating materials, the surface properties were measured and the flashover experiment was performed in vacuum after electron beam irradiation. First, several typical polymeric samples, such as polytetrafluoroethylene (PTFE), polymethylmethacrylate (PMMA) and polyamide (PA6), were exposed by different energy electron beam from 100 eV to 30 keV. Then the conventional dielectric parameters were measured for insulating samples in different processing conditions. Since the surface trap distribution is closely related to the microscopic structure and defects, the trap parameters of several materials were deduced based on the surface potential data. In this measurement, the polymeric surface was charged by needle-to-plane corona discharge, and then the surface potential was measured by Kelvin electrostatic probe. The surface flashover experiment under DC voltage in vacuum was performed using finger-type electrodes, and the relationship between electron beam energy and flashover voltage was analyzed. Combined the flashover voltage with the microscopic morphology and surface trap parameters, the effect of electron irradiation on surface flashover was analyzed, the degradation characteristic of polymeric materials deposed by electron irradiation was also discussed.

[1] Li S, Pan S, Li G, et al. Influence of electron beam irradiation on DC surface flashover of polyimide in vacuum. IEEE Transactions on Dielectrics and Electrical Insulation, 2017, 24(2): 1288-1294.

[2] H. C. Miller, Flashover of insulators in vacuum: the last twenty years, IEEE Transactions on Dielectrics and Electrical Insulation, 2018, 22(6): 3641-3657.

SYNTHESIS OF WATER BASED AL2O3 NANOFLUIDS USING LASER INDUCED PLASMA

Magesh Rajan[1]
1. South Dakota School of Mines and Technology

Nanofluids hold enhanced physical, chemical, thermal and transport characteristics compared to the base fluids, which signify a great potential for a variety of applications including combustion, liquid propellant, microelectronics, optical and thermal emission devices, energy storage, heat exchanger-cooling systems, hydrogen generation, nuclear safety, and in underwater and military applications. Nanofluids are a new class of fluids engineered by dispersing nanoparticles of size less than 100 nm in base fluids.

In this work, we will present the results of producing scalable enhanced nanoparticles in water using laser induced plasmas at liquid-metal phase boundaries. The formation and dynamics of laser plasmas and shock waves at liquid-metal phase boundary was affected by the conditions of strong liquid confinement. The plasma and shock spatio-temporal dynamics and velocities varied for different laser transfer matrix and experimental conditions. The plasma electron density of the laser induced plasma at water-Al phase boundaries was measured using a two-wavelength laser interferometry. In order to better understand the relationship and synthesis of effective nanofluids the results of correlating the plasma characteristics with the nanoparticles size and size distribution will be presented.

The characteristics of nanoparticles produced at the water-aluminum phase boundaries using laser induced plasma has a strong relation with the laser transfer matrix. We present the effects of nanoparticle size distribution for different experimental conditions. We will also present data on nanoparticle characterization using static light scattering, dynamic light scattering, SEM, TEM, SEAD, EDS and XRD.

LASER-DRIVEN ACCELERATION OF TITANIUM IONS FROM ULTRATHIN TARGETS AND THE CALIBRATION OF THE ION BEAM DIAGNOSTIC

Joseph Strehlow, Jun Li[1], Pierre Forestier-Colleoni[2], Christopher McGuffey[2], Tyler Daykin[3], Edward McCary[4], Mathieu Bailly-Grandvaux[2], Jonathan Peebles[5], Guilhem Revet[6], Shu Zhang[2], Todd Ditmire[4], Michael Donovan[4], Gilliss Dyer[7], Julien Fuchs[6], Erhard Gaul[4], Joseph Gordon[4], Andrew Higginson[8], Gregory Kemp[8], Mikael Martinez[4], Harry McLean[8], Michael Spinks[4], Hiroshi Sawada[3], F. Beg[9]

1. Los Alamos National Laboratory
2. UCSD
3. UNR
4. UT Austin
5. LLE
6. LULI
7. SLAC
8. Lawrence Livermore National Laboratory
9. University of California, Sandiego

A super-intense laser pulse, incident on a thin foil target, can create plasma structures with accelerating fields on the order of TV/m, accelerating ions to multi-MeV energies. The 10^{20} W/cm^2, linearly polarized Texas Petawatt Laser (TPW) facility was employed to accelerate high energy titanium ions from ultrathin (60 to 200 nm) planar titanium foil targets. A clear optimum target thickness is observed, with Ti^{20+} ions reaching 18 MeV/nucleon from 80 nm targets. Two Thomson parabolas, spectrometers that separate ions by their charge-to-mass ratio, were aligned to target normal and close to the laser propagation axis. In the spectrometers, BAS-TR image plates were used to detect the ions. A plastic grid of CR-39 was mounted in front of the image plates to measure absolute counts from the deposited titanium ions. This calibration enables the extraction of absolute energy spectra of the titanium ions. Established analytical models, such as target normal sheath acceleration (TNSA) and radiation pressure acceleration (RPA) are applied, along with the fully relativistic 2-D particle-in-cell code EPOCH, to provide insight into the underpinning physics responsible for ion acceleration in this ultrathin target regime.

TOPANGA: A MODERN CODE FOR E3 EMP SIMULATIONS

Bruce Cohen[1], Larson David [1], Mikhail Belyaev[1], Vincent Thomas[2]
1. Lawrence Livermore National Laboratory
2. Los Alamos National Laboratroy

We are developing the Topanga code for predicting E3 electromagnetic pulse building on our experience with hybrid plasma simulation. The E3 component has a long pulse, lasting tens to hundreds of seconds. It is caused by the nuclear detonation's temporary distortion of the Earth's magnetic field. The E3 component has similarities to a geomagnetic storm caused by a solar flare. Like a geomagnetic storm, E3 can produce geomagnetically induced currents in long electrical conductors, damaging components such as power line transformers. Our new code's attributes include the following: spherical geometry for simplified boundary conditions and computational efficiency; couples a hybrid plasma model (fluid electrons and neutrals, particle ions, Ohm's law, and reduced Maxwell's equations) to a finite-difference time-domain electromagnetic solver (FDTD-EM); uses the International Geomagnetic Reference Field magnetic field model, neutral atmosphere profiles from the US Standard Atmosphere or the NRL MSISE (mass spectrometer and incoherent scatter radar + exosphere) model, ionosphere profiles from the International Reference Ionosphere model; has ion-neutral, electron-ion, electron-neutral collisions; uses a fluid algorithm for motion of the neutral atmosphere; and has limited atmospheric chemistry. An overview of the code and simulations examples with some comparison to experimental data will be presented.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 and by Los Alamos National Laboratory under contract DE-AC52-06NA25396.

PERSPECTIVES ON RESEARCH IN COMPUTATIONAL PLASMA PHYSICS WITH DIVERSE APPLICATIONS TO EXPERIMENTS

Bruce Cohen[1]
1. Lawrence Livermore National Laboratory

Computational plasma physics was born some fifty years ago with the development of high-speed computers. Computer simulation is well suited to the challenging nature of fundamental and applied plasma science. Plasma physics exhibits enormous ranges of time and space scales, and the underlying mathematical framework comprised of nonlinear partial differential equations and nonlinear kinetic equations does not generally admit analytic solution except in much simplified conditions. Computational plasma physics has advanced from relatively simple calculations with limited dimensionality and scope to sophisticated and comprehensive simulation models. Moreover, computational plasma physics has matured as a significant scientific discipline with a rigorous mathematical foundation and voluminous literature. While computational plasma physics has greatly benefitted from the growth in computing capability by many orders of magnitude, contributions from innovation in methods and algorithms have been no less important.

This talk presents a personal perspective on the development and application of computational plasma physics to plasmas in nature and the laboratory. The examples described are based on experience over the course of a career in computational plasma physics and illustrate fundamental plasma phenomena and the behavior of natural and laboratory plasmas. Some of the example include simulations of microinstabilities in magnetic mirror, tokamak, and spheromak plasmas, laser-plasma interactions, and Knudsen-layer phenomena affecting fusion performance. The examples will illustrate the development of appropriate models and algorithms that were well suited to simulating the phenomena of interest efficiently. A particular interest has been the development of multiple time-scale algorithms.

I am very grateful to Professor C. K. Birdsall who provided me with my initial exposure to kinetic simulation of plasmas, supported and encouraged my career, and was an enthusiastic research collaborator and friend.

*This work was performed under the auspices of the U. S. DOE by the Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REACTIVITY CHARACTERIZATION DUE TO OZONE GENERATION BY LOW-TEMPERATURE PLASMA DISCHARGES AT ENGINE RELEVANT DENSITIES

Sayan Biswas[1], Isaac Ekoto[1], Riccardo Scarcelli[2]
1. Sandia National Laboratories
2. Argonne National Laboratory

Transient plasma ignition (TPI) – where high-energy, short-pulsed, non-equilibrium plasma are used to ignite flammable mixtures – is of interest to engine developers due to the generation of distributed ignition sites that accelerate initial burn rates and reduced electrode erosion that results from the avoidance of breakdown. Transient plasma discharges produce active radicals (O, OH, etc.) and reactive species such as ozone (O3) that could be used to increase fuel/air mixture reactivity leading to improved auto-ignition characteristics. However, there are currently no experimental or modeling TPI data that explains the role of O3 formation mechanisms by low-temperature plasma (LTP) discharges at high pressures, 1 – 8 bar absolute. In the present study, O3 formation characteristics by LTP discharges in desiccated air are investigated within a custom-built optically accessible spark calorimeter for a groundless barrier discharge igniter (GBDI) with a flush mounted and exposed anode tip. Transient plasma is generated using an available high-voltage ($\sim$ 35 kV peak), short duration ($\sim$12 nanoseconds) pulse generator. Time-resolved in-situ O3 measurement is acquired via UV light absorption method shows the time-evolution of O3 i.e. formation and eventual decomposition of O3 into molecular and atomic oxygen. The effect of pressure, voltage, number of pulses, and types of electrode on O3 generation are studied in detail. The behavior of generated O3 holds the key to understand reaction pathways in TPI. Numerical modeling of LTP discharges is carried out in VizGlow solver in order to better understand the O3 formation and decomposition processes leading to enhanced mixture reactivity. Chemkin-Pro 0D homogeneous reactor simulations are performed to evaluate chemical kinetic pathways responsible for O3 formation. With sufficient knowledge of LTP characteristics from experimental measurements and numerical models, our final goal is to develop a transient LTP igniter for engine applications.

ATOMIC HYDROGEN GENERATION IN THE IONIZING PLASMA REGION AND EFFLUENT OF A HELIUM-WATER ATMOSPHERIC PRESSURE PLASMA JET BY TWO-PHOTON ABSORPTION LASER INDUCED FLUORESCENCE (TALIF)

Yuanfu Yue[1], VSSK Kondeti[1], Peter Bruggeman[1]
1. University of Minnesota

Non-equilibrium atmospheric pressure plasmas received a lot of attentions in the last decade due to promising applications in the biomedical field and for material processing [1]. Reactive species generated by plasmas, such as hydroxyl are considered to play essentials roles for these applications. Atomic hydrogen, another dominant species, shows great potentials in ion reduction leading to nanoparticle synthesis [2].

In this study, we study the H production in a cold atmospheric pressure plasma jet driven by a nanosecond pulser while flowing helium and H2O mixture. The one dimensional two-photon absorption laser induced fluorescence signal of atomic hydrogen (H-TALIF) is recorded along the axis of symmetry of a plasma jet by aligning the laser beam into the quartz tube of the jet. The absolute density calibration is achieved by performing Kr-TALIF without discharge in *situ*.

In this report, the H atom transportation, generation and decay are investigated and particularly the impact of plasma generation and modulating frequencies. The high densities inside the tube, lead to a fast recombination of the H density before it reaches the jet effluent. The results also show memory effects for repetition frequencies in excess of 2 kHz. Combined with information of coupling energy and emission intensity, we will use the spatial and temporal variation of the atomic H density to discuss the main production and destruction pathways.

Acknowledgement: This work is supported by the US Department of Energy through the Plasma Science Centre (DE-SC0001939) and Office of Fusion Energy Sciences (DE-SC0016053).

1. X. Lu. G.V. Naidis, M. Laroussi, S. Reuter, D. Graves and K. Ostrikov, 2016, Phys. Rep. 630 pp1-84

2. S. Kondeti, U. Gangal, S. Yatom and P. Bruggeman, 2017, J. Vac. Sci. Technol. A 35 061302.

HIGH-TEMPERATURE URANIUM PLASMA CHEMISTRY

S. S. Harilal[1], E. Kautz[1], B. E. Bernacki[1], M C Phillips[2], P. Skrodzki[3], M. Burger[3], I. Jovanovic[3]

1. Pacific Northwest National laboratory
2. University of Arizona
3. University of Michigan

U plasma spectroscopic features are very dense with the presence of large number of atomic and ionic transitions. For example, U spectrum contains ∼100000 lines in the UV and visible spectral range originating from ∼1600 energy levels. The spectral features become more complex in the presence of oxygen containing ambient atmosphere which initiates plasma chemistry through oxidation/combustion of U species in the plume. We investigate the oxide emission features in a U metal plasma generated during nanosecond laser ablation of U metal target. The plasma chemistry is manipulated by controlling the ambient environment by varying oxygen partial pressures in an inert argon atmosphere. Time- and space- resolved optical emission spectroscopy, monochromatic 2D imaging employing fast-gated camera are used as diagnostic tools for exploring plasma chemistry. By comparing the expansion dynamics of uranium plumes in argon and in oxygen-rich ambient environment, we discover that chemical reactions modify the hydrodynamics of the plume at later times of its evolution when the oxygen in present in the buffer gas. A strong background-like emission is always observed in the spectral features of U plasma in oxygen-containing environment and our results highlight that it is contributed by uranium oxides. We identified several spectral bands of UO in the visible-NIR region. A study comparing the role of varying oxygen ambient concentration on plasma chemistry showed that the reaction pathways from atoms to diatoms to polyatomic molecules strongly vary with ambient oxygen concentration. Lower oxygen concentrations enhance the formation of UO from atomic uranium, whereas higher oxygen concentrations tend to depopulate both atomic uranium and uranium monoxide concentrations through formation of more complex uranium oxides. 2D monochromatic images of atomic and molecular emission features showed oxidation primarily occurs at colder region of the plume (outer regions).

MAPPING OF 2-D PLASMA-INDUCED FLUID FLOW USING PARTICLE IMAGE VELOCIMETRY

Janis Lai[1], John Foster[1]
1. University of Michigan

Plasmas coming into contact with liquid water is the basis of a range of technological applications for environmental remediation and medicine. These technologies are enabled by complex plasma-driven chemical and physical processes at the plasma-liquid interface. At the interface, however, plasmas can also drive Marangoni flow in the bulk liquid. This effect can thus circulate reactive species in the bulk liquid, to regions far away from the plasma-liquid interface. Mapping this plasma-driven fluid flow gives insight into how plasma locally alters the contact area chemically and physically. Accounting for plasma-driven flow can ultimately impact the design and application of technologies using plasmas.

A 2-D plasma-in-liquid apparatus was used to study the plasma-liquid interfacial region. The observed plasma-driven flow was mapped using particle image velocimetry (PIV). Previous PIV results showed that sharp velocity shear was present near the interface region, which led to the presence of stable Kelvin-Helmholtz perturbation. Additionally, sharp sheer created vortices in the bulk liquid, resulting in large-scale circulation that transported plasma-derived reactive species far away from the interface.

In this work, we present results of a fully calibrated, mapped plasma-induced fluid flow field in the presence of varying liquid conditions. Because conductivity and surface tension impact how streamers propagate along the interface, and as a result alter the induced chemistry, it is also of interest to observe how fluid flow changes as well in response. Furthering the understanding of transport processes at the interface thus becomes relevant for plasma applications seeking to process any liquid or liquid containing media.

THE INFLUENCE OF MICROWAVE PULSE LENGTH AND REPETITION RATE ON LAMINAR BURNING VELOCITY IN LEAN METHANE-AIR FLAMES

Tomas Hurtig[1], Niklas Zettervall[1], Christer Fureby[1], Andreas Ehn[2], Elna Nilsson[2], Hanna Sundberg[1]

1. Division of Defence & Security, Systems and Technology, FOI – Swedish Defence Research Agency

2. Combustion Physics, Lund University

An experimental setup and data analysis method for determination of the laminar burning velocity of flames exposed to pulsed microwaves is presented, and used to investigate lean methane-air flames. The results show an increase in laminar burning velocity with increasing duration of the microwave pulses, at constant electric field strength and for increasing field strength with the same pulse duration. A strong increase in flame instantaneous chemiluminescence is observed as a result of microwave irradiation. High-speed imaging data display a gradual build up of this increased photon emission, the enhancement is strongly dependent on the pulse duration (10 -50 μs) of the microwaves. The rate of increase and the subsequent saturation of photon emission indicate that microwave-flame interaction takes place in a thin layer of the flame. The thickness of this layer correspond to the thickness of the heat release zone where CH and free electrons reach peak density in the flame. A study on pulse length and pulse repetition frequency reveal that, although the average power is held constant in all experiments, longer microwave pulses cause higher burning velocities than short pulses at higher repetition frequency. This indicate that, at least at the rather low values of E/N used in these experiments, the increase in species that contribute to an enhanced laminar burning velocity is slow in comparison to microwave pulse length.

SPECIES DYNAMICS IN AR/H PLASMA SUPPORTING ACTINOMETRY DIAGNOSTICS CORRELATION EXPERIMENTS

Robert Terry[1]
1. Independent Research Professional, LLC

This analysis doesn't seek to create the most complex and definitive Ar/Hydrogen chemistry and radiation model, but rather to gain enough insight from existing literature to support an easily manageable chemistry set, within a more complex transport code, assessing the plasma species dynamics and radiation rates required to infer line intensities for experimental actinometry.

No matter what details of the chemistry rate scheme, a plasma chemistry model can be represented by a straightforward set of (mostly) binary rate equations combining creation C and destruction D operators for all species.

$$\dot{f}_k = f_i f_j (C_{ijk} - D_{ijk}) - A_{\lambda k} f_k$$

The mole fractions f_k are dimensionless fractions decomposing unity and the creation or destruction operators are normalized to the (local) heavy particle density, n_h. In the special case of three body destruction or recombination processes, the $D_{ijk} \rightarrow f_{h \bullet h} D_{ijk}$ with f_h the vector of heavy particle species. For non-LTE electrons, f_e is further decomposed into a electron energy distribution function (EEDF), viz. $f_e \rightarrow f[e, \varepsilon]$ with the energy grid ε spanning the electron phase space generated by a known value of electric field over total density, viz. E/n_h. Each C or D operator then becomes a convolution of the EEDF with a particular cross section for the process of interest, viz. $C_{ejk}(E/n) = \int \sigma_{jk}(\varepsilon) \bullet f_e[e, \varepsilon]$. Finally, the radiative decay channels, $A_{\lambda k} f_k$, diminish the mole fraction of excited states, providing emission intensities for the observed wavelengths λ.

Generally the Boltzmann modeled EEDF achieves ($\sim$10 ns) a steady state with respect to creation, radiation and recombination in the discharge medium for virtually any specified values $[E/n, f_h, f_e]$ — defining all of the rate coefficients and transport coefficients dependence on f_k. Using the frequency shift in RF cavity modes together with the actinometry data, it is expected that a more precise electron density can be inferred.

HIGH-POWER TESTING OF W-BAND ACCELERATOR CAVITIES

Mohamed Othman[1], Julian Picard[2], Samuel Schaub[2], Valery Dolgashev[1], Andrew Haase[1], Sudheer Jawla[2], Jeff Neilson[1], Bruno Spataro[3], Sami Tantawi[1], Richard Temkin[2], Emilio Nanni[1]
1. SLAC National Accelerator Laboratory
2. Massachusetts Institute of Technology
3. INFN-LNF

We are developing high gradient linear accelerator technologies that operate at 100s of GHz and THz frequencies. Vacuum RF breakdown is one of the fundamental factors limiting high gradient performance of these linacs. Accordingly, a comprehensive study of RF breakdown physics in mm-wave accelerating structures is needed, which includes understanding of dependencies of the breakdown rate on electromagnetic, geometric, and material properties. In our previous work, we have tested beam-driven 100 GHz and 200 GHz metallic accelerating structures. In this work we report initial results of high power tests of a 110 GHz single-cell standing wave accelerating cavity powered by a 1 MW gyrotron. The RF power is coupled into the accelerating structure using a “Gaussian to TM01“ mode converter. In order to characterize high gradient behavior of the cavity, including the rf breakdown probability, we have measured RF signals and field-emitted currents. The cavity is fed with 10 ns, 100s of kilowatt pulses. These short pulses were chopped from microsecond-long gyrotron pulses using a fast optical switch. At this power and pulse length the cavity’s accelerating gradient reached up to 150 MV/m.

STUDY OF ELECTRON OPTICS SYSTEM FOR A 300 GHZ SHEET ELECTRON BEAM TRAVELING-WAVE TUBE

Wonjin Choi[1], Ingeun Lee[1], Jinwoo Shin[2], EunMi Choi[1]
1. Ulsan National Institute of Science and Technology
2. Agency for Defense Development

Recently, sheet electron beam traveling-wave tubes are actively researched in the terahertz regime (0.3 - 3 THz). Sheet electron beams have several advantages over conventional pencil beams such as higher beam current and more interaction space.

There are several challenges in using sheet electron beams. One of the difficulties of sheet electron beams is generation of low-emittance beam with planar cut cathode. Planar cathodes are used instead of cylindrical cut cathodes which has been used in lower frequency regime because of fabrication difficulty. Another difficulty is transport of the sheet electron beam in a narrow beam channel. Because of the diocotron instability, periodic magnetic fields such as periodically cusped magnet (PCM) and wiggler have been preferred to solenoidal magnetic fields, although some recent studies use solenoidal fields due to limitation in current permanent magnet technology.

In this work, we study the generation of a 11.7-kV, 40-mA, and 0.32-mm * 0.06-mm sheet electron beam with a planar cathode and elliptical shape focusing electrode. Also, the magnetic focusing system using a newly proposed non-symmetric periodic planar quadrupole magnets (PPQM) is studied. The characteristics of PPQM are studied and checked with simulations using CST Studio Suite.

EXPERIMENTAL CHARACTERIZATION OF A W-BAND PHOTONIC INTERACTION KLYSTRON

Jacob Stephens[1], Guy Rosenzweig[1], John Tucek[2], Mark Basten[2], Kenneth Kreischer[2], Michael Shapiro[1], Richard Temkin[1]

1. Massachusetts Institute of Technology

2. Northrop-Grumman Systems Corp.

Experimental results are presented for the design, development, and test of a 94 GHz, extended interaction klystron (EIK) amplifier, utilizing a photonic slow-wave circuit. The EIK features uncharacteristically large physical dimensions, such as an oversized electron beam tunnel, directly contrasting conventional frequency scaling laws of vacuum electron devices. The circuit was fabricated entirely through direct machining. The microwave circuit is inspected using a three-dimensional laser-optical scanning apparatus, where it was observed that machining tolerances better than $\sim$13 μm were achieved. Microwave cold tests also indicate successful fabrication of the circuit, with all cavity resonant frequencies measuring within a $\sim$400 MHz range. In 5 $\neq$s pulsed operation, the EIK demonstrated zero drive stability, over 26 dB of small-signal gain, and up to 10 W of output power, limited by the power of the input source. The W-Band design is very promising for scaling to frequencies in the hundreds of GHz range.

* This material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA) and Space and Naval Warfare Systems Center Pacific (SSC Pacific) under Contract No. N66001-16-C-4039.

DEVELOPMENT AND TESTING OF THE 190 GHZ DUAL MODE OAM GYROTRON WITH AXIAL OUTPUT

Ashwini Sawant[1], Ingeun Lee[1], Mun Seok Choe[1], EunMi Choi[2]
1. UNIST
2. Ulsan National Institute of Science and Technology (UNIST)

We presented the design of a 190 GHz dual mode OAM gyrotron with axial output configuration for a prototype experiment of Orbital Angular Momentum (OAM) communication. A mode pair of second harmonic modes ($TE_{8,3}$/$TE_{11,2}$) is excited at 28/35 kV, 5A electron beam input in the presence of a uniform magnetic field of 3.56 T. It incorporates a perturbed cavity with two sinusoidal perturbations to excite higher order axial modes with the suppression of spurious fundamental modes. Cavity simulation has been performed by in-house developed code "UNIST Gyrotron Design Tool (UGDT)". It suggests the generation of the $\sim$30 kW power in both the modes at their respective operating voltages. Switching between these modes is to be carried out by tuning the applied cathode voltage from 33.5 kV to 36 kV. Moreover, these mode-pair is directly radiated into free space from a raised cosine taper which is placed after collector to reduce its divergence. It incorporates a quartz RF window with a thickness of 4.87 mm to achieve more than 90% transmission for both the modes. The experimental testing of the gyrotron is currently in progress and we expect to present its detailed performance analysis in conference.

EXPERIMENTAL PERFORMANCE EVALUATION OF A 272 GHZ ENERGY-RECIRCULATING FOLDED WAVEGUIDE TRAVELING-WAVE TUBE OSCILLATOR

Ingeun Lee[1], Wonjin Choi[1], Ashwini Sawant[1], Mun Seok Choe[1], Jinwoo Shin[2], EunMi Choi[3]

1. UNIST

2. ADD

3. Ulsan National Institute of Science and Technology (UNIST)

We present recent experimental results of a 272 GHz energy-recirculating folded waveguide traveling-wave tube oscillator (FWTWTO), developed in Ulsan National Institute of Science and Technology (UNIST) in South Korea.

The developed device is driven by a backward wave oscillator with an initial electron beam and the generated radio frequency (RF) signal is amplified in the traveling-wave tube amplifier by the spent electron beam as an energy-recirculating method. An expected maximum average output power from this device is 43.55 W at a frequency of 272.2 GHz under consideration of ohmic loss and 11 keV beam conditions. In experiment, the generated RF signal from the device is measured by a developed plasmonic THz detector and a heterodyne system. Measured output power and generated frequency from the FWTWTO will be presented in detail and each component fabrication and evaluation results will be discussed. Especially, we present obtained excellent surface roughness results from fabrication of the folded waveguide (FWG) circuit.

THEORY FOR SELF-ORGANIZED PATTERNS ON LIQUID ANODES

Paul Rumbach[1], David B. Go[1]
1. University of Notre Dame

A variety of self-organized structures have been observed in different plasma systems. Among these, radially symmetric patterns of rings and spots often emerge when an aqueous solution is used as an anode in an atmospheric DC discharge. These patterns are confined to the surface of the water, and their size and structure depend on the total plasma current and the salt concentration of the solution.

We propose a theoretical explanation for these patterns based on the interfacial electrostatics and reaction-diffusion equations for electrons and ions in the anode sheath. Using Turing linear stability analysis, we derive an analytical model for the patterns with cylindrical harmonic functions representing the various modes of rings or spots. The model predicts a phase diagram that shows which critical values of plasma current and aqueous salt concentration cause the discharge to transition from a uniform spot to a self-organized ring structure (the lowest order mode). The theoretical phase diagram is then compared to experimental results.

OLMAT: A NEW FACILITY FOR THE STUDY OF MATERIALS EXPOSED TO PLASMA AND LASER INDUCED HIGH THERMAL LOADS AT THE LABORATORIO NACIONAL DE FUSION

Francisco Tabares[1], David Tafalla[2], Daniel Alegre[2], Eider Oyarzabal[2], Macarena Liniers[2], Alfonso Soleto[2]
1. CIEMAT. Fusion Department
2. CIEMAT

The concept on which the OLMAT project is basically the use of the Neutral Beams (NBI) used for the heating of the plasma in TJ-II for the irradiation of materials at relevant powers for the DEMO divertor, up to 20 MW /m2. At present, two NBI systems are available, capable of injecting up to 700KW into the plasma. The beam, generated by extraction of hydrogen ions from a plasma created for this purpose and subsequently neutralized, presents a Gaussian distribution of power with a width at half height (FWHM) of about 15 cm at the position of the plasma, originating a circular area of about 25 cm in diameter of powers greater than 10MW/m2 geometrically limited by openings inserted ad hoc. In its routine operation with TJ-II plasmas, the beams are generated every 10 minutes approximately, but if the power supply of the TJ-II coils is used only to feed the NBI power supply, the repetition frequency of ”shots” NBI It can be increased up to one pulse every two minutes. In this way the materials can be exposed to the thermal loads produced by the NBI hundreds of times each day of operation. In these circumstances it is expected that the thermal-mechanical fatigue of the material can be tested much more quickly than that of any current device, although the duration of the NBI pulse is limited to about 150-200 ms. The elimination of the neutralizer, mandatory in the production of a single beam of neutrals in the presence of the magnetic fields of TJ-II, can increase the real power incident on the material by 35%, although its effect on the creation of a highly radiative plasma on the surface of the material is yet to be explored.

DIAGNOSTIC OF TEMPORAL AND SPATIAL EVOLUTION OF NANOSECOND MICROWAVE-DRIVEN PLASMA

Chao Chang[1], Yindong Huang[1]
1. Xi'an Jiaotong University

The nanosecond microwave-driven breakdowns at window and in microwave devices limit the maximum power capacity of microwave system, keeps the bottle neck of the technology development and international technical challenges [1-3]. Different-length multi-sub-beam optical fibers, together with a spectrometer and Electron-multiplying intensified charge-coupled device (EMICCD) camera were used to realize a time interval between two consecutive frames shorter than 0.1 ns by a length difference of 2 cm for sub-fibers, achieving measurement of ultrafast plasma dynamics [4]. The ultrafast dynamics of a plasma discharge with a time step of 2.5 ns in a single pulse was experimentally studied. A method for simultaneously acquiring the temporal and spatial evolution of characteristic plasma spectra in a single microwave pulse was studied. By using multi-sub-beam fiber bundles coupled with a spectrometer and EMICCD (Electron-multiplying intensified charge-coupled device), the spatial distribution and time evolution of characteristic spectra of desorbed gases at the dielectric/vacuum interface during nanosecond microwave-driven plasma discharge were observed. Arrays of small align tubes punctured with metal walls of feed horn were filled with separate fibers of matched sizes and equal lengths. The output ends of fibers arranged in a single longitudinal column were connected to the entrance slit of a spectrometer, where the optical spectrum inputs to a high-speed EMICCD, to detect the rapid-varying time and space spectra of nanosecond giga-watt microwave discharges. The evolution of spectral clusters of N2 (C-B), N2 t(B-X), and the hydrogen atoms was discovered and monitored. The whole duration of light emission was much longer than the microwave pulse, and the intensities of ion N2 t (B-X) spectra increase after microwave pulses with rise times of 25–50 ns. The brightness distribution of plasma spectra in different space is observed and approximately consistent with the simulated E-field distribution.

This project was supported by NSFC 11622542.

1.C. Chang, M. Zhu, J. Verboncoeur, et al. Enhanced window breakdown dynamics in a nanosecond microwave tail pulse, Applied Physics Letter,104, 253504, 2014.

2.C. Chang, J. Verboncoeur, M. Guo, et al. Ultrafast High Power Microwave Window Breakdown: Nonlinear and Post-Pulse Effects, Physical Review E, 90,063107, 2014.

3.C. Chang, Y. Liu, J. Verboncoeur, et al. The effect of periodic wavy profile on suppressing window multipactor under arbitrary electromagnetic mode, Applied Physics Letters,,106,014102, 2015.

4.C. Chang, C. Wu, Y. P. Pu, et al., Diagnostic of ultrafast temporal plasma evolution in high-power microwave discharge, J. Appl. Physics, 121, 213301,2017.

EFFECT OF NANO-AL2O3 DOPING ON EROSION RESISTANCE OF TUNGSTEN-COPPER ELECTRODE UNDER 100 KA PULSED ARC

shuai ren[1], Li Lee[2]
1. huazhong university of science and technology
2. Huazhong university of science and technonlgy

The erosion resistance of electrode materials is one of the key factors affecting the performance and working life of gas spark switches. In order to explore whether the electrode material doped with nanoscale second phase particles has stronger erosion resistance in the engineering application of strong pulse current,we built an electrode erosion experimental platform, and selected W80/Cu and W80/Cu-Al2O3 as the research object. The experimental study was carried out under a strong pulse current with a peak value of 104kA and pulse width of 601 microseconds. By comparing the mass change and the microstructure of erosion point, it is found that the addition of nanometer Al2O3 makes the tungsten-copper alloy have stronger erosion resistance under strong pulse discharge. Combined with the erosion mechanism of electrode and the law of arc motion, it is analyzed that the erosion resistance of W80/Cu-Al2O3 is better than that of tungsten-copper alloy for the following reasons: the addition of Al2O3 reduces the mass of tungsten-copper alloy sputtering in the form of solid phase and liquid phase, and makes the distribution of cathode arc more uniform. As a result, the mass loss and surface roughness are reduced. Furthermore, it is concluded that the dispersion of cathode arc is the main reason for the improvement of erosion resistance.

RF PLASMA BASED NANOSTRUCTURIZATION OF TUNGSTEN FOR PLASMA FACING COMPONENT MATERIAL APPLICATIONS

Mayank Mishra[1], Rohit Medwal[2], J. Q. Pan[3], N. L. Wang[4], J. H. Xu[5], Paul Lee[1], Rajdeep Singh RAWAT[1], Joseph Vimal Vas[1]

1. Natural Sciences and Science Education, National Institute of Education, Nanyang Technological University

2. Natural Sciences and Science Education, National Institute of Education, Nanyang Technological University, Singapore

3. Hwa Chong Institute

4. Hwa Chong Instituition

5. Hwa Chong Institution

Abstract

Tungsten is the choice for first wall material for future nuclear fusion reactors owing to its properties like high melting point, good ablation resistance, good thermal conductivity, low deuterium/tritium retention etc. The thermal and radiation loads within experimental nuclear fusion reactors like ITER is expected extremely high in the diverter region where the transient and continuous loads are the highest. The mechanical properties of tungsten thus needs to be improved without affecting other thermal and adsorption properties. It is known that nanostructurization of the material surface can lead to better mechanical properties. This paper deals with the improvement of the surface hardness of tungsten substrates by surface nanostructurization using RF plasma. Tungsten substrates were exposed to a capacitively coupled RF plasma in an N2 environment to nanostructurize its surface. The plasma parameters were studied using optical emission spectroscopy and a Langmuir probe. The exposure conditions were optimized so that nanostructures of required dimensions could be achieved. The surface morphology and the chemical structure was studied using SEM and XPS spectroscopy while the surface hardness was studied using a nano-indentor. In order to study the performance of the treated tungsten samples to fusion conditions, the substrates were then exposed to the focused mode operation of the dense plasma focus device and the changes in morphology and hardness were measured.

POTOMAC: TOWARDS A REALISTIC SECONDARY AND BACKSCATTERED EMISSION MODEL FOR THE MULTIPACTOR

Adrien Plaçais[1], Mohamed Belhaj[2], Julien Hillairet[1], Jérôme Puech[3]
1. CEA Cadarache
2. ONERA
3. CNES

Vacuum Radio-Frequency (RF) devices can be subject to the multipactor effect, characterized by the very fast growth of the electron density in the vacuum. The created electrons have many undesirable effects, ranging from the perturbation of the RF signal to the initiation of a corona discharge that can lead to the complete destruction of the device. Hence, it is critical to be able to estimate precisely the RF power threshold P_{max} above which the multipactor appears. As P_{max} measurements require a specific test bed and are onerous, simulation tools are widely used. Even if they are powerful in some simple situations (*e.g.* rectangular waveguides with metallic walls), their reliability is still questionable in many other practical cases: sophisticated geometries, presence of a magnetic field or components including dielectric materials.

P_{max} is highly dependent on the electron emission (EE) properties of the RF compound surfaces. It is thus crucial to improve the modeling of these processes in order to make simulations more reliable. Numerous works use simple electron emission models, based on empirical laws that are not fully representative of the EE processes complexity. Most of the time, no distinction is made between secondary and backscattered electrons. As these two types of electrons are created by very different physical phenomena, their angular and energy distribution are also different.

Therefore, we recently developed a model simulating the multipactor within an infinite parallel-plate waveguide composed of materials representative of the spatial field (silver, aluminium, PTFE. . .). POTOMAC (Physical simulatiOn TOol for Multipactor in Advanced Configurations), a physical EE model that makes a distinction between secondary and backscattered electrons was then implemented. We will show throughout some examples the importance of realistic modelling of the EE on the multipactor dynamics and in particular the importance of the inelastically backscattered electrons.

CHARACTERIZATION OF PLASMA IN CONTACT WITH LIQUID STATE MATERIALS WITH USING OPTICAL EMISSION SPECTROSCOPY

YEONGWOO SON[1], Winfrey Leigh[1]
1. Pennsylvania State University

One of the major issues for nuclear fusion systems is the structural materials for the first wall and divertor system in Tokamak reactors. Liquid materials as plasma facing component has garnered increasing attention for their potential advantages over solid materials. However, a study of plasma liquid interaction has not been conducted as actively as plasma solid interaction so that understanding about their interaction mechanism can be determined. Herein, we present a characterization of plasma in contact with several low melting temperature materials using optical emission spectroscopy to investigate the interaction layer between the plasma and liquid state materials. Radio frequency plasma is generated by RF power supply and propagated from a Cu antenna. Low melting temperature materials, such as Al and Sn, are heated in an evaporation boat inside a vacuum chamber and the surface of the materials are exposed to the plasma. Here we measure basic plasma parameters, electron temperature Te and electron density ne, as a function of distance between surface of the materials and Cu coil and observe the change in plasma parameters in vapor layer and plasma bulk.

1. G. G. Van Eden, V. Kvon, M. C. M. Van de Sanden and T. W. Morgan, “Oscillatory vapour shielding of liquid metal walls in nuclear fusion devices,” Nature Communications, vol. 8, no. 1, 2017.

2. D. L. Crintea, U. Czarnetzki, S. Iordanova, I. Koleva, and D. Luggenholscher, “Plasma diagnostics by optical emission spectroscopy on argon and comparison with Thomson scattering,” Journal of Physics D: Applied Physics, vol. 42, no. 4, p. 045208, 2009.

VACUUM INSULATOR FLASHOVER OF ULTRA HIGH VACUUM COMPATIBLE INSULATORS

Josh Leckbee[1], Sean Simpson[1], Derek Ziska[1], Bill Bui[1]
1. Sandia National Laboratories

High voltage vacuum insulation is a key component of many high voltage and pulsed power systems. High voltage vacuum insulator performance has been investigated for a variety of materials, geometries, and pulsed voltage duration. Experiments have shown that a $45°$ frustum with the base at the cathode is typically the ideal shape to optimize electrical performance. As a general trend, plastic insulators exhibit superior high voltage hold off characteristics [1] whereas ceramic and glass insulators have superior vacuum outgassing properties. As a result, systems with high field stress requirements tend to use materials such as Rexolite or PMMA [2]. Systems with stringent vacuum requirements are often designed with ceramic insulators [3] and are designed with low electric field stress. A plastic with high electrical strength and low outgassing may provide advantages for applications where low vacuum outgassing is required. In this study we compare the electrical and vacuum performance of Rexolite, a pulsed power industry standard vacuum insulator, to Kel-F (PCTFE), a plastic with significantly lower vacuum outgassing [4]. Tests were conducted with 7-mm thick insulators with a $45°$ frustum. The applied voltage pulses have a FWHM of $\sim$100 ns and peak voltage up to 350 kV.

[1]. O. Milton, IEEE Trans. Elec. Insul., EI-7, pp.9-15, (1972).

[2]. W. A. Stygar, et. al., Phys. Rev. ST-AB, 8, 050401, (2005).

[3]. W. L. Waldron, et. al., Proc. IPMHVC, pp.179-182, (2000).

[4]. S. Simpson, "Vacuum Outgassing Study of Candidate Materials for Next Generation Pulsed Power and Accelerators: Improving the Boundary Conditions for Molecular Flow Simulations", Companion Talk, this Conference (PPPS 2019).

* Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

VACUUM OUTGASSING STUDY OF CANDIDATE MATERIALS FOR NEXT GENERATION PULSED POWER AND ACCELERATORS: IMPROVING THE BOUNDARY CONDITIONS FOR MOLECULAR FLOW SIMULATIONS

Sean Simpson[1], Ronald Goeke[1], Kenneth Coombes[1], Karen Dezetter[1], Owen Johns[1], Josh Leckbee[2], Dan Nielsen[1], Matthew Sceiford[1]
1. Sandia National Laboratories
2. Sandia National Labs

Next generation pulsed power machines and accelerators require a better understanding of the materials used within the vacuum vessels to achieve lower base pressures (P $<< 10^{-5}$ $Torr$) and reduce the overall contaminant inventory while incorporating various dielectric materials which tend to be unfavorable for UHV applications. By improving the baseline vacuum, it may be possible to delay the onset of impedance collapse, reduce current loss on MA devices, or improve the lifetime of thermionic cathodes, etc. In this study, we examine the vacuum outgassing rate of REXOLITE (cross-linked polystyrene) and Kel-F (polychlorotrifluoroethylene) as candidate materials for vacuum insulators. These values are then incorporated into boundary conditions in our molecular flow simulations using COMSOL and the results are compared to a pulsed power system [1] designed for 1×10^{-8} $Torr$ operations.

[1]. J. Leckbee et. al., "Vacuum Insulator Flashover of Ultra High Vacuum Compatible Insulators", Companion Talk in this Conference (PPPS 2019).

* Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2019-2518 A

ROLE OF TEMPERATURE IN ELECTRICAL BREAKDOWN AT TRIPLE JUNCTIONS

Giacomo Galli[1], Michael J. Kirkpatrick[2], Emmanuel Odic[2], Philippe Dessante[2], Philippe Molinié[2], Hassen Hamrita[3]
1. Centralesupelec
2. GeePs — Group of electrical engineering - Paris, UMR CNRS 8507, CentraleSupélec, Univ. Paris-Sud, Université Paris-Saclay, Sorbonne Université
3. CEA, LIST, Sensors and Electronic Architectures Laboratory

Recent work by our group, presented at ICOPS Denver and subsequently published[1], demonstrated an effect of temperature on the breakdown voltage in argon between two spherical electrodes at elevated pressure. Experiments in this work were done in a closed vessel, and the result was an augmentation in the breakdown voltage with increasing temperature for a given gas density. This result is in contrast with other previous work done to understand the origin of increased electrical discharge activity with increasing temperature in devices known as fission chambers[2], which contain ceramic insulators.

The present work aims to come to a more detailed understanding of the discharge activity in the fission chambers at elevated temperature by systematically investigating electrical breakdown at triple junctions using braised stainless steel-alumina junctions specifically constructed for this study.

The results of the experiments for breakdown at the triple junction comparing behaviour at ambient and elevated temperature will first be presented, followed by a discussion in light of a proposed mechanism.

1. G. Galli et al., "Paschen's Law in Extreme Pressure and Temperature Conditions," IEEE Transactions on Plasma Science, (2019).

2. G. Galli et al., "Characterization and localization of partial-discharge-induced pulses in fission chambers designed for sodium-cooled fast reactors," IEEE Transactions on Nuclear Science, 65 (2018) 2412.

Work supported by the CEA (Alternative Energy and Atomic Energy Commission) in France and by the GeePs (Group of electrical engineering) laboratory in France.

ELECTRON LOSSES IN SUPER-INSULATED MAGNETICALLY INSULATED TRANSMISSION LINES

Rick Spielman[1], Adam Sefkow
1. University of Rochester, Laboratory for Laser Energetics

Low-loss or loss-free constant-impedance magnetically insulated transmission lines (MITLs) are well understood and are successfully used on the very largest pulsed-power drivers such as Sandia National Laboratories Z Machine. Next-generation drivers must optimize MITL designs to lower their inductance and increase the current per MITL. Super-insulated MITLs are well understood from a theoretical standpoint for equilibrium electron flow and these MITLs have flow impedances close to the vacuum impedance of the transmission lines. Super-insulated MITLs have relatively low levels of vacuum electron flow and very thin electron sheaths. This MITL theory does not address the electron flow in non-equilibrium MITLs. We describe the use of variable-impedance MITLs to lower the driving inductance of disk MITLs and show the first PIC simulations of such MITLs.

FUNDAMENTAL STUDY OF UNIPOLAR AND RF BREAKDOWN IN ATMOSPHERIC AIR*

Ivan Aponte[1], Benedikt Esser[1], James Dickens[1], John Mankowski[1], Andreas Neuber[1]
1. Texas Tech University

RF breakdown at 3.3 MHz is studied experimentally in centimeter sized gaps at atmospheric conditions. As a point of comparison, unipolar breakdown voltages utilizing brass and stainless-steel Bruce profile electrodes are measured to compare with RF breakdown. Various electrode combinations using brass and stainless-steel electrodes were tested, where brass cathodes yielded higher shot-to-shot breakdown voltage fluctuations compared to stainless steel cathodes. In the unipolar case, the choice of anode material caused noticeable breakdown voltage differences, pointing towards a photon governed feedback mechanism.

Gap distances of 1-10 mm were tested in both unipolar and RF cases with slow rise time, $\sim$ 5 V/ms, sources. Under these conditions, RF breakdown fields (crest field values) yielded approximately 80% of unipolar values, which compares favorably with results previously generated from Monte Carlo simulations. Speeding up the amplitude rise of the RF signal to the 100 V/μs range resulted in breakdown voltages up to 20% higher than the slow unipolar breakdown, along with drastically higher shot-to-shot breakdown field amplitude variation. Applying UV radiation with photon energies higher than the work function of the electrodes (less than $\sim$ 280 nm in wavelength) reduced the amplitude variation to a minimum, however, with the average still being higher than the slow unipolar values.

In order to address the magnitude of corona losses in antennas and other RF systems, one of the electrodes is replaced with lanthanated or pure tungsten needle electrodes of varying tip geometry. This corona study also compares the unipolar and RF case.

HIGH FIELD RF BREAKDOWN OF PRESSURIZED SF_6

Melvin Powell, Zach Shaw, James Dickens[1], John Mankowski[1], Andreas Neuber[1]
1. Texas Tech University

Pure N2 and SF_6 as well as their mixtures are evaluated for high electric field breakdown tested at pressures ranging from 756 torr up to 1655 torr at 2.85GHz. Previous research concerning the breakdown characteristics of pressurized SF_6 and SF_6 mixtures at S-Band frequencies is limited, likely due to the high electric fields required to breakdown pressurized SF_6. A stepped impedance transformer is used in conjunction with a traveling wave resonator to obtain the electric field amplitudes necessary to break down the gases. Starting with the output from a 3.5 MW coaxial magnetron the electric field amplitude in the test piece at the center of the stepped impedance transformer yielded a maximum of about 150 kV/cm RMS.

Using Pure SF_6 as a baseline, the electric field breakdown threshold in the low pressure range (750 torr to 1450 torr) is distinctly lower, $\sim$ 80%, for a 20/80 SF_6 to N2 mixture and closer, $\sim$ 88%, at the higher pressures (1,450 torr to 1,650 torr). As a general observation, the measured breakdown field shows a mostly linear dependence upon pressure in a range from 750 torr to 1350 torr, while some levelling out tendency is observed at pressures greater than 1350 torr. Since pure N_2 exhibits a much lower breakdown threshold, $\sim$ 60%, compared to pure SF_6, mixing the two gases also results in a lower effective breakdown threshold; however, the reduction in the electric field breakdown threshold is not strictly proportional. For example, a 60/40 SF_6 to N2 mixture resulted in a 90% breakdown field while a 20/80 mixture still yielded about 80% in the high pressure regime.

EFFECT OF RELATIVE HUMIDITY ON THE FLASHOVER STRENGTH OF SOLID INSULATION

Ruairidh Macpherson[1], Mark Wilson[1], Igor Timoshkin[1], Scott MacGregor[1], Martin Given[2]

1. University of Strathclyde

2. University Strathclyde

Surface flashover across solid dielectric/gas interfaces is a problem that can occur during operation of gas-insulated high voltage (HV) equipment. The present work is aimed at investigation of the surface flashover characteristics of different solid dielectrics and surface topologies, stressed with HV impulses in air at different pressures. An experimental system has been developed to control the relative humidity (RH) of air, to determine the effect on the flashover strength of solids under different combinations of these test conditions. Samples of Delrin (Polyoxymethylene), HDPE (High-Density Polyethylene) and Ultem (Polyetherimide) have been tested between parallel-plane electrodes.

The solid samples were cylindrical, with their surfaces machined to a smooth finish. Samples with a modified, 'knurled', surface finish were also tested after a specific cleaning method was performed on all samples. Both positive and negative polarity impulse voltages were applied across the electrodes using a 10-stage Marx generator, configured to produce a 100/700 ns output voltage waveform, with a peak voltage up to 200 kV. Solid samples were tested in air with low ($<$10%) RH, and in air pre-treated with an ultrasonic humidifier to achieve medium ($\sim$50%) and high ($>$90%) RH. Tests were undertaken at -0.5, 0 and 0.5 bar gauge.

Each solid sample was characterised in terms of average flashover voltage and time to breakdown, over 20 individual breakdown events. The voltage was increased in steps of 3 kV from a 'no breakdown'level until a flashover event occurred, and the process was repeated until 20 flashover data points were recorded per test condition. Two withstand levels were observed before a valid breakdown voltage was recorded, in accordance with the ASTM D3426-97 standard. The results will inform on the flashover performance of the different materials, and on the relative reduction in the breakdown strength of solid/gas interfaces in sub-optimal conditions.

MICROPLASMA PHOTONIC CRYSTALS BEYOND THREE-DIMENSIONS

Wenyuan Chen[1], Peter P. Sun[1], Runyu Zhang[1], Paul V. Braun[1], J. Gary Eden[1]
1. University of Illinois Urbana Champaign

An isotropic dielectric photonic crystal has been designed and demonstrated at the University of Illinois. The entire multidimensional structure is fabricated in a flexible polymer and the lattice constant is currently 500 μm. Interspersing 355 μm diameter microchannels along three spatial coordinates allows the plasma filling factor to increase to $\sim$ 10%. The ignition of plasma within polymer/dielectric microcolumn arrays results in narrowband resonances that are tunable by as much as 1.2 GHz at 164 GHz. Introducing plasma has the effect of blue-shifting attenuation peaks of the resonator and increasing the time-averaged attenuation by 13.7 dB. Electromagnetic induced transparency is also observed in custom-designed waveguide configurations. These crystals offer a higher level of symmetry and Fabry-Pérot resonator modes are observed. These crystals provide functionality not available with conventional photonic crystals that are not reconfigurable at electronic speeds.

EFFECT OF PLASMA MODIFIED BN ON AC BREAKDOWN STRENGTH OF BN/EPOXY RESIN NANOCOMPOSITES

Yan Mi[1], Jiaxi Gou[1], Lu Gui[1], lulu Liu[1], Jiacheng Chen[1]
1. Chongqing University

BN/epoxy resin nanocomposites are expected to be a kind of high thermal conductive insulating material, but when the BN filling amount reaches a certain level, the AC breakdown strength of the composites will be lower than that of pure epoxy resin. In order to improve the AC breakdown strength of BN/epoxy resin nanocomposites with high filling ratio (15wt.%), BN nanoparticles were hydroxylated by non-thermal plasma generated by atmospheric pressure Ar/H2O bipolar nanosecond pulse dielectric barrier discharge, and then modified by silane coupling agent KH560. The pulse voltage amplitude was 6 kV, the pulse width was 300 ns, and the positive and negative pulse interval was 5 μs. X-ray photoelectron spectroscopy (XPS) was used to analyze the effect of pulse repetition frequency and relative humidity on hydroxylation modification. The dispersion of nanoparticles in epoxy resin was analyzed by scanning electron microscopy (SEM). Trap properties and AC breakdown strength of composites were tested. The results show that hydroxyl groups on the surface of BN increases with the increase of pulse repetition frequency, and increases first and then decreases with the increase of relative humidity. After surface modification, the compatibility and dispersion of BN nanoparticles in the epoxy resin are improved, and more deep traps are introduced into the interface region, thereby improving the AC breakdown strength of the BN/epoxy nanocomposites.

Index Terms —bipolar nanosecond pulse, non-thermal plasma, AC breakdown strength, nanocomposites, BN nanoparticles

THE EFFECT OF APPLIED VOLTAGE ON THE LAMINAR-TURBULENT TRANSITION IN ATMOSPHERIC-PRESSURE PLASMA JET

Abdel-Aleam Mohamed[1], Sahar Fadhlalmawla[1], Jamal Almarashi[1]
1. Taibah University

Atmospheric-pressure argon cold plasma jet was used to study the effect of applied voltage on the laminar to turbulent transition. The plasma jet consists of a quartz tube of inner and outer diameters of 2 mm and 6 mm, respectively. Two identical copper-sheets of 7 mm width are warped around the quartz tube. The sheets are separated by 35 mm and the upper sheet is connected to an AC high-voltage power supply and the lower one is grounded. The current-voltage waveforms show that the jet has four modes of operations depending on the number of current pulses per each half a cycle of the applied voltage and the generation of the upstream and downstream jets. Also, the generated modes depend on the applied voltage and the discharge frequency. It was found that the transition from laminate to turbulent flow mode shows a shift towered lower flow rate values with increasing the applied voltage. The transition point shifts from 3.75 to 2.6 SLPM as the applied voltage is increased from 14 kV to 25 kV. It is assumed that this shift is due to the increment in the plasma gas temperature with increasing the applied voltage. Moreover, the gas temperature, measured at 2 mm below the tube nozzle, increases from 310 to 355 K as the applied voltage increased from 14 kV to 25 kV. Consequently, this increment in gas temperature increases the dynamic viscosity and decreases the gas density. Therefore, the measured Reynolds decreases with increasing the applied voltage [1].

References

[1] Song J, Tang J, Huo Y, Wei L, Wang Y and Yu D. Effect of dielectric wall temperature on plasma

plume in an argon atmospheric pressure discharge. Phys. Plasmas 21, 100704 (2014).

DECOMPOSITION OF 2,4-DICHLOROBENZONIC ACID IN HYDROPONIC NUTRIENT SOLUTION USING DISCHARGE INSIDE BUBBLE

Katsuyuki Takahashi[1], Rikuya Oikawa[1], Syuhei Kawamura[1], Koichi Takaki[1], Naoya Satta[1], Takuya Fujio[2]
1. Iwate University
2. Iwate Agricultural Research Center

Decomposition of 2,4-dichlorobenzonic acid (DCBA) in hydroponic nutrient solution using discharge inside bubble is investigated. Air gas is injected into water through a vertically positioned glass tube, into which high voltage wire electrode is placed to generate plasmas at low applied voltage. A magnetic pulse compression circuit is used to generate high voltage pulses. The concentration of DCBA and chloride ion is determined using a high performance liquid chromatography and an ion chromatography, respectively. The concentration of DCBA decreases and the concentration of chloride ion increases with increasing discharge treatment time. The chloro groups in the DCBA are preferentially detached from the DCBA by the oxidation reactions of the chemical species generated by the discharges. Since the nitric acid is generated by the discharge treatment, the pH decreases with increasing discharge treatment. The water treated by the discharge treatment is used as the nutrient solution for cultivating cucumber plants in a hydroponic system. The pH of the water after the discharge treatment is adjusted to 5.7 using a pH adjuster, and is supplied to the plants. The plant height is evaluated as the growth rate of the plants. The results show that the growth of almost plants is inhibited by the DCBA without discharge treatment; in contrast, the plants with discharge treatment grow healthily.

INCEPTION VOLTAGE FOR CORONA-LIKE DISCHARGES GENERATED WITH 100-NS HIGH VOLTAGE PULSES IN WATER DEPENDING ON PULSE SHAPE AND WATER CONDUCTIVITY

Raphael Rataj[1], Hans Höft[1], Juergen F. Kolb[1]
1. Leibniz Institute for Plasma Science and Technology (INP)

The development of corona-like discharges that are instigated in water by the application of high voltage pulses is not only important for switching applications but also for discharges that are exploited for water treatment [1]. A parameter that is affecting discharge developments and foremost inception voltages is the pulse shape (rise time, amplitude, pulse duration) but in particular water parameters, such as conductivity and dissolved gas content [2]. Presumably, the influence of pulse shapes is especially crucial for the application of high voltage pulses of only a few nanoseconds.

For the investigation of discharges that are generated with short high voltage pulses of 100 ns, rise and fall times were adjusted between 20 and 45 ns for otherwise equivalent pulse durations. The pulses were applied to a point-to-plane electrode geometry, which was submerged in water with different conductivities from 1 μS/cm to 700 μS/cm. Voltages, currents and emitted light intensities were recorded together with spatial-resolved images of the individual discharge development. For each parameter-set, a statistical analysis was conducted with respect to inception voltages, time lags and channel lengths.

For water conductivities up to 300 μS/cm, the inception voltages decreased with increasing conductivity. This correlates with a decrease of the Helmhotz-layer thickness, which results in a higher electric field near the needle tip. Interestingly, for higher conductivities, inception voltages are increasing again. This can be explained by the change from dielectric to resistive behavior of water. Concurrently, discharge propagation characteristics and reaction chemistries are changing, as illustrated by the channel lengths, light emission and time lags.

[1] Banaschik, R., et al., Electrochimica Acta 245 (2017): 539-548.

[2] Kolb, J.F., et al., Journal of Physics D: Applied Physics 41.23 (2008): 234007

EFFECT OF SUBSTRATES ON A NANOSECOND HELIUM PLASMA JET IMPINGING ON WATER, SALINE OR PIG SKIN

shutong song[1], Siqi Guo[2], Chunqi Jiang[2]
1. Old Dominion Unviersity
2. Old Dominion University

Atmospheric pressure plasma jets have been widely used for biomedical applications. However, characteristics of discharge could vary dramatically depending on the biological substrates which further affects the treatment results. In this study, effects of three substrates (i.e. water, saline and pig skin) on electrical and optical properties of a pulsed helium plasma jet powered by 200 ns, 7 kV pulses at 1 kHz and with a He flow rate of 70 sccm are evaluated via electrical measurements and optical emission spectroscopy. Energy per pulse for both saline and pig skin are comparable at about 39 μJ, which is 1.2 times higher than that with water. Spatially-resolved optical emission spectroscopy reveals that most of the excited species (i.e. OH*, N2+*, He* and O*) are localized within 2 mm from jet nozzle except for N2 which extends up to 6 mm away from the nozzle when saline or pig skin are used as the substrate. Stronger emissions from excited OH*, He* and O* are obtained using pig skin as the substrate while higher emissions from N2* and N2+* are from the plasma with saline as the substrate. Gas temperature and the ground state OH radicals near the surfaces of substrates are also discussed.

DYNAMIC BAND-PASS AND BAND-STOP FILTERS REALIZED WITH MULTIDIMENSIONAL MICROPLASMA PHOTONIC CRYSTALS

Peter P. Sun[1], Wenyuan Chen[2], Zhang Runyu[2], Zhihu Liang[3], Paul V. Braun[2], J. Gary Eden[2]

1. University of Illinois at Urbana-Champaign
2. University of Illinois Urbana Champaign
3. Xi'an Jiaotong University

Future wireless communications systems are driving system operating frequencies to the 100 - 500 GHz region. The stringent demands of 5G and 5G+ systems are accelerating the development of new sources and devices, such as resonators and filters. We report here the realization of dynamic filters through multidimensional microplasma photonic crystals. These crystals comprise spatially-periodic arrays of metallo-dielectric structures that themselves act as static photonic crystals. Embedded microplasma photonic crystals, reconfigured electronically, enable the design dynamic, band-stop filters with bandwidths from 300 MHz to 4.2 GHz and band-pass filters with bandwidths of 400 MHz to 3.9 GHz over the span of 120 - 170 GHz. The rotational symmetry and longitudinal symmetry of these crystals have been observed at 138 GHz. Coupling microplasma photonic crystals with metallo-dielectric photonic crystals enable functionality extending well beyond that available with conventional photonic crystals.

SPATIALLY AND TEMPORALLY RESOLVED MEASUREMENTS OF LOAD CURRENT DELIVERY ON THE Z PULSED POWER FACILITY USING THE Z LINE VISAR DIAGNOSTIC

Clayton Myers[1], David Bliss[1], Peter Celliers[2], Phil Datte[2], David Erskine[2], Mark Hess[1], Michael Jones[1], Thomas Awe[1], Duane Fratanduono[2], James Hammer[2], Chris Jennings[1], Keith LeChien[2], Kumar Raman[2], Paul Springer[2]

1. Sandia National Laboratories

2. Lawrence Livermore National Laboratory

Measuring the current delivered to a pulsed-power load is key to understanding its expected behavior. On the Z Pulsed Power Facility, the load current is most accurately measured using velocimetry techniques such as VISAR (Velocity Interferometer System for Any Reflector) and PDV (Photonic Doppler Velocimetry). These diagnostics measure the expansion of a metallic plate or 'flyer'that is driven by the magnetic pressure of the load current. To date, only point velocimetry measurements, which are temporally but not spatially resolved, have been obtained on Z. This limits the locations and conditions under which the load current can be inferred. In this paper, we present the first velocimetry data from the new Z Line VISAR (ZLV) diagnostic, which enables spatially and temporally resolved load current measurements.

To validate the performance of the ZLV diagnostic, a series of experiments were conducted using a non-imploding load driven with $\sim$14 MA of current. In these experiments, the ZLV instrument was focused on the top plate of the load to obtain radially and temporally resolved velocimetry over a 4-mm field of view. Standard point velocimetry probes were fielded at several radii to cross-validate the ZLV measurements. High quality ZLV data with 4-μm and 40-ps pixel resolution were obtained on the first attempt, and cross-comparisons to both the point probe data and to numerical models serve to validate the ZLV measurements. Velocimetry data with the newly demonstrated spatial and temporal resolution are expected to transform the understanding of load current delivery on Z.

This work is support by the U.S. Department of Energy's National Nuclear Security Administration under contracts DE-NA-0003525 (Sandia National Laboratories) and DE-AC52-07NA27344 (Lawrence Livermore National Laboratory).

ELECTRO-OPTICAL MEASUREMENT OF ELECTRIC FIELDS FOR PULSED POWER SYSTEMS

Israel Owens[1], Chris Grabowski[1], Nathan Joseph[1], Sean Coffey[1], Benjamin Ulmen[1], Debrah Kirschner[1], Kirk Rainwater[1], Ken Struve[1]
1. Sandia National Laboratories

The electric field strength from the cathode to the anode (or Voltage) of a pulsed power machine is one of the most important operating parameters of the device. However, to date, accurate and precise Voltage measurements on these high energy pulsed power systems have proved difficult if not virtually impossible to perform. In many cases, the measurements to be performed take place in an environment cluttered with electromagnetic interference (EMI), radio frequency interference (RFI), electron pollution, potential for electrical discharge (or arcing), limited physical access or deemed unsuitable due to radiation safety concerns. We report on an electro-optical based approach to measuring strong, narrow-pulse-width electric fields that requires no interfering metallic probes or components to disturb the measurement field. Here we focus on device theory, operating parameters and a laboratory experiment.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy National Nuclear Security Administration under contract DE-NA000352

HIGH CURRENT SENSING THROUGH FARADAY ROTATION OF POLARIZED LIGHT OF VARYING WAVELENGTHS IN FIBERS III*

Israel Owens[1], Sean Coffey[1], T. Chris Grabowski[1]
1. Sandia National Labs

Traditionally, large-amplitude, fast-rising electrical currents and magnetic fields have been measured with electromagnetic probes such as Rogowski coils or B-dot probes. These measurements can be problematic if made near high voltage electrodes with insufficient probe isolation. An alternative method for measuring electrical current and magnetic fields involves using the Faraday effect on linearly polarized light propagating in single mode fibers.

Faraday effect probes have been used to measure magnetic field strength for many years. In this application, when the fiber probe is subject to a magnetic field, the polarized light will rotate within the fiber. For strong magnetic fields, the rotation angle may exceed many hundreds of degrees with the resultant probe receiver output exhibiting a sinusoidal response. Every signal cycle represents a phase shift equal to 180 degrees (one "fringe shift"), and the magnetic field strength is determined by counting the resultant fringes. Such a probe as this has positive features, including relative immunity to signal cable attenuation, and the fact that optical fiber is a dielectric material which reduces breakdown problems near high voltage electrodes. Furthermore, the response of these probes is based solely on the material properties of the sense fiber, thereby making any calibration, in situ or otherwise, unnecessary. Due to technical advances in the telecommunication industry, a robust compact Faraday effect optical assembly is now available at low cost.

This paper builds on this previous work and summarizes experimental data taken with the Mykonos Linear Transformer Driver (LTD) at Sandia National Laboratories. The Mykonos LTD can output a 1 MA pulse with 60 ns risetime and 160 ns FWHM into a 0.5-Ω matched load. A summary of the results using four Faraday probes, optimized at wavelengths 450 nm, 532 nm, 632 nm and 850 nm is presented.

UPGRADE OF THE SPALLATION NEUTRON SOURCE INJECTION AND EXTRACTION KICKER PULSE VERIFICATION SYSTEMS

Ben Morris[1], Doug Curry[1], Robert Saethre[2], Eric Breeding[1]
1. ORNL
2. Oak Ridge National Lab

The Spallation Neutron Source (SNS) injection system transports a chopped 1ms H- ion beam from the Linac into the accumulation ring where two electrons are stripped from each ion, resulting in a proton beam propagating in the ring. The injection kickers use a 1400A current source with a 1 ms discharge time to bump particles into the accumulator ring and transport waste beam to the injection dump. The accumulation ring stacks 1 us bunches from the 1 ms beam pulse to increase peak beam current by 1000 times. The accumulated beam is deflected by the fourteen 38kV 700ns pulsed extraction kicker magnets and delivered to the mercury target where neutrons are spalled for science experiments. Protecting the machine from errant beam, which results from asynchronous firing or insufficient magnetic field intensity in kicker systems, requires a system that monitors and verifies the pulsed current in the kicker magnets prior to and during each 60Hz beam pulse. In addition, the extraction system pulse forming network (PFN) is verified to be charged and ready for triggering prior to injecting beam into the Linac by the Ion Source. This paper describes the two verification systems requirements, limitations of the existing systems, and development of new systems.

CYGNUS SYSTEM TIMING

Eugene Ormond[1], Keith Hogge[2], Michael Garcia[1], Percy Amos[2], John Smith[3], Martin Parrales[1], Michael Misch[2], Mohammed Mohammed[2], Hoai-Tam Truong[2]

1. Sandia National Laboratories
2. Mission Support and Test Services
3. Los Alamos National Laboratory

The Cygnus Dual Beam Radiographic Facility consists of two identical radiographic sources each with a dose rating of 4-rad at 1 m, and a 1-mm diameter spot size. The development of the rod pinch diode was responsible for the ability to meet these criteria[1]. The rod pinch diode in a Cygnus machine uses a 0.75-mm diameter, tapered tip, tungsten anode rod extended through a 9-mm diameter, aluminum cathode aperture. When properly configured, the electron beam born off the aperture edge can self-insulate and pinch onto the tip of the rod creating an intense, small x-ray source. The Cygnus sources are utilized as the primary diagnostic on Subcritical Experiments that are single-shot, high-value events. The system timing on Cygnus will be evaluated as related to system elements: delay generators, trigger generators, Marx, pulse forming line, inductive voltage adder and rod pinch diode. As Cygnus trigger generators are a significant jitter source, spare trigger generators will also be included in this evaluation.

1. G. Cooperstein et al., ”Theoretical Modeling and experimental Characterization of a Rod-Pinch Diode,” in Physics of Plasmas, Vol. 8, Number 10, October 2001.

----

* Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

CYGNUS PERFORMANCE ON SEVEN SUBCRITICAL EXPERIMENTS

John Smith[1], Michael Garcia[2], Eugene Ormond[2], Martin Parrales[2], Paul Flores[3], Keith Hogge[3], Steven Huber[3], Michael Misch[3], Jesus Perez[3], Thomas Romero[3], Hoai-Tam Truong[3]

1. Los Alamos National Laboratory
2. Sandia National Laboratories
3. Mission Support and Test Services

The Cygnus Dual Beam Radiographic Facility includes two identical radiographic sources - Cygnus 1 and Cygnus 2. Cygnus is the radiography source used in Subcritical Experiments (SCEs) at the Nevada National Security Site (NNSS). The machine specifications are: Electric 2.25 MV, 60 kA, 60 ns; Radiation 4 Rad, 1 mm, 50 ns; Operation single shot, 2-shots/day. Cygnus has operated at the NNSS since February 2004. In this period, it has participated on seven SCE experiments - Armando, Bacchus, Barolo A, Barolo B, Pollux, Vega, and Ediza.

SCE projects typically require over a hundred preparatory shots culminating in a single full-fidelity or SCE shot, and typically take over a year for completion. Therefore, SCE shots are high risk and high value making reproducibility and reliability utmost priority. In this regard, major effort focuses on operational performance. A quantitative performance measurement is valuable for tracking and maintaining Cygnus preparedness. In this work, we employ a model for analysis of Cygnus performance that uses dose distribution as the basis for calculation of reproducibility and reliability. It will be applied both to long-term (historical) and short-term (readiness) periods for each of the seven SCEs.

FLASH LAMPS CURRENT MONITORING USING OPTICALLY INSULATED FPGA TECHNOLOGY UNDER HARSH PULSED POWER ENVIRONMENT

Jean Marie Larbaig[1], Robert Ruscassié[2], Baptiste Cadilhon[3], Jean Marc Dienot[1], Anca Petre[1]

1. Univ Pau & Pays Adour/ E2s Uppa, SIAME EPHT

2. Univ Pau & Pays Adour/ E2s Uppa,SIAME EPHT

3. CEA

Within the frame of the Common Research Laboratory initiated in 2017 between French Atomic Energy and Alternative Energies Commission (CEA) and Pau University (UPPA), FPGA based developments have been initiated in order to evaluate the potential benefits of such technology regarding the pulsed power applications domain.

Thus, some investigations are currently undergoing on the monitoring possibilities of electrical characteristics (and more specifically currents) in order to improve some maintenance and reliability aspects related to the operation of flash lamps used on high power lasers.

These very specific lamps need to be pre-ionized during a short period of time by a bi-exponential shaped current whose value has to be around 2kA before the true lamp ignition which is achieved through a 30kA pulsed current flow obtained by the discharge of a dedicated energy bench.

In order to try to reduce the number of inefficient ignitions, a control strategy based on the measurement of the pre-ionization phase is implemented. This strategy is based on Analog to Digital Conversion (ADC) as well as FPGA acquisition processing which was chosen due to its speed capabilities, and abilities to be stacked in order to perform multiple tasks in parallel. Our aim is to be able to acquire the signals rapidly and with sufficient accuracy, as well as to analyze them fast enough to make it possible to stop the ignition if necessary.

Since the environment where this system will be deployed can be considered as harsh due to the high transient currents levels being monitored and to the High Voltage switching elements operating near by, the choice of optical fibers insulation has been made.

This project made it possible to explore FPGA acquisition and control behavior under harsh perturbed environment. Recent developments regarding this implementation will be presented in details.

HIGH SPEED IMAGING OF POLYMER BONDED EXPLOSIVES UNDER MECHANICAL STRESSES

Ryan Lee[1], Austin Hewitt[2], Raimi Clark[1], Tyler Buntin[1], David Barnett[1], James Dickens[1], W. A. Harrison[3], E. Tucker[4], Andreas Neuber[1], John Mankowski[1]
1. Texas Tech University
2. Center for Pulsed Power and Power Electronics(P3E)
3. CNS Pantex
4. Mission Engineering Development Group

The impact of mechanical stresses on polymer bonded high explosives, HE, is investigated. High-Speed photography in the visible spectrum, VIS, as well mid-wave infrared (MWIR) of HE during small diameter drilling and controlled skidding is presented. Controlled drilling into the HE enables recording the size and temperature of shavings under varying feed and speeds. Even at very high drill speeds, the HE phase transition temperature of approx. 180 degree Celsius is rarely exceeded. The MWIR signals radiated are recorded with FLIR's X6901sc High-speed MWIR camera, which uses InSb technology, with a wavelength range from 3.0 to 5.0 μm, and up to 1,004 fps at a resolution of 640 x 512 in the temperature range of interest. The physical shaving's path and size of the HE is recorded with Phantom's VEO710s high-speed camera at much higher frame rate of 7,400 fps at a resolution of 1280 x 800 in the VIS.

In the skidding case, the HE is pushed with measured force against a rotating surface with controlled roughness. The roughness of the impact area is determined by varying the type and surface density of distributed grit. While it is straightforward to observe the HE-grit interaction in the VIS by employing a glass or BK7 window as interface surface, the MWIR range poses a greater challenge as such glasses are opaque in the MWIR. Thus, for the temperature measurements the HE is skidded across a sapphire optical window. The window is chosen for its IR transparency up to 5.5 μm wavelengths and mechanical toughness. Thus, the grit size and distribution is recorded in the VIS, while the MWIR provides information on the HE-grit interface temperature, which in the extreme case, leads to full or partial detonation of the HE.

PROBABILITY OF PBX DETONATION DUE TO IMPACT FORCES AND SURFACE GRIT

Austin Hewitt[1], W. A. Harrison[2], E. Tucker[3], Raimi Clark[1], Tyler Buntin[1], David Barnett[1], James Dickens[1], Andreas Neuber[1], John Mankowski[1], Ryan Lee[1]
1. Texas Tech University
2. CNS Pantex
3. Mission Engineering Development Group

The response of PBX HE under varying impact forces and impact surface area grits is analyzed to form a probability of detonation function. Using an air ram and rotating disk, the forces exerted in the normal and transverse directions of the impact plane are controlled to emulate skidding of PBX. The employment of a hopper system feeds grit onto the impact area with the ability to vary the grit density and individual grit size. While confirmation of the desired surface grit density is done with a high-speed visible spectrum camera, the use of a high-speed IR camera viewing the contact of the PBX with the surface through an IR transparent window allows for the analysis of evolving thermal hotspots during impact. Overall, the setup enables varying normal force and surface speed independently with high accuracy in a small apparatus footprint. It will capture hotspots in PBX before they culminate into a chemical reaction that would then also be visible with a standard high-speed camera.

A microcontroller is used to automate the experiment where a desired normal and transverse impact force is translated to air ram firing pressure and impact disk rotation speed. Alignment of the air ram impact with the IR transparent window embedded into the impact disk and acquisition of the experienced forces are handled by the microcontroller and relayed to a PC for post processing of the data. The compression of metals braces is measured with strain gauges to back calculate the forces experienced during the emulated skidding to insure the proper forces were observed during impact

NUMERICAL INVESTIGATION OF THE PLASMA LOAD MATCHING WITH THE CURRENT SOURCES BASED ON EXPLOSIVE MAGNETIC GENERATOR

Valentina Zavalova[1], Mikhail Shurupov[1], Andrey Mashtakov[1], Andrey Gusev[1], Alexander Kozlov[1], Nina Shurupova[1]
1. Joint Institute for High Temperatures of the Russian Academy of Sciences

Electro physical studies of pulsed plasma loads, such as plasma accelerators (PA), plasma focus, etc. are interesting both from the point of view of theory and practice. Their current-voltage characteristics have nonlinear dynamics, which is difficult for mathematical modeling. However, their field of application is extensive and extends from plasma current-breaker to controlled thermonuclear fusion. Computational models to describe the operation of plasma loads such as PA, powered by both capacitive storage (CS) and explosive magnetic generators (EMG) at comparable energy levels of the order of 0.5 MJ are presented in the report. The obtained numerical data are compared with experimental ones. The good agreement of the results of calculations based on the developed numerical model with experiment is demonstrated. This allows using the developed model for matching of the power sources on the basis of the EMG with other types of non-linear plasma load.

AN ULTRA-PORTABLE X-PINCH DRIVER FOR HARD X-RAY DIAGNOSTICS

Simon Bland[1], Nikita Chaturvedi[2], Andreas Georgakis[1], Theodore Gheorghiu[1], Hannah Horton[3], Philip Moloney[1], Sergei Pikuz[4], Tania Shelkovenko[4], Seophine Stanislaus[1], Savva Theocharous[1], Christopher Wilson[1]

1. Imperial College London
2. First Light Fusion
3. Cambridge University
4. Cornell University

High energy density physics experiments often require the use of short pulses of hard X-ray probing radiation to make measurements of the conditions produced - for instance using X-ray diffraction to examine phase changes in a material subject to multi-Mbar pressures. Whilst there are several methods of producing such bursts of radiation, the use of a pulsed power driven X-pinch is highly appealing, given their relatively low cost and the potential high yields available.

In an X-pinch two or more crossed fine metallic wires are driven by a $\sim$100kA 100ns current, and the magnetically driven implosion at the crossing point of the wires causes the formation of a micro-diode that can emit $\sim$100mJ of $>$10KeV radiation on ns timescales. X-pinches have been studied for $\sim$25years in the pulsed power community but have rarely seen use outside of the area, due to the perceived complexity of the drivers required and their lack of portability.

In this poster we report on a new X-pinch driver designed and built at Imperial College London. Based on LTD technology, we have been able to significantly reduce the size and weight of the driver, whilst maintaining the required currents and rise times for successful X-pinch operation. Now entering a second stage of development, we are turning our attention to the LTD bricks that make up the driver, incorporating built in charging, safety and triggering. This negates the need for bulky external support equipment and could provide an interesting route scaling to larger facilities.

Acknowledgements This research was supported by EPSRC, First Light Fusion, The Institute of Shock Physics, Sandia National Labs and the US DoE under DE-NA003764 & DE-SC018088.

HIGH-ENERGY ELECTRIC GUN FOR EXPLODING FOIL INITIATORS

M. A. Rhodes[1]
1. Lawrence Livermore National Labs

Exploding Foil Initiators (EFI) are one method used to detonate secondary high-explosives without the use of sensitive, primary high-explosives. EFI's are typically driven by low-inductance, capacitor discharge units (a.k.a firesets or electric guns). Electric guns with stored energy of around 500-J and peak currents of 10's of kA are in common use to drive plastic-film flyers with areas of several mm^2 to the velocities required to determine energetic material detonation thresholds.

Anticipated experiments require much larger flyers (up to 2500-mm^2) driven to high-velocity and that will require much higher energy and current (100 kJ and 100's of kA).

To meet these requirements, we are developing a new, high-energy E-gun system based on repurposed Atlas capacitors and rail-gap switches. The new E-gun system is modular, and modules may be combined for increased capability. Each module stores up to 60-kJ at 60 kV and can deliver a current pulse of 500-kA in less than 2us.

To date, we have constructed three high-energy E-gun modules: one prototype and a two-module system designed specifically for operation at the LLNL HEAF facility. In this paper we will discuss the various design features and show test results.

----

* LLNL is operated by LLNS, LLC, for the U.S. D.O.E., NNSA under Contract DE-AC52-07NA27344.

STUDY ON THE RESTRIKE CHARACTERISTICS OF METAL ELECTRICAL EXPLOSION

YU Hong-Xin, RAN Han-Zheng, TAN Rong-Rong, ZHONG Hua

Abstract: The burst current will appear a brief pause phenomenon during the electrical explosion process, which is known as restrike, restricting the sedimentary energy of metal conductors in the exploding progess, changing the energy transfer process, thus affecting the propagation of detonation products. In order to study the factors affecting the restrike characteristics of electric explosion, a segmented control resistivity-specific action model based on current density is established in this paper. The effects of metal conductor size, materical and loading characteristics on second discharge were studied by numerical simulation and experiment , and the influence law of different factors was obtained. The results show that the current dwell time and the peak value of second-strike current are closely related to the charging voltage, length and meterial of metal conductor. The research results lay a foundation for the further research and application of metal electria explosion.

Keywords: Electrical exploding;restrike;Current pause;Resistivity;Specific action

PULSED POWER SUPPLY FOR 2 KA, 5 MEV LINEAR INDUCTION ACCELERATOR

Aleksandr Akimov[1], Petr Bak[1], Kirill Zhivankov[1], Michail Egorychev[1], Aleksey Panov[1], Aleksey Pachkov[1], Yaroslav Kulenko[1], Andrey Eliseev[1]
1. BINP

A 2 kA, 5 MeV linear induction accelerator has been built and successfully set in operation in Budker Institute. The accelerator consists of 2 MeV injector and 8 induction cells rated at energy gain up to 380 keV each. The accelerator pulsed power supply is based on an induction adder technique and aimed to supply 96 inductors of the injector and 128 inductors of all induction cells. The 112 pulsed modulators are used for this purpose. Each modulator is able to supply two inductors in parallel with pulsed voltage up to 23.5 kV at 60 ns flat top duration. The operation results of the pulsed power system loaded with a beam current at full energy are described in the paper. The injector and induction cells operation data are presented. Also paper describes the tested parameters of the basic modulator's elements such as pseudospark switches operated at voltage up to 43 kV and anode current up to 8 kA, and low impedance lumped PFNs based on mixed paper-film cells with oil impregnation.

ADVANCED CIRCUIT MODELING OF THE PHELIX PULSED POWER SYSTEM

Lee Merrill[1], Joseph Bradley III[1], Christopher Rousculp[1], David Oro[1]
1. Los Alamos National Laboratory

The Los Alamos National Laboratory (LANL) Precision High Energy-Density Liner Implosion Experiment (PHELIX) is a pulsed power system theoretically capable of delivering 0.5 MJ of capacitive energy in a 10 μs pulse to a hydrodynamic liner experiment. It is comprised of four Marx generators connected in parallel through four rail-gap switches to the primary of a 4:1 air-core toroidal transformer (k=0.9) via 40 RG217 cables. It has been simulated previously using Los Alamos RAVEN code which modeled the four marx modules as one capacitive source with a starting voltage, the RG217 cables modeled as series resistance and inductance, and the rail-gap switches were assumed to be closed at t=0.

To improve on the circuit model for simulation purposes we will show a more complete model of each marx generator and corresponding rail-gap switch using a spark gap model in LTSpice, with the addition of random distribution on the spark gap closing times to demonstrate a statistical response. The 40 RG217 cables to the transformer can be further explored by including them as sets of parallel transmission lines. Lastly, modeling of the Lorentz forces at the beginning of a pulse which can cause the secondary of the transformer to flex, which affects the inductance. The simulations will be compared to existing experimental data.

Creating a highly realistic circuit model of PHELIX will allow for a study on the efficiency of the marx generators'delivery of energy from the rail-gap switches through the transformer to the load. With a more complete understanding of the current system we can determine where potential issues may exist, in addition it can be used as a tool for improvements and upgrades. Beyond PHELIX, this research may assist other Pulsed Power Engineers in their modeling of magnetic-flux compression generators.

LA-UR-19-21495

TECHNICAL DEVELOPMENT AND FIRST RESULTS OF ISENTROPIC COMPRESSION EXPERIMENTS ON THE ICE-16 TEST FACILITY

Francis Lassalle[1], Frédéric Zucchini[1], Thierry Chanconie[1], Philippe Combes[1], David Sol[1], Régis Lample[1], Bernard Roques[1], Georges Gaillard[1]
1. CEA Gramat

High current drivers are key tools for material-physics experiments. For this study, the range of interest is to reach 0.1 to 3 GPa magnetic pressure in a sample area of several tens of square centimeters. An accurate control of the pressure wave is needed: 1D propagation, pressure homogeneity on sample area, reproducibility of pressure between experiments, modularity of pressure amplitude between experiments, etc. For this range of pressure, this accurate control of shockless compression doesn't need a pulse tailoring capability and can be reached with a several hundred ns rise time.

Such isentropic compression experiments are done at CEA on GEPI driver since 2002. GEPI can deliver a 3.5 MA – 500 ns pulse to a low inductance (< 1 nH) strip line load, for load widths less or equal to 70 mm. An upgrade, named GEPI-2, is under development with the goal to deliver a 6 MA – 1 microsecond pulse to a higher inductance (several nH) load, for load widths reaching 140 mm. ICE-16 is a test facility used to develop diagnostics, demonstrate enhanced performances and optimize different capacities of interest for GEPI-2: capacitors and switches with high reliability and high performance/cost ratio, strip line or curved loads with up to 130 square centimeters sample area, vacuum switch crowbar to control the ringing shape of the current pulse delivered to the load. Design, circuit or EM simulations and first results of isentropic compression experiments on ICE-16 are presented.

This work is supported by the DGA (Direction Générale de l'Armement)

A 30 KV AND HIGH AVALANCHE BULK GALLIUM ARSENIDE SEMICONDUCTOR SWITCH

Cheng Ma, Wei Shi[1], Hong Liu[1], Lei Hou[1]
1. Xi'an University of Technology

In this letter, we show that a high avalanche of gallium arsenide photoconductive semiconductor switches (GaAs PCSS) can be achieved with an bias voltage as 30 kV. The concept of avalanche gain is proposed to define the avalanche level through the experimentally obtained avalanche gain and the ionization rate at different bias voltages. The obtained values for maximum avalanche gain, maximum ionization rate, and minimum ON-state resistance of the GaAs PCSS were 1194, 708 cm-1, and 30 Ω. Furthermore, the method of stability calculation is given, by this means, the avalanche GaAs PCSSs is measured as 164.3 ps under 30 kV.

* Corresponding author: Wei Shi Email address: swshi@mail.xaut.edu.cn.

DESIGN AND EXPERIMENT OF A NEW TYPE OF ENVIRONMENTALLY FRIENDLY INTELLIGENT ELECTROMAGNETIC PULSE WELDING SYSTEM

Dan Chen, Xuyu Liu, Si Wu

The electromagnetic pulse welding (EMPW) is one of the promising technology, which is the application of pulse power in the dissimilar metal jointing. In order to obtain higher welding effect and more flexible control. A new EMPW system is proposed and simulated in this paper, which is composed of a pulse generator and an intelligent welding platform. The pulse generator includes some discharge module with an energy-saving circuit. This circuit can improve energy efficiency and reduce the system charging time. FPGA is used to control the trigger signal of each discharge module. Based on this function, the discharge current waveform can be changed according to different welding requirements. Different energies are generated by different currents, resulting in different welding effects. The intelligent welding platform is consisting of multi-dimensional mechanical arm, welding coil and the fixed platform. It abandons the traditional method and uses the mechanical arm to process the workpiece. In this way, labor costs can be saved and the system can be intelligent and automatic. Simulation model is built in the PSPICE, the results shows that this EMPF system can work normally, the energy efficiency of discharge module can be increased of about 30% and the discharge current waveform can be controlled by the FPGA. This work provides an important basis for EMPW technology in industrial production applications.

CINCO: A COMPACT HIGH-CURRENT DRIVER FOR HIGH ENERGY DENSITY PHYSICS

Rick Spielman[1], David Reisman[2], Travis Bejines[1]
1. Idaho State University
2. Sandia National Laboratories

Many current high-energy-density physics (HEDP) and material science experiments require a large investment of time and research funds, and often come with a low duty factor. We have developed the Cinco HEDP driver, which is a compact pulsed power generator that can be fired more than four times a day (load limited) and has a footprint of only $2m^2$. Cinco will be capable of providing pressures up to $1Mbar$ on an $8mm$ wide strip-line load, with current-pulse tailoring. Cinco is comprised of sixty bricks connected in parallel with the load. The bricks will be able to be tested individually for performance and reliability prior to installation in the larger structure. Each brick consists of two, 150-nF capacitors (also in parallel), connected in series with a low-inductance multi-channel gas switch. The bricks are then connected to a parallel-plate transmission line, insulated with Mylar, and connected to a small strip-line load for high current densities. Depending on the load construction, a range of peak pressures and pressure profiles can be achieved. When modeled with a $16mm$ long and $8mm$ wide load, and all 60 bricks firing simultaneously, a peak pressure of $1Mbar$ was seen with a rise time of approximately $300ns$. When a flyer plate was used, however, the velocities achieved were comparable to current, two-stage gas guns. Overall, the Cinco meets a need in HED physics for portability, duty factor, cost, and ease of use. Also, with the coupling of x-ray diffraction, we can quantitatively explore material properties under extreme pressures. We will present the design details of the Cinco bricks and the Cinco HEDP driver and preliminary performance data.

OPTIMIZING COMPACT MARX GENERATOR NETWORKS FOR CHARGING CAPACITIVE LOADS: SEQUENTIAL TRIGGERING AND PRACTICAL CONSIDERATIONS

C. Jerald Buchenauer[1], J. Cameron Pouncey[1], Jane Lehr[1]
1. Department of Electrical and Computer Engineering, University of New Mexico

Efficient pulse charging of small high-voltage load capacitors with Marx-generators is limited by the parasitic capacitance within the Marx network. Yet the stray capacitance to ground is essential for proper Marx erection. For successful triggering, this capacitance can not be much smaller than the inter-stage capacitance. In earlier work, Marx-network designs were shown that transfer energy with perfect efficiently [1]. Ideal network-component values are determined by constraints imposed by energy and charge conservation and by network resonant-frequency symmetries. Energy transformation in lossless linear networks between states of purely magnetic and/or purely electrostatically stored energy must exhibit waveforms that are periodic in time [2]. This intrinsically time-domain problem is then recast in the frequency domain where the network resonant frequencies must be arranged with prescribed harmonic relationships. In the final design step, Marx-network resonant-mode frequencies are assigned to be odd harmonics of the fundamental frequency, and simultaneous switch triggering is required.

For regular network solutions, only the zero and third harmonic and fundamental frequencies carry appreciable energy. Thus, other modes may be ignored, and stray capacitances to ground may be set to a common optimal value. When the total parallel parasitic capacitance to ground exceeds the Marx capacitance or approaches the total inter-stage capacitance, ideal solutions are no longer found.

Sequential triggering breaks the harmonic symmetry and invalidates the ideal solutions. The few percent of energy remaining induces high frequency oscillations in the circuit that could lead to early component failure. Correction attempts have had limited success except for mid-stage Marx triggering, which shows significant benefits.

1. C. J. Buchenauer, "Optimizing Compact Marx Generator Networks," IEEE Transactions on Plasma Science: Special Issue – Pulsed Power Science and Technology 2010.

2. C. J. Buchenauer, "Temporal Symmetries in Lossless Linear Networks that Efficiently Transport or Transform Electrical Energy," SDAN 46, October 2015: http://www.ece.unm.edu/summa/

PERFORMANCE ANALYSIS OF A COMPACT PULSE FORMING STAGE AND A MICROSTRIP TYPE BALUN FOR HIGH POWER ELECTROMAGNETICS APPLICATIONS

Ozge Eren Demirgoz[1]
1. Middle East Technical University

High power microwaves can be used in the field of medical, military and civil applications like cancer treatment, destruction of some explosive devices, food preservation etc. This paper presents the design and experiment results of a high power ultra-wide band source. The system mainly consists of a low inductance Marx Generator, Pulse Forming Stage (PFS), a balun and a linear TEM Horn antenna. The power supply is a coaxial Marx generator composed of 16 stages. In this configuration, the rise time of the output signal can be less than 15 ns with an operating voltage reaching values up to 200 kV with an open circuit configuration. This study especially focused on the design of the PFS which includes a spark gap and a peaking capacitor. A compact and coaxial PFS is designed with 50 Ω characteristic impedance and directly connected to the output of the Marx Generator. Then a linear TEM Horn antenna with a customized microstrip balun is integrated to the output of the PFS. Effects of the system inductance to the rise time of the signal is observed. The PFS, balun and the antenna has been simulated together and the spark gap is simulated as a short circuit. Results of CST simulations like S11 parameters across a broad frequency range 200 MHz to 2 GHz of the system and the radiation patterns of the antenna are shown in this paper. A D-dot probe is used to measure the electric displacement value at the different distances from the antenna and the results are compared with the simulations and good agreement is observed. A capacitor voltage divider is also constructed to determine the output signal of the PFS and preliminary tests show that the system can produce pulses which have the rise time under 1 ns.

DESIGN OF MODULAR HIGH-VOLTAGE NANOSECOND PULSE GENERATOR WITH ADJUSTABLE RISE/FALL TIME BASED ON MMC TOPOLOGIES

Yan Mi[1], Hui Wan[1], Lulu Liu[1], Jiaxi Gou[1], Jiacheng Chen[1]
1. Chongqing University

In order to study the influence of the rise/fall time of high-voltage nanosecond pulses on cell killing effect, a high-voltage nanosecond pulse generator with adjustable rise/fall time is needed. A novel generator topology based on half-bridge modular multilevel converter (HB-MMC) is proposed. Several HB-MMC submodules are connected in series as two arms to generate unipolar/bipolar high voltage nanosecond pulses. MOSFETs are used as v solid-state switches. By controlling the switching sequence of the MOSFETs, the rise/fall time of the pulse can be adjusted. In this paper, the proposed topology as well as its operating principle are introduced in detail and verified by PSpice simulation software. A 5-stage generator is implemented and tested. The test results show that the generator can output nanosecond pulses with adjustable amplitude of $0\sim\pm4$ kV, pulse width of $100\sim500$ ns and frequency of $0\sim5$ kHz. The rise time of the pulse can be smoothly adjusted in the range of 15-65 ns, and the fall time of the pulse can be smoothly adjusted in the range of 30-100 ns.

THE OPTIMIZATION OF HIGH VOLTAGE NANOSECOND PULSE GENERATOR WITH AUXILIARY TRIGGER CIRCUIT

Saikang Shen, Jiaqi Yan[1], Yanan Wang[1], Lanxi Li[1], Kaisheng Mei, Weidong Ding[1]
1. Xi'an Jiaotong University

High voltage nanosecond pulse generator has numerous applications on industry, such as triggering the Pockels cell, triggering the spark switch, and generating the discharge plasma. All of these applications require the generators have high amplitude, great stability, fast rise time and low jitter. In this case, solid-state switches have great advantages comparing with gas spark switches. Because of the merits of extremely fast switch speed (over 100 V/ns), tiny size, low jitter, long lifetime, and commercial availability, the avalanche transistors have been widely used to generate the nanosecond and sub-nanosecond pulses. In order to obtain the high voltage output, a Marx-type pulse generator was developed. And there are several avalanche transistors in series at each stage of the Marx circuit. However, the failure rate of transistors was very high in our Previous experiments.

In this paper, we attribute the failure to the short circuit of the emitter and base at each avalanche transistors except for the first one at the first stage. Therefore, a kind of auxiliary trigger circuit is designed and can be used in every stage of the 4×10-stage Marx circuit. This special topology is aimed to provide triggering pulse to each transistor. Therefore, the conduction mode of avalanche transistors will be changed from "over-voltage mode" to "trigger mode". The result shows that the failure rate is significantly reduced. And then, the effect of the auxiliary trigger circuit on the output pulse is studied carefully. The testing result indicates that with the increase of improved stage number, the amplitude of output voltage increases first and then decreases. Finally, improve five stages for 4×10-stage Marx circuit with the output parameters: amplitude of 9.04kV, rise time of 4ns, full width at half maximum of 17ns, and repetition rate of 2 kHz.

CHARACTERIZATION OF COMPACT SHORT PULSE POWER SUPPLY FOR NON-THERMAL PLASMA DISCHARGE APPLICATIONS

Ajeet Dhakar[1], S. K. Rai[2], V. K. Saini[3], S. K. Sharma[4], Udit Narayan Pal[5]

1. CSIR- Central Electronics Engineering Research Institute, Pilani Raj 333031 India
2. B.K. Birla Institute of Engineering & Technology, Pilani-333031, Raj. India
3. CSIR- Central Electronics Engineering Research Institute (CEERI),Pilani, Rajasthan-333031, India
4. Energetic & Electromagnetic Division, Bhabha Atomic Research Center, Visakhapatnam-530012, A.P, India
5. CSIR-Central Electronics Engineering Research Institute, Pilani, India

There is resurgent of interest in the development of high voltage, short pulse, fast rise time and high frequency modulators for the generation of uniform and diffuse plasma in the dielectric barrier discharge (DBD) based non-thermal plasma (NTP) sources useful for potential biological, medical, surface modification, food, agriculture, sterilization, etc. [1-2]. The DBD based non-thermal plasma sources are effectively a capacitive load where breakdown occurs in the gas gap. It has been found that a high voltage, high frequency and short pulse power modulator (SPPM) is required to generate the efficient plasma for DBD devices. In this paper, an effort has been made to design and develop a high frequency, high voltage SPPM. The development excludes primary side RCD clamping circuits while it has been incorporated in secondary side to discharge the stored capacitive energy. This eliminates the sinusoidal oscillations caused by interaction between NTP load capacitance and leakage inductance of the transformer. This makes the HV-SPPM more compact, simple and light-weight for efficient plasma generation. The designed SPPM is capable of generating voltage 10 kV (max), frequency 50 kHz, pulse duration $<1\mu$s. The paper has also discussed the design and characterization issues of the SPPM and its utilization for the generation of NTP at different operating and geometrical conditions.

[1] S. K. Rai, A. K. Dhakar and U. N. Pal, 'A Compact Nanosecond Pulse Generator for DBD Tube Characterization', Rev. Sci. Instrum. 89, 033505, 2018.

[2] N. N. Misra, O. Schluter and P. J. Cullen, 'Cold Plasma in Food and Agriculture-Fundamental and Applications', Academic Press, Elsevier, U.K., 2016.

NEW DESIGN FOR COMPACT HIGH VOLTAGE POWER SUPPLY FOR PULSED POWER APPLICATIONS

Howard Sanders[1]
1. Sanders Pulsed Power LLC

A typical, high-efficiency, capacitor-charging power supply uses a bridge for the inverter section. These circuit designs allow for very efficient zero-voltage switching (ZVS) when properly aligned with the resonant frequency set by the inductance and capacitance of the circuit. Unfortunately, these circuit designs are susceptible to inverter failures and they have complicated requirements for the switch control timing to match changes in resonant frequency. This paper will describe a new design for the inverter stage that achieves high efficiency with ZVS but does not need to operate at a specific control timing related to the resonant frequency of the circuit. Integrated with the compact design are the components needed for safe operation with typical pulsed power applications such as a high voltage discharge relay. Details of the topology, simulations and data will be presented.

ULTRA-HIGH VOLTAGE NANODIELECTRCAPACITOR DEVELOPMENT, AND TESTING FOR COMPACT PULSED POWER*

Randy Curry[1], Luke Brown[2], Sarah Mounter[2], Samuel Dickerson[1], J. Thomas Camp[3], Aaron Maddy[2]

1. University of Missouri

2. University of Missouri, Center for Physical and Power Electronics

3. Naval Surface Warfare Center, Dahlgren Division

The Center for Physical and Power Electronics has developed a nanodielectric material (MU100) to reduce the size of ultra-high voltage (UHV) pulsed power capacitors. In the discharge regime of interest the dielectric constant of the material is 200. The UHV dielectric, 3.4 cm diameter, 2 cm thick substrates with voltage ratings on the order of 260 kV, were assembled into a series stack of 4 each using a eutectic solder. Nine of these encapsulated capacitors were paralleled in a modular 130 pF capacitor assembly, and physically tested for operational capability. Results of the development and testing demonstrated two full-scale devices capable of withstanding over 1E04, 500 kV pulses with 55% voltage reversal, showing no signs of degradation; exceeding all pre-specified performance specifications. The test capacitor was part of a peaking circuit placed at the output of a 15 stage compact Marx bank to achieve the voltage amplitudes and reversals to meet the performance specifications. The capacitor was subjected to 2-second bursts of 100 Hz repetition rate pulses with 10 seconds between bursts, which was required for the thermal management of the Marx bank. The submodules demonstrated a thermal rise of less than three degrees centigrade during continuous operation.

Further testing of the capacitor sub-modules, demonstrated reliable performance under pulses of greater than 1 MV at a lifetime of 1E03 pulses. The smaller capacitance of the submodules allowed for voltage doubling across the test capacitor when connected to the 15 stage Marx bank through a charging inductor. The capacitor submodule was subjected to 2-second bursts of 100 Hz repetition rate pulses with 6 seconds between bursts. The results of the ultra-high voltage capacitor tests are discussed as well as the impact of the technology for compact pulsed power applications.

*Work supported by the JNLWD under contract number W15QKN-14-9-1001

HARD X-RAY AND PROTON RADIOGRAPHY OF UNDERWATER ELECTRICAL WIRE EXPLOSION

Alexander Müller-Münster[1], Marcus Iberler[2], Joachim Jacoby[1], Paul Neumayer[3], Dmitry Varentsov[3]

1. Goethe University Frankfurt
2. Goethe Universität Frankfurt
3. GSI Darmstadt

By the use of Underwater Electrical Wire Explosion (UEWE) one can create and study warm dense matter (WDM) in laboratory. With a moderate pulsed power generator (10μF@40kV, cylindrical strip line, thyratron as switch) it is possible to create dense strongly coupled plasmas with 10-100 kJ/g specific energy, near-solid density and 1-2 eV temperature. Due to the high electric breakdown threshold of water ($>$300 kV/cm) and relatively small wire expansion velocity ($\sim$ 1km/s) there's no parasitic plasma formation along the wire surface. This makes UEWE an efficient method to study the fundamental properties of metals in extreme states.

One of the main challenges is the determination of plasma parameters and especially the temporally and spatially resolved measurements of the target density. For the radiography of an opaque exploding wire in water one needs high energy x-rays or charged particles, which are able to penetrate the surrounding water and the windows of the target chamber too. Hence soft (few keV) x-rays, which are often used for radiography of thin tungsten wires exploding in vacuum are not suitable for UEWE experiments. This is the reason why the majority of all the EOS and conductivity data obtained in the numerous UEWE experiments during the past four decades rely on the assumption of the radial uniformity of the density distribution during the whole course of wire explosion. In most UEWE experiments only the evolution of the wire radius is measured by optical means. Therefore the question of uniformity of liquid metal in near critical state, formed by rapid ohmic heating in water bath still remain open [1,2,3].

References:

[1] A.W. DeSilva and J.D. Katsouros, Phys. Rev. E 57 (1998) 5945.

[2] Y.E. Krasik et al., IEEE Trans. Plasma Sci. 44 (2016) 412.

[3] T.A. Shelkovenko et al., Plasma Phys. Rep. 42 (2016) 226.

ALL-SOLID-STATE BIPOLAR HIGH VOLTAGE NANOSECOND PULSE ADDER WITH OUTPUT PARAMETERS ADJUSTABLE

Yonggang Wang[1], Yifan Huang[1], Min Jiang[1]
1. Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences

Nanosecond high voltage pulse generators are widely used in dielectric barrier discharges, plasma jets, corona discharges in water, et al. In this paper, a novel bipolar pulse adder with output parameters adjustable is proposed. Several full bridge MOSFET units are connected in series. And the storage capacitors in each units is charged isolated by a high-frequency resonant power supply. In order to solve voltage unbalance between storage capacitors, a third winding is added to each magnetic core transformer. The mechanism of eliminating voltage difference by third windings is analyzed in theory, and validated by simulation and experiments. Optic fibers, together with gate drivers, are used to drive MOSFETs. Thus, each switch can be turned on or off independently and the rising/falling time of each pulse is adjustable. A 6-stage prototype is implemented in laboratory. The pulse adder can generate 5 kV bipolar pulses with voltage polarity, amplitude, repetition rate, pulse width, and rising/falling time adjustable independently. The experimental results are shown in this paper and discussed at last.

COMPACT, MOBILE, AUTOMATED PULSER DESIGNED FOR EASE OF USE

Wayne Cox[1], Stephen Bayne[2]
1. Texas Tech University
2. Center for Pulsed Power and Power Electronics, Department of Electrical and Computer Engineering, Texas Tech University

A 4 kV/4 kA compact Pulse Forming Network (PFN) system is designed that incorporates a ten stage Rayleigh PFN in five configurable blocks to control the pulse length in increments of 25 μs up to a maximum of 125 μs for a peak energy delivery of 1.5 kJ. Prior to CNC machining and implementation into a mobile package ,with dimensions of 96.5X81X79 cm, the system was fully CAD modeled and as designed provides an energy density of 2.5 kJ/m3 and significant ruggedness for transportation between facilities. A Spartan 3-AN based control system is implemented into the mobile platform to minimize end user interaction while also allowing for remote management and automated application using a UART transport layer. This results in a PFN that requires very little setup on site and scant technical knowledge to run without sacrificing any capabilities or inherent safety. In addition, the platform has been designed to reduce the radiated Electro-Magnetic Interference by incorporating 430 stainless mesh and a double shielded coax load connection method.

INDIGENOUSLY DEVELOPED PULSED POWER SOURCES FOR NONEQUILIBRIUM PLASMA APPLICATIONS

Suryakant Gupta[1], Keena Kalaria[1], Naresh Vaghela[1]
1. Institute for plasma research

Nonequilibrium plasma techniques offer an innovative approach to the cost effective solution of various preeminent environmental problems lacing the world today such as acid rain, global warming, ozone depletion, and smog etc. In the developing world, polluting and less efficient conventional equipment need to be upgraded with eco-friendly and energy efficient technologies. Plasma based technologies have proved their significance as an eco-friendly and energy efficient solution in various areas including surface engineering (metallic and non-metallic), water, food and medical engineering etc. In developed countries, plasma based systems have started taking a lead role in the surface coating industries. In plasma equipment, mostly RF or DC power sources are used as an energy source. RF power sources have certain limitations such as high capital and maintenance cost. Similarly DC power source have poor control on process parameters. Therefore due to above mentioned inherent limitation of RF and DC power sources, existing user hesitate to replace polluting equipment with costly plasma based system. In order to increase the penetration of plasma based systems among developing nations, pulsed power sources gives a hope that can overcome the limitations of RF and DC based plasma sources. At institute for plasma research Gandhinagar India, several pulsed power based equipment have been developed and commissioned at various locations in India for Nonequilibrium plasma applications. This includes plasma nitriding, plasma source ion implantation, physical vapor deposition (PVD), and high-power pulsed magnetron sputtering (HPPMS). The results of above mentioned indigenously developed system confirm that pulsed power sources are better alternate over conventional RF and DC power sources. These indigenously developed power sources are economical, compact and capable to provide better control on process parameters as well. In this paper, technical experience gained during the development of pulsed power sources for various Nonequilibrium industrial plasma system will be presented.

DESIGN OF A COMPACT MAGNETICALLY SWITCHED 200-KV, 4-KA, PULSE FORMING LINE MARX GENERATOR

James Schrock[1], Susan Heidger[2], Brad Hoff, Jerald Parker[3], Joshua Gilbrech[4], ROBERT RICHTER-SAND[4], Paul LePell[5]

1. AFRL

2. U.S. Air Force Research Laboratory

3. Leidos, Inc.

4. Leidos

5. Leidos Inc

A magnetically-switched Marx generator is being developed by the Air Force Research Laboratory as an engineering exercise to evaluate methods of improving the reliability of compact, high repetition-rate, pulsed power generators. This paper provides an overview of the design and simulation of a 200 kV, 4 kA Marx generator utilizing magnetic switches for Marx erection as an alternative to the spark gaps traditionally implemented for this power regime. The Marx generator is designed with ten 8.5 ns, 5 Ω, Mylar stripline transmission line stages wrapped around low saturation inductance Metglas switches. The size and weight of the magnetic switches are minimized by a fast resonant charge of the transmission lines. The fast charge is achieved by leveraging a single in-house built thyristor module and a coupled charging inductor methodology. Results presented include the design of the magnetic switches, the common mode choke cores for the coupled charging inductors, the Mylar transmission lines, Spice modeling of the overall system, and the generator assembly concept drawings. This Marx generator will inform the SWaP trade space of high repetition-rate pulsed power technologies.

REPETITIVE TRIBOLUMINESCENCE X-RAY SOURCE BY PEELING TAPES

Seizo Furuya[1]
1. Saitama Institute of Technology

Triboluminescence is a luminous phenomenon resulted from friction; for example, peeling scotch tape, breaking rock sugar with a hammer, peeling mica and so on. Triboluminescence is well known over 50 years but in 2008 UCLA group reported the radiation of x-ray region by triboluminescence in vacuum for the first time(1). UCLA group made an automatic machine which peels scotch tape. With a view to practical application of triboluminescence to roentgen diagnosis we made an automatic peeling machine similar to that of UCLA group. An x-ray tube for conventional roentgen diagnosis needs a high voltage power supply. In contrast, triboluminescence does not need it. So it is very useful for roentgen diagnosis to replace a conventional x-ray tube with triboluminescence. Thus far, we have attempted to confirm the x-ray generation from triboluminescence using a filtered phosphor screen when the parameters such as the followings are changed; peeling speed, atmospheric pressure, variety of scotch tape, emission angle etc. Then in a similar way we have also attempted to measure x-ray dose from triboluminescence using a potable dosemeter. It was found that the x-ray generation has a directional property. Because the method to peel scotch tapes does not enable to operate continuously, we have made a novel machine enabling continuous operation by peeling tapes. In this conference, we have reported a new-type triboluminescence equipment and showed its characteristics when the following conditions are changed; varieties of tapes, operating velocity, radiation direction, pressure and so on.

(1) Correlation between nanosecond X-ray flashes and stick-slip friction in peeling tape: C.G.Camara, J.V.Escobar, J.R.Hird and S.J.Putterman, nature Vol.455 (23 Oct 2008) pp.1089-1092

PULSED POWER DISCHARGE UNDER A HIGHLY CAPACITIVE LOAD

James Allen[1], Marcus Ashford[2], Jennifer Zirnheld[3], Kevin Burke[3]
1. Primary Contributor
2. Secondary Contributor
3. Faculty Advisor

This paper outlines the design and tradeoffs of a compact custom capacitive charging and discharging circuit. The system has a maximum charging voltage of 10 kV at 2 mA and utilizes an external capacitor both of which can be chosen by the user. To maintain the user's set voltage a micro-controller (MCU) in conjunction with feedback from voltage monitoring is used to make real-time voltage adjustments until the user triggers the discharge. The discharge sequence is initiated by the user via a tethered switch that isolates the user from the high voltage components and has an option to abort the discharge by bleeding the capacitor through an internal resistor. The discharge circuit is capable of handling current surges up to 5 kA and voltage spikes up to 15 kV. The design metrics are discussed, and experimental results are presented.

SUSTAINING HIGH POWER RF SIGNAL GENERATION IN A POSITIVE FEEDBACK NETWORK

A N M Wasekul Azad[1], Faisal Khan[1]
1. University of Missouri-Kansas City

RF signal continuity from a nonlinear transmission line (NLTL) requires continuous supply of input signal, which may not be feasible in all practical applications. We have constructed a closed-loop setup that can sustainably generate RF signals from the NLTL using a single input pulse for a significant amount of time. An LDMOS based 1.5 kW (continuous) rated power amplifier, RF transformers used at the matching networks of the amplifier, 1200 V rated reverse biased Schottky diode based 16-section NLTL, and a pulse generator circuit designed in half-bridge configuration construct our closed-loop setup. The pulse generator can produce 150 ns pulses at full width at half maximum (FWHM) with rise and fall times less than 10 ns. In our test setup, the amplifier is excited by the output of the NLTL, and the amplifier signal is connected back to the input of the NLTL. The biggest strength of our design is the flexibility to change the NLTL length to change the frequency and the amplitude of the output signal. We have generated a continuous sequence of RF pulses with a voltage modulation depth (VMD) of 64 V and pulse width of about 4.5 ns at FWHM from a single 250 mV input pulse. The RF pulses generated in the NLTL circulate in the closed loop and sustain for a significant amount of time. Incorporating the in-house pulse generator in the closed loop setup, we have generated sustaining RF pulses with VMD close to 170 V, pulse width and rise time close to 6 ns at FWHM and 2 ns respectively from a single input pulse. This corresponds to a peak pulsed RF signal power of 2.17 kW across a 50-Ω resistive load.

This work was supported by the Office of Naval Research under award no. N00014-17-1-3016.

TRIGGERED GAS SWITCHES FOR USE IN CAPACITOR-SWITCH ASSEMBLIES FOR LTD TECHNOLOGY

Ivan Lavrinovich[1], Denis Molchanov[2], D. Rybka[3], Semen Vagaytsev[4], Aleksander Erfort[4], Anton Artemov[4], Aleksander Lensky[4], Alexander Zhigalin[5]

1. HCEI SB RAS

2. IHCE SB RAS

3. Institute of High Current Electronics SB RAS, Tomsk, Russia

4. Institute of High Current Electronics

5. Institute of High Current Electronics SB RAS

Currently, active development of the element base for high-current generators is underway. The previously proposed and implemented new type Capacitor-Switch Assembly - HCEIcsa 160-0.1 required the development of new triggered gas switch. The design of the electrodes determines the largest possible operating voltage, the required pressure and jitter of the CSA, which ultimately affects the output parameters of the whole Ltd generator.

The report shows the test results of our new switches for such type of CSA. The design and calculations of electric fields are presented, experimental data on the dependence of the switching characteristics on the pressure in the spark gap and the parameters of the discharge circuit are given.

The work was supported by the Russian Science Foundation (project No. 17-79-20292)

CONCEPT DESIGNS OF A COMPACT LTD GENERATOR WITH A PULSE RISE TIME OF 100 NS.

Ivan Lavrinovich[1], Denis Molchanov[2], D. Rybka[3], Semen Vagaytsev[4], Aleksander Erfort[4], Anton Artemov[4], Aleksander Lensky[4], Alexander Zhigalin[5]

1. HCEI SB RAS

2. IHCE SB RAS

3. Institute of High Current Electronics SB RAS, Tomsk, Russia

4. Institute of High Current Electronics

5. Institute of High Current Electronics SB RAS

The paper presents the structure of the LTD generator on the basis of HCEIcsa 160-0.1 with an output current level of about 1 megamper and a rise time of 100 ns. We have considered various design options and carried out a numerical simulation of the LTD cavity operation. The dependences of the output pulse parameters for different arrangement are obtained. The possibilities for creating a LTD generator with a petawatt output power are discussed.

The work was supported by the Russian Science Foundation (project No. 17-79-20292)

IMPROVEMENT OF THE SWITCHES RELIABILITY ON THE CEA 1MV LTD

Arnaud LOYEN[1], Stéphane LACOSTE[1], Francis LASSALLE[1], Bernard ROQUES[1], Frederic ZUCCHINI[1], Sandra RITTER[1], Martial TOURY[1]
1. CEA

The CEA 1MV Linear Transformer Driver (LTD) has been operated since 2010 for flash X-ray radiography studies. This generator is composed of 10 cavities; each cavity includes 16 bricks representing two capacitors (GA 35436, 100kV, 8nF) and one multi-gaps air pressurized switch. The switches consist of a stack of annular electrodes inside an insulating body of polyamide. The postential distribution is carried out by corona effect using needles. The feedback of experience on the reliability of this concept after more than 4000 shots shows an aging of spark gaps inducing self-breakdowns before the end of the voltage charging of the cavities. We present here the different observations made during the maintenance operations of the switches and method used to qualify them after these operations. We propose also a solution to improve the reliability of these spark gaps from an analysis on the distribution between the corona and the current in the spark gap body.

LINEAR TRANSFORMER DRIVER FOR HEDP EXPERIMENTS AT UC SAN DIEGO

Nicholas Aybar[1], Fabio Conti[1], Julio Valenzuela, Jeffrey Narkis[1], Vladimir Fadeev[1], Alejandro Baez[1], Reisman David, Farhat Beg[1]
1. UC San Diego

Linear Transformer Drivers (LTDs) are a valuable class of pulsed power generators capable of efficient energy coupling to experimental loads and high repetition rate in a compact footprint when compared to conventional Marx bank-based systems. Presented here are results of operation of an 800 kA, 150 ns LTD at UC San Diego. These engineering tests results include current and voltage waveforms for a series of short-circuit and matched-load shots are compared with SPICE simulations and Initial experiments performed using wire-array z-pinch loads. The wire-array z-pinch experiments include multi-frame laser interferometry, x-ray spectroscopy and time-gated visible spectroscopy, XUV and optical gated imaging, and time-resolved x-ray emission measurements via filtered photodiodes

PULSE POWER SYSTEM

Peter Stone

Peter Stone (aka Peter V. Vassioukevitch)

Free-Lance Researcher, USA

Abstract

This Article is a continuation of the research of Pulse Power Systems [1], [2]. Current features as well as complications of Electromagnetic Launchers (EL) of projectile are well known. The low efficiency of EL prompted the research for a fundamentally new type of devices, as well as a new type of electromagnetic energy sources. This Article is considering a new type of EL combined with modified Bitter Magnet and High-Frequency Pulse energy generator as a power source for sections of EL. Devices are protected by international applications for inventions. The absence of galvanic contact between the accelerated projectile and the EL barrel resolving the issue of friction and the heating. Also Sectional design of the EL resolving the issue of useless accumulation of electromagnetic energy in the barrel. Using modified Bitter Magnet in EL sections allows to create magnetic fields tens of times higher density than in a well known EL, which increases the electromagnetic pressure by hundreds of times to accelerate the projectile. This Article illustrates EL in greater details along with test results of the EL prototype.

[1] P.V. Vassioukevitch "Iron-Core Compulsator", Proc. of 9th IEEE Pulsed Power Conference, Albuquerque, New Mexico USA, June 21-23, 1993, Paper 224-227.

[2] P.V. Vassioukevitch "Segmented Electromagnetic Launcher", Proc. of 10th IEEE Pulsed Power Conference, Albuquerque, New Mexico USA, July 10-13, 1995, Paper 1273-1277.

DESIGN OF A PULSED ALTERNATOR TO DRIVE A SINGLE STAGE INDUCTION COILGUN

Apurva Kulkarni[1], M. Joy Thomas[1], Ashish Sharma[1], Ranashree Ram[2]
1. Indian Institute of Science
2. IISc Bangalore

An induction coilgun launcher is being designed and developed in the author's laboratory to propel a solid aluminium projectile of 20 g. Pulsed alternators have several advantages over capacitor banks such as higher energy density, occurrence of natural current zero in the wave form and non-requirement of any external pulsed conditioning/ crowbarring circuit.

A single phase, iron core, slotted stator, cylindrical rotor, no-compensation topology of the pulsed alternator has been selected for this application. The maximum peripheral speed, the magnetic loading, i.e. flux densities in the stator and rotor iron parts and the electric loading, i.e. the temperature rise of the alternator windings as well as the coils of the coilgun have been selected as the main criterion for the study. The pulsed alternator has been modeled as armature, field and one damper circuit on each of the d and q axis magnetically coupled with each other. The damper circuits are modeled as per the transient eddy currents induced in the rotor teeth. The inductance and the resistance of the damper circuit are formulated by considering it as a winding with one turn per pole pair and having a cross sectional area equal to the width of the teeth multiplied by the skin depth of the induced currents.

A number of designs have been simulated and their performances have been analyzed for various design variables of the pulsed alternator. Projectile velocity, peak current and the temperature rise of the coil per shot (to understand the behavior under multi-shot operation) have been selected as the output variables. Similar analysis has also been done for different initial position of the projectile which gives some idea about the sensitivity of the multistage configuration.

On the basis of this analysis, final design of the pulsed alternator has been selected for the further work.

DECELERATION AFTER ACCELERATION OF ARMATURE THAT PASSES THROUGH STATOR COIL DURING COIL GUN INJECTION

Yongkyu Lee, Huimin Kim, Myunggeun Song

Research and development of coil gun business for cold launch system recently

In order to inject 100 kg projectile at a speed of 20 m/s or more, we developed a 4 stage multi-stage induction type coil gun system.

And the injection results satisfying the target performance were obtained.

In the future, if the coil gun is used in the weapon system, it is expected to be used to make a launching platform and a launching tube which are more usable.

In this paper, we describe the deceleration phenomenon that occurs while passing an armature coil stator coil while performing an experiment.

Experiments were carried out to measure the armature speed with sensors and the results were compared with the launch vehicle.

As a result, the armature coils that move as they start to move are passed through the center of the stator coil

The acting force acts in reverse and the armature decelerates without a continuous acceleration.

Refer to the contents of this document to design the induction coil gun. In order to achieve the target performance, the deceleration of the armature must be considered.

EXPERIMENTS AND ANALYSIS OF DOWN-SLOPE LOW-VOLTAGE TRANSITION IN C-TYPE SOLID ARMATURE RAILGUN

Lixue Chen

It is undesirable that arcing contact between armature and rail throughout launch in solid armature railgun, because transition is associated with severe damage to both armature and rail interface. Current down-slope (-di/dt) transition is one of the most significant transition mechanisms for C-type solid armatures. Most railgun experiments were shown that transition to high voltage contact after the driving current starts to decrease from its peak value. A statistical examination of existing data revealed that such contact transitions occur at approximately 80% of peak current during down-slope.

In this paper, three types of armatures with different tail structure were launched in a 20mm*30mm rectangular caliber railgun. Low-voltage transitions occur at approximately 90% of peak current during down-slope. Then, considering velocity skin effect (VSE) in liquid film and magnetic diffusion processes in armature, a simplified one-dimensional electromagnetic model was used to illustrate –di/dt effect. It can be shown that the origin of –di/dt low-voltage transition may be mainly attributed to destabilization of liquid film at the armature-rail interface which is maintained by electromagnetic pressure. Electromagnetic force by negative net current in armature's tail is not the main cause of transition, because reversal Lorentz force by circulating current is not strong enough to lift off tail from rail.

UTILIZATION AND OPTIMIZATION OF SUPERCONDUCTING COIL PARAMETERS IN ELECTROMAGNETIC LAUNCHER SYSTEMS

Hakan Polat[1], Doğa Ceylan[2], Ozan Keysan[2]
1. Middle East Technical University/ Electrical and Electronics En
2. Middle East Technical University

Electromagnetic launchers are electrical machines which converts electrical energy to mechanical energy using pulse power supplies (PPS). Magnitude of currents are usually in the order of hundreds of kilo-amperes and their efficiencies are below 30%. High current generates heat which is one of the limiting factor of the whole system. Utilization of external coils placed on top and bottom of rails increases the Lorentz force on the armature which increases the efficiency. However, high B field limits the current capability of conventional copper wires. Superconductivity is achieved under the critical temperature of the materials which is usually below 10 K. However, with recent developments there exists high temperature superconductors (HTS) which can keep its superconducting properties in higher temperatures around 70K and only under DC currents. HTS wires have high current carrying capability around 100 $A/(mm)^2$ at self field at $77K$. B field and maximum current carrying capability of the HTS wire is inversely proportional. In order to maximize the electromagnetic force in the shot direction ,a real coded genetic algorithm (RCGA) is used. Optimization parameters are coil current, coil position, number of turns of the coil and number of layers of the coil. 2D finite element (FE) model is developed to calculate the objective function. The 2D FE model has $25mm$ x 25 mm square bore and the rails are 3 m long and has 1 MJ PPS. Moreover the developed optimization algorithm is repeated for different rail currents to observe the feasibility of the HTS with different energy levels for coil reinforced electromagnetic launcher system.

VELOCITY IN-BORE TEST COMPARISON BASED ON MAGNETIC PROBE AND OPTICAL PROBE IN ELECTROMAGNETIC LAUNCH

Wang Zhenchun, Yuting Zhang[1], Bao Zhiyong, Dong Zonghao
1. Yanshan University

The armature velocity distribution in the bore of launcher is an important reference indicator for characterizing electromagnetic launch performance. At present, the velocity of the armature is mainly measured by magnetic probe, and there are some problems such as error and serious electromagnetic interference. In this paper, the principle of magnetic probe velocity measurement is analyzed. It is found that the size and installation position of the magnetic probe, the current distribution in the rail and armature, the current skin texture of the high-speed motion of the armature and electromagnetic interference are the main factors affecting the accuracy of magnetic probe. The optical probe speed measurement is based on the optical armature in-bore velocity measuring device, which uses optical signals for transmission and reception, and avoids the influence of electromagnetic interference on the speed measurement. This paper uses simulation software to simulate the speeds, which obtained by the two methods of magnetic probe and optical probe, and fits the velocity and displacement curves. The obtained curve was calculated and analyzed by the error analysis method. The results show that the two methods of velocity measurement are in good agreement, and through the analysis of two speed measurement errors, provides a basis method for improving the speed measurement method and reducing the measurement error.

DESIGN AND ANALYSIS OF THE ELECTROMAGNETIC INTERCEPTOR FOR THE ANTI-UNMANNED AERIAL VEHICLE

Chunyan Liang[1], Hongjun Xiang[2], Xichao Yuan, Qing-ao Lv[2]
1. Army Engineering University
2. Shijiazhuang Mechanical Engineering College

The unmanned aerial vehicle (UAV) is widely used in different areas at present. However, the phenomena of UAV abuse is becoming more serious, which is a great threaten to the military, personal privacy, economic, public security and etc. Thus, the technologies of anti UAV are developed by many countries. Aiming to the defect of the traditional method for anti UAV, the method based on electromagnetic launching and catching net projectile is put forward in this paper. The working principle and the structure of the electromagnetic interceptor for the anti UAV is introduced. The numerical simulation model of the electromagnetic interceptor is built based on finite elements soft, and then the effect of different parameters to the performance of the electromagnetic interceptor is analyzed. It can be seen from the analysis that the catching net projectile can be launched by the electromagnetic interceptor, and the optimal parameters of the electromagnetic interceptor have been obtained.

DESIGN OF A VEHICULAR 200-KJ PULSED POWER SYSTEM FOR ELECTROTHERMAL-CHEMICAL LAUNCH EXPERIMENT

LIN XU, JUN ZHANG, HAO WANG, JIANNIAN DONG, HAO SUN

This paper has designed and established a vehicular 200-KJ pulsed power system (PPS) for Electrothermal-Chemical Launch (ETC). The PPS consists of pulsed power module, high power charger, remote control system and high power connector. Two independent 100KJ pulse forming units (PFUS) are integrated in a pulse power module. Each PFU can be controlled independently by remote computer to meet the needs of pulse waveform modulation. In each PFU, a pulse capacitor, a semiconductor switch stack, an inductor, a dump system, and a data acquisition system were integrated. The PFU was designed to be triggered for a maximum charging voltage of 10KV and the peak current up to 40KA. The high power charger was integrated into the PPS to reduce the volume of the system and improves the compactness. At the same time, the layout of each component was optimized to reduce the influence of EMI and electromagnetic force. The performance of PPS was verified through some ETC experiments. The experimental current curve showed good agreement with circuit simulation data. The design methods and results in this paper have both theoretical and pragmatic value in improving the performance of PPS for ETC system.

THE DEVELOPMENT OF CAPACITIVE NONLINEAR TRANSMISSION LINES AND THEIR PERFORMANCE LIMITS

Elizete Gonçalves Lopes Rangel[1], Jose Rossi[2], Joaquim Jose Barroso[3], Fernanda Sayuri Yamasaki[2], Leandro Carvalho Silva[1], Lucas Reis Raimundi[2], Lauro Silva Neto[4], Edl Schamiloglu[5]

1. INPE

2. National Institute for Space Research

3. Aeronautics Institute of Technology

4. Federal University of São Paulo

5. University of New Mexico

The generation of radiofrequency through Nonlinear Transmission Lines (NLTLs) have been investigated as an alternative way to build RF generators for application in telecommunication, medical and defensive electronic countermeasures systems. Two main configurations of NLTLs were reported in the literature: discrete lines that comprise a network of LC sections built with nonlinear components and the gyromagnetic line that consists of a coaxial transmission line loaded with ferrite-based magnetic cores. Gyromagnetic lines produce high voltage microwave oscillations with frequency ranging from few hundred of MHz up to less than 10 GHz requiring, however, an external magnetic polarization. On the other hand, discrete lines are suitable for RF generation in a lower frequency range from a few MHz to hundreds MHz, having a better prospect for use in compact systems. Capacitive NLTLs require the use of components that present voltage dependence behavior of the capacitance as ceramic capacitors or special diodes. While lines built with ceramics capacitors show a maximum operating frequency around tens of MHz requiring high input voltage, the use of silicon varactors diodes allows the construction of low voltage lines, nevertheless by using carbide silicon Schottky diodes the output of a capacitive NLTL can provide a few kV of oscillation peaks. This paper presents some experimental results that show the development of the capacitive NLTLs at the Plasma Laboratory (LABAP) of the National Institute for Space Research (INPE) in Brazil. The analysis of the experimental results points that performance limits of capacitive NLTLs are closely related to the characteristics of the nonlinear component used in their construction and leads to the conclusion that an improvement of their performance requires the development of new nonlinear components, which present simultaneously nonlinear capacitance to voltage behavior, low losses and thermal stability.

*Work supported by SOARD/AFOSR under contract no. FA9550-18-1-0111.

DYNAMICS OF MELTING SOLENOIDS FOR LASER EXPERIMENTS ON THE NATIONAL IGNITION FACILITY

Phil Arnold[1], Evan Carroll[1], Steve Hawkins[1], Glen James[1], Brad Pollock[1], Mark Rhodes[1], Jay Javedani[1], John Moody[1], Anthony Johnson, Bruno Le Galloudec[1]
1. Lawrence Livermore National Laboratory

A new pulse power system has been developed to investigate the use of ”exploding” solenoids for

establishing large magnetic fields for laser-driven inertial confinement fusion experiments. A 40 kV, 4 μF capacitor, switched by spark-gap drives up to 30 kA in small solenoids inside a vacuum chamber, establishing peak axial magnetic field strengths of 30 T in approximately a 1 cm^3 volume. The solenoids are specifically designed to reach melt temperature just after the peak magnetic field has been established allowing the solenoids to rapidly disassemble into fine debris, thus mitigating potential risk for optics damage. Diagnostics used for the experiments include a 10 MHz video camera, current and voltage probes, high-density B-dot probes (magnetic field probes), two-color pyrometry and an Aerogel debris catcher. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

DEVELOPMENT OF AN RF CIRCUIT AMPLIFIER FED BY A LOW POWER NONLINEAR TRANSMISSION LINE

Lauro Paulo Silva Neto[1], Henrique Monteiro Moraes [1], Jose Rossi[2], Joaquim Barroso [3], Elizete Rangel[4], Arlindo Conceição [1]
1. Federal University of São Paulo
2. National Institute for Space Research
3. Technological Insitute of Aeronautics
4. National Institute for Space Research Brazil

The lumped nonlinear transmission lines have been studied for the radiofrequency signals generation in the range of the order of tens of MHz up to a few hundreds of MHz depending on the nonlinear element used to build the LC line. The oscillations obtained at the output of these lines are applied in defense mobile platforms and communications systems. Low power nonlinear transmission lines use varactor diodes as nonlinear elements, which show a good nonlinear effect with capacitance variation of the order of 90% at their P-N junction with the applied voltage, which is an excellent performance to obtain oscillations at the line output. However, these semiconductor devices operate at low voltage, producing small voltage modulation depth, low power, and consequently reduced signal range. Looking for increasing the voltage modulation depth of the signal generated with nonlinear transmission lines, this work developed a radiofrequency amplifier using a Metal Oxide Semiconductor Field Effect Transistor – MOSFET model RD06HVF1. A 30-section line using varactor diodes MV209 as nonlinear elements can work as an RF source to obtain oscillations with 40 MHz of frequency at the line output. By means of SPICE simulations, it has been demonstrated that an amplifier circuit connected to the output of this varactor diode transmission line can produce an increase of the voltage modulation depth produced at line output from 10.7 V to 41,08 V approximately, thus allowing higher level power to electromagnetic wave propagation and consequently higher signal range. Experimental comparison using a PCB prototype with the corresponding simulation will be also shown.

IMPLEMENTATION OF LINE TYPE HIGH VOLTAGE NANOSECOND RECTANGULAR PULSE GENERATOR WITH ADJUSTABLE PULSE WIDTHS FOR LIQUID DISCHARGE APPLICATIONS

Amol Deshpande[1], Uttam Goswami[2], G Veda Prakash[3], Raj Singh[2], Anitha V P[2]
1. Institute for Plasma Research, Gandhinagar, India.;Sardar Patel Institute of Technology, Mumbai, India.
2. Institute for Plasma Research, Gandhinagar, India.
3. Center for Energy Studies, Indian Institute of Technology, New Delhi, India

Recent advances show the increasing demand of fast rise time pulse generators with variable high voltage and pulse durations with high repetition rate because of its wide range of applications. Considering the above, a low cost, simple, rugged and compact high voltage, nanosecond pulse generator is developed using coaxial transmission line with output voltage level up to 10 kV. Variable pulse widths in the range of a few 100 ns are achieved by varying the physical length of the transmission line. The pulse widths obtained are 120ns, 160ns, 240 ns, 300 ns, 400 ns with rise time of $\sim$20ns. An in-house developed spark gap switch is used for obtaining 20 ns rise time. This paper discusses the use of designed pulse generator for liquid discharge applications to study several discharge properties of the Oil and Water.

PULSED IOT POWER SYSTEM FOR MEDICAL APPLICATIONS

Francisco Cabaleiro Magallanes[1], Sylvain Candolfi, Andres Sanchez Gonzalez[2]
1. A.D.A.M. Applications of Detectors and accelerators to Medicine
2. Ministere des affaires etrangeres et europeennes (FR)

Inductive output tubes (IOTs) are used to power the radio-frequency quadrupole (RFQ) of the LIGHT accelerator. Common requirements belonging to this next generation of accelerators for proton therapy include very tight RF gain and phase stability constraints, while keeping the foot-print of the entire power system as compact as possible to minimize the civil engineering costs.

A new pulsed power system based on commercially available IOTs from E2V able to deliver pulses of 520 kW of RF power with a pulse-width of 20μs and repetition rates of 200Hz has been recently developed. The power system is based on a low-voltage pulse forming system, a transformer that steps-up the voltage up to –40kV, and several floating power supplies.

This paper presents in detail the selected pulsed power converter topology, the step-up transformer design, and the experimental tests on a commercial IOT unit. The impact of the high voltage stability on the RF gain and phase is measured and studied in order to dimension the final IOT power system which must respect the tight RF stability constraints coming from the medical requirements. Finally, the results and final retained topology is compared with common IOT transmitter topologies.

MODULAR, HIGH-FREQUENCY, HIGH-VOLTAGE INDUCTIVE ADDERS

Chris Bowman[1], Tim Ziemba, Kenneth E. Miller[2], James Prager[1], Nick Yang[2]
1. Eagle Harbor Technologies, Inc.
2. Eagle Harbor Technologies, Inc

Eagle Harbor Technologies, Inc. (EHT) has developed an inductive adder for driving nonlinear transmission lines (NLTLs). This inductive adder is composed of three modules, each with eight printed circuit boards. This modular approach allows systems to be easily configured for 12, 24, or 36 kV outputs. This 36 kV inductive adder can drive 50-ohm loads with fast rise times (sub-10 ns) and adjustable pulse widths (30 – 120 ns) at high pulse repetition frequency (up to 22 kHz CW or 50 kHz for short bursts). EHT will present details of the inductive adder construction and output as well as the development of the high voltage cable used to connect the inductive adder to the load.

HIGH AVERAGE POWER NANOFARAD-SCALE CAPACITOR CHARGING ON SUB-MICROSECOND TIMESCALES

Tim Ziemba, James Prager[1], Kenneth E. Miller[2], Chris Bowman[1], Ilia Slobodov[1], Morgan Quinley[2]

1. Eagle Harbor Technologies, Inc.
2. Eagle Harbor Technologies, Inc

Eagle Harbor Technologies, Inc. (EHT) has developed a high voltage nanosecond pulse generator that operates at high average power levels for industrial applications including water treatment, semiconductor processing, materials processing, and sterilization. EHT's previous generation of high voltage nanosecond pulsers operated at 5 kW of average power and pulse repetition frequencies up to 100 kHz. This work has been extended to an average power of 30 kW. This new nanosecond pulser can drive capacitive loads to 10 kV: up to 850 pF at 400 kHz and up to 3.5 nF at 100 kHz. Typical rise times are 55 ns and pulse widths are up to 200 ns. The system can produce pulses continuously or in bursts with higher peak power. The output voltage can be modulated between 500 V and 10 kV on the load's RC timescale. This system can be air or water cooled. EHT will present output waveforms as well as the trade studies conducted showing the safe operating area.

SOLID-STATE LTD MODULE USING SIC-MOSFETS

Yu Feng[1], Taichi Sugai[1], Akira Tokuchi[1], Weihua Jiang[1]
1. Nagaokaut University of Technology

Pulsed power generator based on LTD (linear transformer driver) has various advantages over those based on traditional pulse compression schemes. Efficiency and rise time are important issues for the performance of pulsed power generators, especially for industrial applications. A solid-state LTD module using silicon carbide (SiC) MOSFETs as switches has been designed and tested. Experiments have been carried out for evaluation of its output performance and total energy efficiency. The results have been compared with that obtained with LTD modules using silicon (Si) MOSFETs.

A MEANS OF PRODUCING PRECISELY DELAYED HIGH PEAK POWER OPTICAL PULSES WITH LOW JITTER

Maxwell Fazekas[1], Scott D. Kovaleski
1. MIZZOU

A Means of Producing Precisely Delayed High Peak Power Optical Pulses with Low Jitter

Max Fazekas and Scott D. Kovaleski

Department of Electrical Engineering and Computer Science

University of Missouri

Columbia, MO 65211 USA

Abstract. An electronically controlled optical system is being preliminarily designed to generate carriers in two or more photo-conductive semiconductor switches (PCSS) with precisely controlled relative delays. To minimize heating and support high voltages, the PCSS must be triggered with sub-nanosecond high energy optical pulses. A number of means of generating controllable delayed sub-nanosecond optical pulses have been researched, with fiber lasers being pursued to produce these pulses because of their low entry cost, power scalability, and robustness. A commercial fiber laser system consists of a diode seed laser and a doped fiber amplifier. The pulse length and relative timing is set strictly by the diode seed laser. This implies that a low energy system can be developed on low cost fiber coupled diode lasers and the pulse energy can be scaled to relevant magnitude with the addition of a fiber amplifier. The relative delay between the sub-nanosecond optical pulse input into one switch and successive switches requires very low jitter, down to tens of picoseconds. The initial fiber laser design aims to produce precise and adjustable time delayed optical pulses. The optical pulse delay is produced by a fiber coupled seed laser diode, a short pulse laser diode current driver, and a delay module acting as an electronic trigger for the current driver. A survey of means of producing delayed optical pulses will be presented, with a comparison of their relative merits. A more detailed analysis of a delay system based on fiber lasers will also be presented, with designs and analysis for production of short optical pulses and adjustable time delays.

Index Terms—Fiber laser, optical delay, photo-conductive semiconductor switch (PCSS).

This work is supported by the Office of Naval Research (ONR) Contract # N00014-18-C-1017

PRESENT STATUS OF THE CHOPPER-TYPE MARX MODULATOR DEVELOPMENT AT KEK

Hiromitsu Nakajima[1], Mitsuo Akemoto[1], Masato Kawamura[1], Takuya Natsui[1], Weihua Jiang[2], Taichi Sugai[2], Akira Tokuchi[3], Yo Sawamura[3]

1. High Energy Accelerator Research Organization

2. Nagaoka University of Technology

3. Pulsed Power Japan Laboratory Ltd.

The Chopper-type Marx modulator is being developed to drive a 10MW L-band multi-beam klystron for the International Linear Collider (ILC) at High Energy Accelerator Research Organization (KEK). It consists of 20 units in series to provide the klystron with a -120kV 140A 1.65ms pulse at a repetition rate of 5pps. The each unit has a control board and 4 chopper circuits in series. Each chopper circuit (Marx cell) is charged in parallel up to -2kV and the unit outputs in series -6.4kV 140A 1.65ms pulse. The droop of the output pulse is compensated by the PWM control of each Marx cell, and the ripple of total output pulse is reduced by the phase shift of the PWM for the each Marx cell. This paper describes present status of the Chopper-type Marx modulator development at KEK.

INVESTIGATIONS ON AN OPTIMIZED CURRENT PULSE FOR PULSED FLASH LAMPS DEDICATED TO HIGH ENERGY LASER IN REPETITIVE MODE.

Baptiste CADILHON[1], Robin VERGE[2], Antoine de Ferron[3], Thierry REESS[4], Laurent PECASTAING[4], Gaël PAQUIGNON[1], Luc Voisin[5]
1. CEA CESTA
2. Univ Pau & Pays Adour/ E2S UPPA, SIAME Laboratory
3. Pau University
4. UNIV PAU & ADOUR, Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique, IPRA, EA4581, 64000, Pau, France
5. CEA

Increasing the repetition rate of high energy lasers is of great interest for several applications. "Flashdence" is part of a larger program driven by CEA and devoted to the light amplification with Nd-glass pumped by flashlamps in order to progress on high energy laser technology in the range of 1kJ, 10PW at 1 shot per minute.

Increasing the repetition rate of such lasers generates a high thermal stresses on the Nd-glass (amplification plate) which deforms the laser front surface shot after shot. The main consequence is a laser profile inhomogeneous and unusable for the application. Several solutions could reduce this thermal stress. The idea presented here is to reduce and optimize the optical energy transferred form the flashlamps to the amplification plates by decreasing the pulse length of the current pulses feeding the flashlamps to the strict necessary.

CEA CESTA and the SIAME laboratory of Pau University are working in collaboration to develop solutions for a specific energy bank which could generate the appropriate current pulses to flashlamps. In this way, we have built a specific IGBT-PFN which provides 1kA square current pulses to a 100mm xenon flashlamps amplifier. We also have developed a 1kA crowbar branch based on a power thyristor dedicated to a standard RLC energy bank to deliver a bi-exponential current wave to the flashlamps amplifier.

Both of these systems are detailed and compared and we present first experimental results on each one. This work is a first step toward a one scale 300mm Nd-Glass amplifier.

GENERATION AND PROPAGATION OF NITROGEN LASER PULSES OF LONG ($< 3\ \mu$S) DURATION IN AIR

Mladen M. Kekez[1]
1. High-Energy Frequency Tesla Inc.

This paper describes three sets of experiments regarding the generation and propagation of nitrogen emission at 337.1 nm. 8 stage PFN (Pules forming network) Marx generator was used in the first set of experiments. The generator of 50 Ω internal impedance produces a "square" shaped voltage waveform across 50 Ω resistor. When the generator is applied to the experimental setup, the glow-like discharges containing numerus filamentary (spark) channels were created in air The discharge induces the multiphoton ionization of air molecules, the excitation of the molecules and ions to yield the laser emission. By varying the geometrical arrangement in the setup, the laser pulses of both: long ($<$3 μs), and of short ($\sim$10 ns) duration were generated in air at 337.1 nm (=principal laser line of N2 laser). The laser beams are attenuated as they traverse away from the laser output. The scaling law was derived describing the attenuation of the emission vs the distance for long ($<$ 3 μs) duration pulses. In the second set of experiments, the energy stored in the single capacitor was discharged into 2 mm wide gap to generate the radiation at 337.1 nm in air. The relationship between the current through the discharge and the emission was established. In the third set of experiments, the processes of the photo-preionization were further investigated.

POWER SUPPLIES FOR NON-THERMAL ATMOSPHERIC PRESSURE PLASMA GENERATION

Alexander Gutsol[1], Yuriy Mirochnik[1], Volodymyr Tymoshuk[1]
1. LDS Technology Consultants, Inc.

Conventional gliding arc (GA) power supplies (PSs) with ballast resistors have power losses >50%. When we started developing a hand-held plasmatron on the basis of low-current GA inside 'tornado'flow, we ordered a new generation PS from Advanced Plasma Solutions (APS) that produces small customizable PSs with oscillating high voltage. We required unipolar current (for thermo-chemical cathode use), high ignition voltage (15kV), and continuous power adjustment between 400W and 2000W with the average current <2A.

APS provided for testing two PSs: (#1) with direct ignition when the initial breakdown is caused by the no-load high voltage of the same circuit that supports the discharge existence; and (#2) with a separate ignition circuit that is responsible for the discharge initiation and is connected in parallel with the major power-providing circuit of the relatively low voltage.

Oscillograms of the plasmatron with these PSs show the following:

(#1): The voltage modulation doesn't change the gliding nature of the discharge – it elongates by the motion of the anode spot to the nozzle and the voltage amplitude grows. When it reaches 2.5kV, a new breakdown happens between the discharge channel and the nearest anode point, and the voltage amplitude drops to 600V. Then a new discharge elongation starts.

(#2): Relatively high average power (2 kW) allows stabilizing the discharge length in our device at a maximum when the anode spot circles around the nozzle exit. The lower voltage doesn't cause new breakdowns between the discharge channel and the anode, and with the higher power, it requires higher current settings.

We did not observe any 'sparks'in the plasma jet that can indicate intensive electrode erosion with both PSs, while their efficiencies were about 75-80%. Thus, high-voltage power supplies with the high-frequency oscillation of the unipolar voltage allow efficient energy transfer to a gliding discharge.

ESS KLYSTRON PRODUCTION TEST STAND

Michael Kempkes[1], Marcel Gaudreau[1], Rebecca Simpson[1], Ian Roth[1], Noah Silverman[2]

1. Diversified Technologies, Inc.
2. Diversified Technologies, Inc

Diversified Technologies, Inc. (DTI) has delivered a new long-pulse modulator klystron test stand to Communication and Power Industries (CPI) in Palo Alto, CA for full power testing of production VKP-8292A klystrons for the European Spallation Source (ESS). The output is flat to less than 0.5% over 3.3 ms. This test stand was built using hardware and designs from an earlier SBIR effort for the Department of Energy, with modifications to support ESS requirements and klystron testing operation. Earlier versions of this design are in use at IPN Orsay and CEA Saclay in France to test RF components for ESS.

This new klystron test stand allows testing of klystrons at the full ESS specifications: 120 kV, 50 A, 3.5 ms pulse, 14 Hz with margin for operating at voltages up to 130 kV. This design is based on a patented non-dissipative regulator that compensates for the capacitor droop voltage (approximately 20%) during the pulse. This allows a much smaller capacitor than would nominally be required for the long ESS pulse, eliminating the need for a larger, more expensive capacitor bank. This test stand will speed delivery of ESS klystrons, and similar, long pulse, high power klystrons at CPI.

A control cabinet houses the main system controls and interface, including most of the power distribution and a Programmable Logic Controller (PLC) for system sequencing and other functions. The HVPS is a switching power supply operating at 6 kV DC at up to 40 A. The HVPS high voltage output is supplied to the capacitor bank in the modulator. The HVPS uses an advanced PWM inverter to provide voltage and current regulation over the full output range. Nominal output behavior is 0.1% ripple and voltage regulation, with fast response to transients.

A METHOD OF ENERGY RECOVERY SWITCHING FOR PULSED POWER USING SIC-MOSFET

Tomohiko Yamashita[1], Ryo Fujimoto[1], Toru Tagawa[1], Kunihiko Sakamoto, Takashi Sakugawa[2]
1. Kumamoto University
2. Institute of Pulsed Power Science, Kumamoto University

There are develop pulse generator that are active in industry as drivers of excimer laser for semiconductor lithography light sources and pulsed power generation devices using magnetic pulse compression (MPC) circuits. Application studies such as shock wave generation using the same kind of pulsed power generator, biological application, chemically active species generation and the like are actively conducted. In these pulse power generators, not all of the input energy is consumed by the load. The energy remaining without being consumed by the load is consumed as heat in the pulsed power circuit. Effective utilization of this residual energy is necessary for high repetition pulsed power generator. We are conducting research on application to pulsed power switching circuit of SiC device, which is attracting attention as next generation power device. In this research, we describe a method of energy regeneration in pulsed power generation circuit using SiC-MOSFET. We succeeded in regenerating energy by turning-off the SiC-MOSFET at the timing when the forward current flows in the reverse parallel body diode connected to the SiC-MOSFET. Furthermore, we succeeded not only in energy recovery but also in turn-off surge voltage reduction.

ALL SOLID STATE ULTRA-FAST TURN-ON TIME COMPACT MARX GENERATOR

Alexander Gertsman[1], Zeev Rubinshtein [1], Moshe Hershkovitz[1]
1. Rafael Advanced Defense Systems LTD

It will be presented in this work development, production and experimental results of HPM modulator based on Marx topology. In general, drivers for HPS devices based on PFL or capacitor source coupled to the HPM devices by means of high voltage transformer. In our case, due to strong requirement on ultra-fast rise time, common concept was unacceptable, and direct coupling of the source was proposed. To supply high voltage pulse (30kV) having width of about 1μS and rise time less than 100nS with output current of 10Amps, Marx topology generator was chosen. In order to keep the design compact (portable application) solid-state switches as well as ceramic capacitors where considered in Marx circuit. All power stage components were chosen through optimization procedure that will be addressed in this paper. Switches of the Marx circuit where implemented by high voltage fast switching MOSFETs. Energy storage capacitors where implemented by high voltage Class2 ceramic capacitors.

A unique gate drive scheme was used to achieve ultra-fast turn on and simultaneous operation of all switches. It will be shown that even in the case of not truly simultaneous switching of the circuit the reliability would not be compromised. This excellence based on avalanche ability of the switches. This ability allows the switch, in the case of late triggering, to absorb some energy before its impedance falls due to gate drive signal.

In order to minimize the size and weight of the generator auxiliary power for the gate circuitry was derived from the hold off voltage of the switch. This allows reducing the complexity of the design by removing the need for floating power supply.

This paper presents design and implementation concepts, experimental results of all solid state Marx generator HPM modulator under development.

DEVELOPMENT OF A COMPACT NANOSECOND PULSE GENERATOR

Ryuki Matsukawa[1], Takehiro Yamaguchi[1], Mikiya Matsuda[2], Douyan Wang[3], Namihira Takao[3]

1. Graduate School of Science and Technology, Kumamoto University, Japan

2. Faculty of Engineering, Kumamoto University, Japan

3. Institute of Pulsed Power Science, Kumamoto University, Japan

Recently, pulsed power technology has been used in various field such as high density energy, industrial, medical, food, and agricultural applications. Non-thermal plasma generation is the key research for those applications. There are many papers report that the shorter duration and faster rise time, fall time of input voltage enables the higher energy efficiency in plasma processing. Therefore, development of a pulse generator with extremely short pulse duration is needed. Nanosecond pulse generator that developed in our research group can generate high voltage which rise time and fall time of 2 ns each, and the FWHM is 5 ns. This nanosecond pulse discharge has better results in ozone generation and NO treatment than other non-thermal plasma methods. The reason is because nanosecond pulse discharge mainly consists of streamer discharge phase so that the heat loss caused by glow discharge phase is small. Therefore, the nanosecond pulse discharge system including a nanosecond pulse generator and a reactor is known as a highly energy efficient method for plasma processing. However, Miniaturization of the nanosecond pulse discharge system is needed. Our nanosecond pulse generator consists of a microsecond pulse generation circuit and a nanosecond pulse forming line. Currently, the devices is relatively large and the volume of the total system is 91.3 L. In this research, the miniaturization of both microsecond pulse generation circuit and the nanosecond pulse forming circuit were developed aimed for miniaturization with keeping its output characteristics. The IES pulse generation circuit employing an IGBT was designed as the microsecond generation part, and the high voltage coaxial cables were designed as the nanosecond generation part. The total volume was successfully reduced to 12.1 L.

ENERGY DENSITY OPTIMIZATION OF INDUCTIVE PULSED POWER SUPPLY MODULE

Zhen Li[1], Xinjie Yu[1], Peiqi Zhu[1], hao sun
1. Tsinghua University

In an inductive pulsed power supply (IPPS) system, the energy density optimization of IPPS module is important for building a higher energy IPPS system. However, in the existing papers, the optimization of modules is rarely mentioned. This article uses meat grinder with SECT circuit as the background for module optimization. For the meat grinder with SECT circuit, the charging current and the energy are generally given, and the volumes of the thyristors and the counter-current capacitor that control the current are also fixed accordingly. In an IPPS module, there might be an optimal placement within thyristors and the counter-current capacitor. When designing the inductor, such an optimal placement, in addition to the constraint on the charging current and energy, puts forward a new constraint on the dimension of inductor (such as the outer diameter or the height). The optimized design of the inductor structure with certain constraint on the dimension is essentially the optimization for energy density of the entire module. In this paper, a 100kJ energy, 5kA charging current meat grinder with SECT module is taken as an example to realize the optimal design of the inductor under the dimension constraint, thus achieving the energy density optimization of the meat grinder with SECT module.

STUDY ON THE COLLABORATIVE WORK OF MULTIPLE MEAT GRINDER WITH SECT MODULES

Bei Li[1], Xinjie Yu[1], hao sun, Zhen Li[1]
1. Tsinghua University

The meat grinder with SECT circuit is a basic circuit for inductive pulsed power supply. When it comes to a practical electromagnetic launch system, collaborative work of multiple modules is necessary. This paper discusses the performance feature of two meat grinder with SECT modules in Fig. 1 which are charged in parallel by C_0 and then discharge in parallel to load with different time sequences.![enter image description here][1]

Firstly, appropriate triggering delays of two modules are designed. To reduce the magnetic field coupling between the two modules, thyristor T_{11} and T_{21}, T_{12} and T_{22} are triggered at the same time respectively. Afterwards, in previous research, a relatively high ratio of L_{i1} and L_{i2} lead to large second current peaks. As a result, T_{13} is triggered exactly when pulse-forming capacitor C_1 is fully reversely charged. The only adjustable trigger time is T_{23}. However, for other applications, the ratio of L_{i1} and L_{i2} is smaller. So the second current peak of the load is small. In this paper we determine the best trigger times of T_{13} and T_{23} to make sure that the load current form is the most similar to a rectangular waveform.

Secondly, if the trigger time of T_{22} is later than that of T_{12}, according to the simulation results, there will be a high overvoltage across T_{11} when T_{22} is triggered. This overvoltage could be reduced by cascading a protection inductor with T_{21}. And this method could be extended to cases of multiple meat grinder with SECT modules, i.e., all modules need the protection inductor except the module which have the earliest trigger time of T_{i2}. As it is hard to guarantee that the switches work simultaneously in engineering practice, applying protection inductors to all modules is necessary to ensure the reliability of the system.

[1]: https://cloud.tsinghua.edu.cn/thumbnail/2d297f15c7284b91a154/1024/fig1.png "Fig.1"

MEAT GRINDER WITH ACC CIRCUIT

Hao Sun[1], Xinjie Yu[1], Zhen Li[1]
1. Tsinghua University

Inductive pulse power supplies play an important role in electromagnetic launch. Among various power supply topologies, the meat grinder with SECT circuit (as shown in Fig. 1) attracted researchers'attention with its advantages of high energy density, good output waveform and low main switch voltage. C1 is the current turning-off source and the leakage inductive energy absorber simultaneously. In real application, the self-recovery ratio of C1 voltage is too low, so users need to pre-charge C1 before the charge of inductors. This requires each power module in the system to keep a pre-charging port for C1, and adds the complexity of integration. In addition, the pre-charged voltage of C1 is different from the voltage of the primary supply US. Therefore, an extremely large current will appear and destroy the device when primary supply and C1 are accidentally short-circuited.

![][1]

To solve these problems, the meat grinder with auto-charged commutating capacitor (ACC) circuit is proposed, as shown in Fig.2. At the beginning of operation, T1 is triggered. While charging inductors L1 and L2, US primary supply charges can also charges C1 through D and L2 until its voltage is higher than US. After the current through L1 reaches the designated value, T2 can be triggered. C1 uses its energy to turn off T1 through C1-T2-T1-US-LS-L2. L1 and L2 constitute a meat grinder circuit and achieves pulsed high current output. So ACC circuit inherit almost all the properties of SECT circuit but call off the pre-charged procedure.

![][2]

In simulation, the meat grinder with ACC circuit can generate a pulse current with amplitude of 23.8kA and half-wave time of 7.8ms. The voltage of C1 drops to zero after discharging, i.e. the repetitive operation can be realized without any adjustment. The experiment results support the above conclusions.

[1]: https://cloud.tsinghua.edu.cn/thumbnail/ada972b411d44516b045/1024/Fig.%201%20meat%20grinder%20with%20

[2]: https://cloud.tsinghua.edu.cn/thumbnail/c00ae030493043c28906/1024/Fig.%202%20meat%20grinder%20with%20

DEVELOPMENT OF BIPOLAR PULSED TRANSMITTER BASED ON MODULAR STRUCTURE FOR MINERAL EXPLORATION

Jung Soo Bae[1], Jong Soo Kim[2], Hyoung Suk Kim[2], Chan Hun Yu[2], Kim Shin[1], Sung-Roc Jang[3]

1. University of Science & Technology
2. Korea Electrotechnology Research Institute
3. KERI

This paper describes a 25kW bipolar pulsed transmitter based on modular structure for mineral exploration. The specifications of unit module including a LCC resonant converter and full bridge-based bipolar pulse switching unit are 500V, 12.5 A of output voltage and current, and DC to 8 kHz of pulse frequency. The LCC resonant converter having a trapezoidal-shaped resonant current is designed to reduce conduction loss. The leakage inductance of the transformer is utilized as resonant inductance without an additional inductor to achieve the high power density. Furthermore, to operate the frequency range from DC to 8 kHz and decrease the size of gate transformer, the gate drive circuit with the repetitive short pulse is proposed. According to the load condition, the bipolar transmitter capable of delivering the required high voltage and low current (2kV, 12.5A) or low voltage and high current (500V, 50A) is performed either grounded dipole mode or loop mode respectively. Four unit modules are connected in series and parallel in order to operate the power supply in either loop mode or grounded dipole mode. To satisfy the output voltage balancing between four unit modules, the tertiary wire is wound to compensate the phase difference of power transformer on LCC resonant converter. Finally, based on the development of the bipolar pulsed transmitter, experimental results with the inductive resistor load and field test will be discussed in conference.

PUSH-PULL PLASMA POWER SUPPLY – COMBINING TECHNIQUES FOR INCREASED STABILITY

Piotr Krupski[1], Henryka Danuta Stryczewska[2], Grzegorz Komarzyniec[3]
1. Lublin University of Technology, Faculty of Electrical Engineering and Computer Science
2. Lublin University of Technology, Poland
3. Lublin University of Technology, Faculty of Electrical Science and Computer Engineering

The case which is being described regards the means of supplying a miniature plasma reactor. The matter concerns mainly the sliding arc discharge which is developed in the conditions of air or other gases that are difficult to ionize. From the ecological point of view, the discharge in the air as a plasma-creating gas is especially important, since it is currently widely used in the field of environmental protection.

Typically the gliding arc reactor is a receiver with a non-linear resistance characteristic and, even in high frequency, the share of capacity is irrelevant. Nonetheless, the conductivity of the receiver is much less linear. In order to fulfil the requirements of the power supply and at the same time provide appropriate ignition properties, efficiently limit the research current and obtain the stability of non-thermal discharge, many advanced techniques were used. The power supply is switched-mode and of high-frequency, which gives it maximum efficiency in the process of energy conversion.

Insulated gate bipolar transistors were used in the power supply in push-pull topology and what is extraordinary here is the transformer which consists of 5 double secondary coils. Another technique that was used here was the ignition improvement obtained in switching overvoltages that come from parasitic parameters in the circuit of the transformer and the primary current switching system. The features mentioned are exceptional for the power supply and provide a very high quality of operation in the supply and plasma generator system. There are very wide adjustment properties in the range of 13-26 kHz and it has been proven to be exceptionally efficient in fulfilling its purposes.

DEVELOPMENT OF HIGH VOLTAGE POWER SUPPLY FOR THE UPGRADE KSTAR HELICON CURRENT DRIVE SYSTEM

Kwangho Jang[1], Sonjong Wang[1], Sunggug Kim[1], Jeehyun Kim[1], Hyunho Wi[1], Hyunyong Lee[1], Wook Cho[1], Daejun Choi[1], Jonggu Kwak[1]

1. NFRI (National Fusion Research Institute)

A new off-axis current driving method for high electron beta plasma using Helicon wave have been experimentally demonstrated in the KSTAR tokamak. Low power level coupling experimental analysis was performed in the KSTAR tokamak under various plasma conditions using traveling wave antenna, and moderate coupling and load-resilient characteristics were confirmed. Currently, KSTAR aims to upgrade the system to inject the 1MW helicon wave in 2019 campaign. This system requires a high power klystron and power supply. As a source of RF, we will use klystron which can output power 1MW at 476MHz.

A 5.9MW (92kV/64A) DC power supply system was developed for the 476MHz Helicon current drive system in KSTAR. The power supply is capable of supplying a maximum voltage of -92kV and a total current of 64A (32A, 2ea) to the cathode with respect to the collector using Pulse Step Modulator(PSM). This power supply system will be operated for two 1MW klystron units. The power supply switching circuits of PSM were made by fast IGBT which can turn off the high voltage within 5us in situation of klystron breakdown. In addition, HVS using IGBT device was configured at the output end to reduce the arc energy delivered to the load to 5J or less when the output short circuit or breakdown occurs. The output voltage is coarse adjustment by PSM, and the fine adjustment is controlled by the ripple control module.

Currently, manufacturing and testing of individual components of this power supply have been completed. Future plans are to perform a load test of the full power supply system and an output test by connecting to the klystron.

THE INFLUENCE OF THE ARCHITECTURE OF THE POWER SYSTEM ON THE OPERATIONAL PARAMETERS OF THE GLIDARC PLASMA REACTOR

Henryka Danuta Stryczewska[1], Grzegorz Komarzyniec[2], Piotr Krupski[3]
1. Lublin University of Technology, Poland
2. Lublin University of Technology, Faculty of Electrical Science and Computer Engineering
3. Lublin University of Technology, Faculty of Electrical Engineering and Computer Science

The GlidArc plasma reactor together with an electrical energy supply and a gas delivery circuit are inseparable elements of the plasma generation system. The plasma generated by such a system must have properties and parameters determined by the conducted plasma-chemical process. The parameters of all the elements of the system are dependent on each other, and a change of one of them forces changes of other parameters. The parameters and properties of the plasma generated are influenced by the design of the plasma reactor, the electrical parameters of the power supply system and the physical and chemical parameters of the process gases. Analysis was made of the reactor's cooperation with power supply systems using various specially designed transformer constructions and with an AC/DC/AC converter system. Transformer systems are a reliable power source, but with limited control possibilities. These are highly specialised devices developed for the needs of specific plasma reactors of one particular type and for a strictly defined plasma process. Advantages of converter systems are large regulatory possibilities. These systems can be designed as universal for a whole range of plasma reactors of a given type. Interesting possibilities are provided by the frequency regulation of the voltage supplying the plasma reactor. By changing the frequency while maintaining the voltage and current of the discharge one can influence the size of the reactor chamber space covered by the discharge and its power. The tests have shown a strong relationship between the performance characteristics of the plasma reactor and the construction of the power supply system. Clear differences occur even within the transformer systems, because the characteristics of the plasma reactor's operation are determined by the properties of their magnetic and electrical circuits (induction in the core, core material, magnetic flux dissipation, etc.).

REDUCTION OF THE CONDUCTED DISTURBANCES GENERATED BY THE IGNITION SYSTEMS OF GLIDARC PLASMA REACTORS

Grzegorz Komarzyniec[1], Michał Aftyka[2], Henryka Danuta Stryczewska[3]
1. Lublin University of Technology, Faculty of Electrical Science and Computer Engineering
2. Lublin University of Technology, Faculty of Electrical Engineering and Computer Science
3. Lublin University of Technology, Poland

A plasma reactor with a gliding arc discharge is a source of electromagnetic interference both radiated and conducted. They affect the operation of the reactor power systems and devices controlling their operation. Disruptions in the reactor's operation can cause uncontrolled extinguishing and ignition of an electric discharge, which in the case of accumulation of flammable compounds in the reactor discharge chamber can lead to an explosion. When analysing the GlidArc plasma reactor in terms of electromagnetic interference emission, two sources of interference should be taken into account: the ignition system, generating an ionising discharge on the ignition electrode between the reactor's working electrodes, and the working electrodes system. Particular attention should be paid to the ignition system, which is often supplied from a separate circuit. The source of interference from the ignition system is a discharge that burns on the ignition electrode. Depending on the solution applied in the power system, the ignition electrode is supplied with a voltage from 10 kV to 15 kV and a frequency from 50 Hz to 20 kHz, with a current limit of 40 mA, while working electrodes are supplied with a voltage of up to 1.5 kV and a frequency of 50 Hz up to 200 Hz, with a current limit of up to 2 A. Through the working electrodes, interference from the ignition discharges is transferred to the current paths of the secondary side of the reactor's supply. The nature and levels of these disturbances were analysed for various solutions of the supply systems of working electrodes and the ignition electrode. Power supply systems for working electrodes with power converters proved to be particularly susceptible to damage. Reduction of disturbances can be obtained by selecting the parameters of the ignition system and by other solutions of this system.

PULSED POWER MODULATOR WITH ACTIVE PULL-DOWN USING DIODE REVERSE RECOVERY TIME

Su-Mi Park[1], Seung-Ho Song[2], CHANGI CHO[1], Hong-Je Ryoo[1]
1. Chung-Ang University
2. Chung-Ang Univ.

This paper describes a pulsed power modulator with a new structure for an efficient active pull-down function. In some applications where a capacitive load such as plasma reactor is used, the output pulse has slow falling time since the residual energy of the load slowly decreases. Therefore, an effective pull-down performance is required to generate the output pulse in square wave form. The pull-down circuit configuration of the proposed pulsed power modulator utilizes the diode reverse recovery characteristics without using pull-down resistor which is conventionally used. The pull-down diode is forward-biased at pulse discharging mode. When the pulse discharging mode ended, the diode provides a path where the residual energy of the load can be discharged quickly, during the reverse recovery time. Therefore, the proposed modulator can achieve the fast pulse falling time without a large loss problem, which can occur when the pull-down resistor is used, or requirements of the complex control scheme. Through the simulation of conventional system with the pull-down resistor and the proposed system, the performance and superiority of the proposed structure are analyzed. Finally, the proposed modulator is developed and tested for plasma source ion implantation (PSII) application.

PRESENT STATUS OF THE KLYSTRON MODULATOR FOR SUPERKEKB INJECTOR LINAC

Mitsuo Akemoto[1], shigeki fukuda[2], Hiromitsu Honma[1], Masato Kawamura[1], Takuya Natsui[1], Hiromitsu Nakajima[1], Tetsuo Shidara[2]
1. High Energy Accelerator Research Organization
2. KEK

This paper describes present status of the klystron modulator for SuperKEKB injector linac. The rf system of this linac consists of 60 high-power klystrons, each capable of 50 MW, 4.0 μs pulsed power at a repetition rate of 50 Hz. Each klystron is pulsed by its own PFN-type modulator, containing a thyratron switch tube. Average lifetime of the thyratron is approximately 34,500 hours. A solid-state switch based on an array of thyristors to replace the thyratron is in development to improve the reliability and maintainability of the modulator. A 43 kV, 34 kJ/s PFN-charging power supply has been also developed to realize compact modulator, which makes space for new equipments in klystron gallery.

DESIGN AND COMMISSIONING OF A MEDIUM VOLTAGE TESTBED DEPLOYING TRANSIENT LOADS*

David Wetz[1], David Dodson[1], Brian McRee[1], Jacob Sanchez[1], Alexander Johnston[1], John Heinzel[2]

1. University of Texas at Arlington

2. Naval Surface Warfare Center - Philadelphia Division

Microgrids have been studied considerably over the last decade and are now able to be uniquely designed and controlled to handle a wide variety of loads, many of which may operate in a transient manner. Historically, electric grids have relied upon fossil fuel powered motors to spin generators that source the vast majority of the electric power they need. Microgrids deploy a host of different distributed generation sources that are interconnected and controlled in real time to improve overall grid reliability and redundency. Multiple microgrids are able to be interconnected to form a larger grid where power can be shared across smaller grids when needed. The use of a medium-voltage-direct-current (MVDC) is one possible solution to minimize power loss in the conductors and to reduce the power conversion requirement when high voltage loads are used. The non-continuous operation of such loads could introduce harmonics into the power system that severly impact power quality. In an effort to study the reliable operation and control of such a power system, the Pulsed Power and Energy Laboratory (PPEL) at the University of Texas at Arlington (UTA) has designed and installed a testbed that can be used to study a small microgid deploying transient loads. The testbed, operating at power levels in excess of 300 kW, utilizes distributed AC and DC power sources and loads operating at the 480 VAC, 4160 VAC, 1 kVDC, 6 kVDC, and 12 kVDC, respectively. The testbed is being extended utilizing a hardware in the loop (HIL) simulator. The paper presented here will discuss the design of the testbed, the test plan methodology, and the results collected so far.

----

* Work supported by the US Office of Naval Research (ONR) under grants N00014-17-1-2801 and N00014-18-1-2206

OPTIMIZED POWER AND ENERGY GENERATION, STORAGE AND CONDITIONING FOR ARMY ROTORCRAFT

Thomas Podlesak[1]
1. U.S. Army C5ISR Center

The Army is completely revamping its fleet of rotorcraft under a program designated Future Vertical Lift. Amongst the capabilities forecast for this next generation of manned and unmanned air platforms is the ability to use directed energy weapons, to include laser and high power RF devices. The rationale is a virtually unlimited magazine, lower in cost than conventional munitions and with longer range. The Power Division of the Command Power and Integration Directorate of the C5ISR Center is currently researching the key technical aspects that will enable this capability, to include pulsed power. Power Division's two main areas of research are power and energy supply and conditioning, and thermal management. Power and energy must be provided in an efficient way, combining both power generation and energy storage to produce the necessary conditioned pulsed input to the radiation sources in a reliable manner. In case of power and the related issue of thermal management, there are severe constraints regarding size and weight on the air platforms. This would encourage new approaches to pulse formation, such as more active rather than passive pulse formation, in order to reduce the weight incurred by passive components. It is also critical in thermal management, where advanced active cooling techniques are being studied. Amongst other technologies, wide bandgap power semiconductors are of particular interest due to their ability to address both the power and thermal issues, in that wide bandgap semiconductors tend to have fewer losses and require less cooling than conventional silicon semiconductors. Performances of the various component technologies must increase, in some cases by orders of magnitude.

PULSED POWER SYSTEMS DEVELOPED FOR THE LOCKHEED MARTIN COMPACT FUSION REACTOR

Adam Steiner[1], Nicolo Montecalvo[1], Maxwell Bilodeau[1], Jordan Locano[1], Thomas McGuire[1]

1. Lockheed Martin Aeronautics

The Lockheed Martin Compact Fusion Reactor (CFR) Program endeavors to quickly develop a compact, 100 MWe-class fusion power plant using a high-beta, linear encapsulated ring-cusp magnetic confinement scheme. Plasma sources, heating elements, and confinement coils incorporated into CFR prototypes require significant power and have motivated the development of several MW-class, medium- and high-voltage pulsed power systems with pulse lengths in the range of tens to hundreds of milliseconds. Topologies utilized on CFR include simultaneously-triggered and independent module-triggered pulse forming networks; ultracapacitor-driven DC/DC converters; resonant LC voltage amplifiers; ultracapacitor-driven buck converters; and stiff, variable-load capacitor banks. The performances of several of these pulsed power sources are analyzed for efficiency, stability of output pulses, and magnitude of noise generation. Existing, in-process, and planned integrations of pulsed power machines on CFR prototypes are presented, and the compatibility of pulsed power drivers with nearby plasma diagnostics is discussed.

DESIGN AND PERFORMANCE OF A 4 MV, 14 KJ MARX GENERATOR

Jon Mayes[1], Jeremy Byman[1], Chris Hatfield[1], David Kohlenberg[1], Paul Flores[1]
1. Applied Physical Electronics L.C.

Applied Physical Electronics, L.C. (APELC) has built and characterized a large Marx generator designed for a maximum erected voltage of 4 MV, with a maximum pulse energy of 14.5 kJ. The generator is based on a dual polarity charging topology, which helps reduce the source impedance to approximately 70 Ohms. When driving a matched resistive load, a peak power of 230 GW is delivered, with an approximate rise time of less than 200 ns, and a pulse width of approximately 300 ns. The generator is uniquely designed to be generally insulated with transformer oil, but switched in a dry air medium. Sets of spark gap switches are uniquely encased in common “switch blocks”, making use of UV-coupling to better the switching performance. This paper describes the design and performance of the Marx generator.

DESIGN AND PERFORMANCE OF A HIGH REPETITION RATE COMPACT MARX GENERATOR

Jon Mayes[1], Jeremy Byman[1], Chris Hatfield[1], Paul Flores[1]
1. Applied Physical Electronics L.C.

Applied Physical Electronics, L.C. (APELC) has built a high repetition rate Marx generator. APELC has previously presented on similar generators capable of operating at high repetition rates in very short bursts. This paper describes a new topology, in which the Marx-circuit is insulated with transformer oil, while the switching medium remains in a dry breathable environment. The transformer oil is used to manage the thermal problems associated with the high repetition rates. The dry air switching medium maintains the desired switching properties, including UV coupling between the spark gap switches. This Marx generator erects at 600 kV, with per pulse energies of up to 33 J. The Marx has been reliably operated with repetition rates of 450 Hz. This paper describes the design and results of the Marx generator.

A THEORY OF AC CONTACT RESISTANCE

Foivos Antoulinakis[1], Yue Ying Lau[1]
1. University of Michigan

Electrical contact is an important issue to high power microwave sources, pulsed power systems, field emitters, thin film devices and integrated circuits, and interconnects, etc. Contact resistance, and the enhanced ohmic heating that results, have been treated mostly under steady state (DC) condition. In this paper, we consider the AC contact resistance for a simple geometry [1], namely, that of two semi-infinite slab conductors of different thicknesses joint at z = 0. The conductivity of the two slabs may assume different values. In the DC case, this model was solved exactly by Zhang and Lau [1]. We have constructed an exact solution under AC condition, and we have shown that in the limit of zero frequency, our AC solution reduces to those of Ref. [1]. New features that accompany AC condition, such as the resistive skin effect, inductive, and capacitive effects, as well as radiation losses are explored.

[1] P. Zhang and Y. Y. Lau, J. Appl. Phys. 108, 044914 (2010).

*Work supported by Air Force Office of Scientific Research Award No. FA9550-18-1-0153, and L3 Technologies Electron Devices Division.

GENERALIZED SELF CONSISTENT MODEL FOR TUNNELING CURRENT IN DISSIMILAR METAL-INSULATOR-METAL JUNCTIONS

Sneha Banerjee[1], Peng Zhang[1]
1. Michigan State University

When two conductors are separated by sufficiently thin insulating layer, electrical current can flow between them by quantum tunneling. Tunneling conductivity is important to nanoscale electrical contacts, plasmonic resonators, carbon nanotube, graphene, and other novel two-dimensional (2D) material based devices. Tunneling effects between electrodes separated by thin insulating films have been studied extensively by Simmons [1,2] in 1960s. Simmons formula is reliable only in low voltage regime for limited parameter space (insulator gap $>$ 1nm, barrier height $>$ 3eV) [3]. Zhang [3] improved Simmons's theory by including space charge and electron exchange correlation potential in the nanogap formed between similar electrodes. Here, we extend the theory for tunneling current density in nano- and subnano-meter metal-insulator-metal (MIM) junctions with dissimilar work functions. Unlike similar MIM junctions, the current is polarity dependent. The forward (lower work function metal is positively biased) and reverse (lower work function metal is negatively biased) characteristics cross over at higher voltages. The influence of material properties (i.e. work function of the electrodes, electron affinity and permittivity of the insulator) on the reverse and forward bias J-V curves are examined in detail for various regimes.

1. J. G. Simmons, "Generalized Formula for the Electric Tunnel Effect between Similar Electrodes Separated by a Thin Insulating Film", J. Appl. Phys. 34, 1793–1803 (1963).

2. J. G. Simmons, "Electric Tunnel Effect between Dissimilar Electrodes Separated by a Thin Insulating Film," J. Appl. Phys., vol. 34, no. 9, pp. 2581–2590(1963).

3. P. Zhang, "Scaling for quantum tunneling current in nano- and subnano-scale plasmonic junctions", Sci. Rep., 5, 9826 (2015).

This work was supported by AFOSR YIP Award No. FA9550-18-1-0061.

SIMULATIONS OF TRANSIENT MULTIPACTOR SUPPRESSION DUE TO DIELECTRIC SURFACE CHARGING

Matthew Feldman[1], Aimee Hubble[1], Rostislav Spektor[1], Nicolas Rongione[1], Preston Partridge[1]

1. The Aerospace Corporation

Multipactor breakdown occurs in vacuum when RF fields cause a growth of electrons as primary electrons impact various surfaces to generate multiple secondary electrons. On dielectric surfaces, this can lead to charge build up as electron-holes accumulate. This charge accumulation affects the field structure near the dielectric surface, which may then alter or suppress a nascent multipactor breakdown and limit the ability to detect these events. To understand this process, we have used a new Systematic Multipactor Research Tool (SMRT) developed at The Aerospace Corporation. This modularity of our new tool allows us to simulate various geometries and surface types, alter secondary yield behaviors, track surface charge accumulation, and solve space-charge fields. In this work, we simulate breakdown on a two-surface stripline while including space-charge and surface-charge effects. With only conducting surfaces present, the multipactor breakdown will grow until it saturates due to space-charge limitations. However, when one or two of the surfaces are given dielectric properties, a steady-state electric field develops that can limit and suppress the growing breakdown. By including these surface charging effects, we can simulate the maximum electron population as well as the timescale of the transient multipactor event.

ADVANCED MULTIPACTOR DIAGNOSTICS AND TOOLS

Aimee Hubble[1], Matthew Feldman[1], Preston Partridge[1], Nicolas Rongione[1], Rostislav Spektor[1]
1. The Aerospace Corporation

There are a number of advanced techniques which can be used in addition to the standard suite of multipactor diagnostics to discern important information about a multipactor breakdown event. In this work some of these techniques are presented. First, a photomultiplier tube is used to measure photon emission from breakdown. The magnitude of the measured PMT events are correlated with other multipactor diagnostics to assess sensitivity and applicability relative to the standard suite of multipactor diagnostics. Next, signal phase shift and amplitude dropout is measured in several device geometries using a fast oscilloscope. The measured phase shift and amplitude change is compared to the phase null signal excursion. This technique helps translate a common measurement performed during hardware screening to real potential signal impact. Finally, the effect of multipactor breakdown on surface charge on dielectrics is examined. A small amount of surface charge is not necessarily damaging but can temporarily suppress breakdown, giving an indication that an event is short-lived or non-repeatable when in fact the temporary space charge condition is merely suppressing the breakdown for a period of time. These techniques together give greater insight into the physics and severity of multipactor breakdown.

THEORETICAL INVESTIGATION OF THE MAGNETIC ASYMMETRY EFFECT BY USING A LUMPED ELEMENT MODEL

Dennis Engel[1], Moritz Oberberg[1], Berger Birk[1], Laura Kroll[1], Julian Schulze[1], Peter Awakowicz[2], Ralf Peter Brinkmann[1]
1. Ruhr University Bochum
2. Ruhr-Universität Bochum

Latest experimental results have proven the existence of the magnetic asymmetry effect (MAE) in radio frequency capacitively coupled magnetron discharges [1]. Like the electrical asymmetry effect, the MAE allows to control the symmetry of a capacitive discharge. This contribution presents a lumped element model for such an RF driven magnetron which is an extension of a previously published lumped circuit description of unmagnetized RF discharges [2]. As its predecessor, the model represents the discharge by separate bulk and sheath zones which communicate via Kirchhoff relations. The extension accounts for the presence of a magnetized region with reduced electric conductivity [3,4]. The model provides short computation time and may be used for the purpose of model based control.

Similar to the experiment [1] a nearly geometric symmetric discharge is set up with the model. Due to a variation of the applied magnetic field strength, the sheath and bias voltage become significantly affected. The theoretical model and the experimental results show very good qualitative agreement. The main goal of this work is to theoretically investigate the influence of the MAE to capacitively coupled discharges and the non-linear electron resonance heating.

[1] M Oberberg et al., PSST 27, 105018 (2018)

[2] T. Mussenbrock et al., PSST 16, 377385 (2007)

[3] D. Bohm, The characteristics of Electrical Discharges in magnetic fields (1949)

[4] S.M. Rossnagel, H.R. Kaufman, Journal of Vacuum Science and Technology A 5, 88 (1987)

VLASOV-POISSON SIMULATION OF CURRENT-CARRYING ION ACOUSTIC INSTABILITY: NONLINEAR SATURATION AND ION KINETICS

Kentaro Hara[1], Cameron Treece[1]
1. Texas A&M University

Current-carrying ion acoustic instability is one of the most fundamental phenomena in plasma physics. The electron stream relative to the ion stream undergoes an electrostatic instability, e.g. Buneman instability. In the presence of thermal effects, the ion Landau damping occurs, which sets a minimum threshold for the drift velocity for the instability to grow. In this talk, a grid-based direct kinetic (DK) simulation is used to investigate the long-time nonlinear saturation and particularly the ion kinetics of this streaming instability. The phenomenon is characterized by the electron Mach number, namely, the ratio between the electron drift velocity and the electron thermal velocity. First, the numerical results are verified against the theory which is valid for small electron Mach numbers. Second, transition to a large-amplitude waves that propagate in both directions (along and opposite direction of the original electron stream) is observed at electron Mach number larger than 1.3, which was previously reported. Finally, the potential amplitude and high-energy ions formed by the large-amplitude plasma waves are characterized. Using a simple sputtering rate model, the numerical results show that such high-energy ions may be a potential cause of enhanced erosion in hollow cathodes.

PULSED MECHANICAL DEVICE GENERATES PLASMA IN WATER VIA CAVITATION

Xin Tang[1], David Staack[1]
1. Texas A&M University

Plasmas are conventionally generated by manipulating electric and magnetic fields[1]. A bio-inspired mechanical device mimicking snapping shrimp snapper claw based on micro X-ray computed tomography (μ-CT) scanning was designed to explore the possibility of producing plasma mechanically[2]. The major parts of the bio-inspired device including dactyl plunger and a matching socket with sophisticated 3D geometry were manufactured using additive manufacturing technique to produce a pulse of high speed water jet for inducing cavitation. High-frame-rate charge-coupled device (CCD) camera was applied to capture the cavitation generation of the device in water, and an intensified charge-coupled device (ICCD) camera was utilized to capture the light emission signals. Light emission evidence was verified in distilled water with air doping and argon doping respectively. The comparison of electrical generated cavitation and mechanically generated cavitation were presented. Organic compounds like isopropyl alcohol and mineral oil were also used as working fluids for the bioinspired device compared to water. The bio-inspired device has an insightful potential to be implemented as a pulsed plasma source and an efficient cavitation source. Therefore, this design can be applied to enhance microfluidics, chemical processing, physical processing and hydroacoustics.

1. Samukawa, Seiji, et al. ”The 2012 plasma roadmap.” Journal of Physics D: Applied Physics, 2012, 45(25), pp. 253001.

2. Xin Tang, David Staack. ”Bioinspired mechanical device generates plasma in water via cavitation.” Science Advances, 5, eaau7765 (2019).

———-

* Work supported by National Science Foundation (grant PHY-1057175) and the Robertson-Finley Foundation

STAGED Z-PINCH EXPERIMENTS AND SIMULATIONS USING DIFFERENT GAS SHELLS

H. U. Rahman[1], E. Ruskov, P. Ney[1], F. Conti[2], J. Narkis, J. Valenzuela, F. Beg[3], E. Covington[4], E. Dutra[4]

1. Magneto-Inertial Fusion Technology Inc.
2. University of California, San Diego
3. University of California, Sandiego
4. University Of Nevada, Reno

Staged Z-pinch experiments at the Nevada Terawatt Facility at UNR show evidence of uniform compression of a deuterium plasma target compressed by a high-Z, Argon or Krypton gas-puffed liner. Pinch stability is improved by seeding the implosion with an axial magnetic field of 0.1 to 0.2T. Implosion dynamics and stagnation conditions are also studied computationally with the radiation-MHD code MACH2 and Hydra, by applying initial conditions similar to those in the experiment. Simulations show that magnetic field diffuses through the outer shell and piles up at the interface providing narrow profile, high intensity current that Ohmicly preheats the target. This secondary piston launches shock waves in the target plasma that heats the target to several 100 eV. Finally, the preheated target is compressed adiabatically to stagnation. Simulations show: (a) stronger shocks and more pronounced pre-heating with Kr than Ar, (b) the axial magnetic field is compressed preferentially in the liner plasma, providing greater magneto-Rayleigh-Taylor mitigation during run-in phase compared to the self-similar model. For typical Ar liner on D target experiments we measured neutron yield up to 2×10^9 and for Kr liner up to 2.5×10^{10}. Experimental observations limited to the liner exterior (plasma current, visible streak images, gated-XUV pinhole images, and laser shadowgraphs) are compared with simulations, and show general agreement. The experimentally measured neutron yield is also in good agreement with simulations. Scaling up for high current machines like 10 MA and 20MA providing scientific breakeven and beyond using both MACH2 will also be presented. Conceptual design of the next generation machine of 10 MA will also be presented.

This work was funded by ARPA-E grant DE-AR0000569.

DEVELOPMENT OF A 750KJ DENSE PLASMA FOCUS FOR RADIATION TEST APPLICATIONS

Michael Butcher[1], Manuel Alan[1], Matt Domonkos[1], Nick Myers[1], Joseph Ruscetti[1], Bruce Freeman[2], Dan Treibel[1]
1. Verus Research
2. Integrated Applied Science

We present initial test results and design considerations for a Dense Plasma Focus (DPF) device designed and built by Verus Research for the next generation of neutrons for Test and Evaluation applications. The DPF concept, developed in the late 1950's, was used in part as a method of investigating plasma physics phenomena. The neutron radiation generated from a DPF can be used for multiple purposes, including investigation into short-pulse radiation source capabilities or material properties. The Verus Research DPF utilizes a 750kJ capacitor bank discharged through a coaxial anode-cathode assembly, with a high-pressure backfill gas of >10 Torr deuterium, to generate a high-flux neutron pulse on the order of 100 ns. Optimization and development of the system to maximize yield while achieving a repeatable and reliable system is presented. The initial testing of the DPF uses a drive voltage up to 50 kV generating a total current of 3 MA. A maximum current of 3.6 MA at 60 kV is expected in our configuration. Test results indicate yields $>$8e11 neutrons per pulse. This report focuses on test configurations that further increase yield while improving reliability and repeatability. Methods of neutron detection, calibration and associated quantification challenges are also discussed. Results on the variations of pressure and geometry are presented as well as other variations that impact the individual yield per shot or general reliability concerns.

This work is performed under contract through the U.S. Army's Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI) and funded by the Test Resource Management Center's Test and Evaluation/Science and Technology (TRMC T&E/S&T).

EXPERIMENTAL OBSERVATIONS OF A HIGH-PRESSURE, 750-KJ DENSE PLASMA FOCUS

Manuel Alan[1], Michael Butcher[1], Matthew Domonkos[1], Joseph Ruscetti[1], Nicholas Myers[1], Dan Treibel[1], Bruce Freeman[2]
1. Verus Research
2. Integrated Applied Science

Verus Research designed, built, and operates a dense plasma focus (DPF) in Albuquerque, NM, providing a high-flux fusion neutron source for Test & Evaluation applications. Our DPF operates in direct drive with a 750-kJ capacitor bank providing 1.5-3 MA at 30-50 kV, producing $10^{11} - 10^{12}$ neutrons in a sub-microsecond pulse using $>$10 Torr deuterium background gas. This report focuses on unique physics considerations driving machine operation at high pressure. Running at high pressure enhances neutron production by enabling hot-target interactions with increased volume species in the pinch region; however, high-pressure operation brings additional concerns not encountered in low-pressure operation. We report on the highly ablative characteristics of the plasma due to the large mass content, where downstream surfaces are subject to high momentum impact from accelerating particles. We discuss the impact of ablation/desorption on all surfaces, as well as operational concerns including obliteration of target substrates and asymmetries. We also report an observed bimodal operation correlating $\dot{I}$ diagnostic against yield. Our shot sequences at nominal voltage typically show distinct $\dot{I}$ trace characteristics, alternating between "shallow" (small $\ddot{I}$) and "deep" (large $\ddot{I}$) traces, comparing the trace post-pinch back-end. "Deep" traces average 25% greater yield than "shallow" traces, and we observe operations can favor a single mode. We discuss the appearance of bimodal operation, including the effect of contamination on pinch characteristics and/or the dominance of mode instabilities in the pinch.

This work is performed under contract through the U.S. Army's Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI) and funded by the Test Resource Management Center's Test and Evaluation/Science and Technology (TRMC T&E/S&T).

DETAILED MODELING OF DPF ON HAWK GENERATOR

Andrey Beresnyak[1], John Giuliani[1], Stuart Jackson[1], Steve Richardson[1], Alexander Velikovich[1]

1. Naval Research Laboratory

Dense Plasma Focus (DPF) experiment on the HAWK pulsed power generator (640 kV, 665 kA peak current) in Naval Research Laboratory had been recently modified to include hollow anode and on-axis gas puff. The increased neutron yield, up to 3.6×10^{10}, of the new configuration deserves precise modeling, which was the goal of the reported work. We simulate the gas puff, the plasma injection and the dynamics after the voltage is applied to compare with available measurements, which include current and voltage on the device, the measurement of line density along the axis as a function of time, as well as the integrated X-ray images. This modeling allow us to narrow down unknowns present in the injection physics and obtain more robust estimates of the plasma and magnetic field state during the pinch. We use these parameters to further study potential non-MHD mechanisms of acceleration, such as electric field introduced by current disruption.

LABORATORY ASTROPHYSICS - COLD ABSORPTION

Itay Gissis[1], Ehud Behar[1], Fisher Amnon[1]
1. Technion Inst. Of Technology Israel

The ability to create plasma sources similar in nature to astrophysical sources, but scaled to the laboratory, is extremely challenging. Specifically, photo-ionized plasmas that are common around black-hole accretion sources, nebulae and the cold interstellar medium, require powerful radiation sources that are not usually accessible in the laboratory. This leaves the photo-ionized plasma models and codes used by astrophysicists with severe uncertainties.

In the following study, we use a high-energy current generator combined with a gas-puff z-pinch load, to create a controlled X-ray source. The source is used to photo-excite and photo-ionize cold gas of astrophysical abundant elements such as oxygen and nitrogen in vacuum. We developed a spectroscopic apparatus dedicated to measure absorption spectra from which we calibrate atomic and molecular electronic transitions, coefficients, wavelengths, oscillator-strengths and cross-sections of the cold absorber. These measurements can be used to mitigate the lack of accurate atomic data in these elements, which is specifically important to better analyze many astrophysical spectra.

The experimental plasma source, the diagnostic system, and preliminary results of the X-ray source characterization will be presented.

EFFECT OF THE PREPULSE CURRENT ON THE PRECONDITIONED ALUMINUM WIRE ARRAY Z-PINCH

Yihan Lu[1], Jian Wu[1], Huantong Shi[1], Daoyuan Zhang[1], Ziwei Chen[1], Xingwen Li[1], Shenli Jia[1], Aici Qiu[1]
1. Xi'an Jiaotong University

Preconditioned wire array Z-pinch experiments are carried out based on a double-pulse current generator "Qin-1" facility. The facility can generate a ∼300 kA/300 ns current pulse with a charging voltage of ±35 kV, when driving the preheated aluminum wire array (8 wires, diameter of 1 cm, length of 1 cm). The feature of this facility is that an adjustable prepulse current (∼15 kA/45 ns) can be preset to preheat the wire array. The implosion dynamics of the wire array are highly related to the initial mass distribution of the wires, which can be regulated by the prepulse parameter.

The initial mass distribution and spatial size of the load can be regulated by changing the time interval (Tdelay) between the prepulse and the main pulse. Experimental images show that the ablation behavior changes dramatically when Tdelay varies from 400 ns to 1 us. It is noteworthy that a thin shell implosion is obtained in the case of Tdelay=1 μs. The characteristic parameters of instability are also different in the cases with changing Tdelay. The radiation power of X-ray is recorded with filtered PIN detectors, and the results shows that an optimized Tdelay can exist to obtain a higher X-ray power.

An optimization of the prepulse current can be achieved using a vacuum gap switch in the connection area of the electrodes of the main pulse and prepulse generators. In the case with the gap switch, it is observed that the gasification degree of the load is greatly improved compared to the condition without the switch. The X-ray radiation power of preconditioned wire array Z-pinch in this case is close to the normal electrode condition. However, the X-ray power of Z-pinch driven by a single pulse current is greatly improved compared to the case without the gap switch.

PLASMA FORMATION AND ABLATION DYNAMICS OF METALLIC LINER

Daoyuan Zhang[1], Jian Wu[1], Yihan Lu[1], Huantong Shi[1], Xingwen Li[1], Shenli Jia[2], Aici Qiu[1]
1. Xi'an Jiaotong University
2. Xi'an Jiaotong Unversity

The formation of plasma and ablation dynamics of metallic liner z-pinch is investigated. The size of 2mm in diameter, 0.1mm in thickness liners are exploded on the Qin-1 facility (∼250ns, 300kA). Radial and axial laser diagnostic platforms are set up to observe the dynamics from different direction simultaneously. We use screws to fix the liner which constructs a special point-contact structure. Consequently, we can study the plasma formation at the outside surface and inside surface during the whole process. According to the interferometry fringe shift, the electron density distribution is investigated. The formation of plasma at inside surface is about 20ns after the formation of plasma at outside surface. While the major part of liner keeps stationary, plasma generated from inside surface moves inward with ∼100 km/s and accumulates at center which is similar to the precursor of wire array Z-pinch. Meanwhile, a high density plasma layer is established at outside surface and the outside plasma expands outward with only 10-20 km/s.

The perturbations development at outside surface are investigated through transverse laser shadow image. We consider the stratifications as pure MHD (m=0) instabilities rather than ETI (electro-thermal instabilities) because the major part of ablations are plasma. We also discussed the growth law of wavelength and amplitude of perturbations.

CHARACTERIZING BREAKDOWN VOLTAGE IN MICRO-GAPS WITH MULTIPLE FIELD EMITTERS AT ATMOSPHERIC PRESSURE*

Yangyang Fu[1], Janez Krek[2], Peng Zhang[1], John Verboncoeur[1], Guy Parsey[3], Mark Kushner[3]
1. Michigan State University
2. Michigan State University, CMSE
3. University of Michigan

Insulation between high voltage electrodes is often in the form of micro-gaps which leverage the high breakdown voltage that occurs on the near-side of Paschen's curve. Structures on the electrodes are a concern due to electric field enhancement that can occur. The breakdown voltage in atmospheric pressure micro-gaps having multiple cathode field emitters was computationally investigated using a hybrid plasma hydrodynamics model in which electron transport following cathode emission is addressed using a Monte Carlo simulation [1]. Three mechanisms for electron emission from the cathode were included - ion-impact secondary emission, photo-electron emission, and thermionically enhanced electric field emission. The cathode had three post electron emitters with a work function of 4.0 eV, diameter of 5 μm and with a cathode-tip to anode distance of 30 μm. A linearly ramping voltage was applied to the anode and the cathode was grounded. The electric field at the top of the cathode posts was enhanced by a factor of 100 to account for surface roughness. The rate of applying voltage was varied from 1 to 100 V/ns. It was found that in the thermionic emission regime the electron emission induced by ions and photons have a minor impact on the breakdown, which is much different from the processes in Townsend mode regimes [2, 3]. The consequences of cathode work function, field enhancement factor, surface temperature and surface morphology on breakdown voltage will also be discussed.

[1] M. J. Kushner, *J. Phys. D: Appl. Phys.* 38, 1633, 2005.

[2] Y. Fu, P. Zhang, and J. P. Verboncoeur, *Appl. Phys. Lett.* 112, 254102, 2018.

[3] Y. Fu, J. Krek, P. Zhang, and J. P. Verboncoeur, *Plasma Sources Sci. Technol.* 27, 095014, 2018.

*This work was supported by the Air Force Office of Scientific Research (FA9550-18-1-0062, FA9550-18-1-0061) and the Department of Energy Office (DE-SC0001939).

SPATIO-TEMPORAL DYNAMICS OF PULSED GAS BREAKDOWN IN MICROGAPS

Guodong Meng[1], Qi Ying[1], Amanda Loveless[2], Feihong Wu[1], Kejing Wang[1], Yangyang Fu[3], Garner Allen[2], Yonghong Cheng[1]
1. Xi'an Jiaotong University
2. Purdue University
3. Michigan State University

Microscale gas breakdown plays a critical role in microplasma generation for numerous applications and device lifetime for miniaturized electronics. This work provides further insight into the spatio-temporal dynamics of pulsed gas breakdown for different gap distances using an in-situ electrical-optical measurement method. Time-resolved sequential images and the corresponding photon number distributions are obtained to demonstrate the dynamic evolution of the breakdown channel morphology and the ionization intensity during breakdown development. For a 15 μm gap, breakdown transitions from a spot area on both electrode surfaces to a broad discharge region comprised of filamentary main breakdown channel (2.00 μm) and surrounding weak ionization area due to the local field enhancement. For a 2 μm gap, it transitions from a thin channel (1.09 μm) to a wider and uniform channel (2.14 μm) because the electric field is more uniform at smaller gaps. Interestingly, the main breakdown channel width at the instant of breakdown is independent of the gap width. For the 2 μm gap, field emission dominates the initial stage of breakdown and collision ionization (α process) dominates during breakdown development, while the Townsend avalanche dominates the breakdown process for the 15 μm gap. We apply a simple asymptotic theory to quantify the relative contribution of these phenomena and predict that breakdown will follow Paschen's law for gaps larger than 17.8 μm.

A PULSE-SEQUENCE RESOLVED STUDY ON EVOLUTION OF STREAMER DYNAMICS AND DISCHARGE MODE TRANSITION UNDER REPETITIVE FREQUENCY NANOSECOND PULSES IN HIGH-PRESSURE NITROGEN

Zheng Zhao[1], Shuhan Liu[1], Yanan Wang[1], Jiangtao Li[1]
1. Xi'an Jiaotong University

Nanosecond repetitively pulsed discharge (NRPD) is attracting extensive attention recently due to its unique chemistry and physics properties, which are important for various applications including the plasma fruit sterilization. Streamer dynamics and discharge mode transition were fundamental properties of NRPD. Previous studies mainly investigated the NRPD by using two consecutive pulses and in relative low pressure. However, the streamer dynamics in the long-time continuous operation and high pressure would be dramatically different. In this paper, a pulse-sequence resolved study was carried on streamer dynamics and discharge mode transition under repetitive frequency nanosecond pulses (RFNP) in high-pressure nitrogen.

Two high voltage RFNP generator were designed including the long-pulse-width generator based on the magnetic switch and the short-pulse-width generator based on the avalanche transistor Marx circuit. The gap voltage, light intensity and discharge ICCD image were collected. The pulse-sequence resolution study (every pulse waveform collected in a complete sequence) was achieved by the sequence acquisition mode.

Spatial movement of streamer initiation position and different morphological characteristics under positive RFNP were found, which were determined by the space charge behavior. The steamer channel was found to be narrower under latter voltage pulse than that of the first corona discharge. Under negative RFNPs, the streamer propagation speed decreased with the PRF. The discharge mode would quickly change from the corona discharge to the spark discharge for the 5 mm rod-plane gap under 10 ns pulses. Meanwhile, the spark discharge would transform into the corona discharge in the quasi-stable stage, which was confirmed by the voltage and emission light intensity waveforms.

Streamer dynamics and discharge mode transition were studied based on the pulse-sequence resolved analysis. Several unique characteristics were found in the high-pressure nitrogen, revealing that the positive ions may play the dominating role in the discharge developing process as well as the metastable species.

EVOLUTION OF NS BREAKDOWN IN GASES: DYNAMIC STREAMER MODEL IN AIR, N2, CO2, AND SF6

Ting Liu[1], Igor Timoshkin[1], Scott MacGregor, Martin Given[2], Mark Wilson[1], Tao Wang

1. University of Strathclyde

2. University Strathclyde

The dielectric performance of gasses in gaseous insulation systems is a fundamental aspect which should be considered in design and optimisation of power and pulsed power HV systems. Significant number of published papers on experimental and modelling aspects of ns and sub-ns discharges in gases reflects the importance of the understanding of the fundamental mechanisms of fast streamer breakdown processes for insulation coordination, design and the development of plasma closing gas switches and for the utilisation of transient gas discharges in environmental, bio-medical and other practical applications. However, there is a lack of detailed information about the development of fast nanosecond transient discharges in gasses used in different practical applications.

The present paper is focussed on systematic modelling of the development of fast negative discharges in common gases used in practical power and pulse power, environmental and biomedical applications and processes:. The model, which was developed in COMSOL Multi-physics, is based on the transport and continuity equations for ions and electrons.

The dynamic nature of the breakdown process including streamer inception and propagation across the gap was investigated in 1.5 mm inter-electrode gaps filled for dry air, N2, CO2 and SF6 at atmospheric pressure. The obtained formative time(the time required for the ionization front to cross the gap), and normalised breakdown field, E/N, have been compared with available experimental breakdown data reported in [1]. The model can be used in more complex electrode topologies for optimisation and coordination of gaseous insulation. This model may also help in the development of high voltage pulsed power gas-based systems such as fast plasma switches filled with environmentally friendly gases.

[1] P. M. Felsenthal, J. Proud, Physical Review, 139(6A), A1796-A1804, 1965.

Kew Words: Breakdown in gases, streamer development, dry and humid air, N2, CO2, SF6.

BURIED CONDUCTOR DETECTION IN THE SEABED

jane Lehr[1], David Sanabria[1], Joong Kim[2]
1. University of New Mexico
2. Office of Naval Research

Unlike pure water, electrical breakdown in seawater has not been studied broadly, in seawater the ions are provided by the salt content leading to a conductivity of about 53mS/cm in contrast, purified water has a theoretical conductivity of 55nS/cm, when short pulses are applied the contribution of the ions to current conduction is weakened due to the low drift velocity of the ions and consequently it can exhibit an insulator like behavior. Based on this hypothesis and on previous research done by Jon C. Pouncey on detection of buried conductors in the soil, UNM is testing the properties of seawater breakdown to identify opportunities to develop an effective method to detect conductors buried in the seabed. Tests have been performed with a variety of Na2S2O3 aqueous solutions applying $\sim$6ns pulses in a custom designed chamber, breakdown events are observed at low concentrations and high voltage, FWHM, rise time, and inter-electrode distance are also correlated, different electrode geometries are also used. Analysis of the obtained results shows that breakdown in seawater is achievable and future experiments with longer pulses and more energy are contemplated.

INVESTIGATION OF STEROLITHOGRAPHIC LASER ADDITIVE MANUFACTURING RESINS FOR PULSED POWER APPLICATIONS

Robert Beattie-Rossberg[1], Salvador Portillo[1]
1. University of New Mexico

Investigation of Sterolithographic Laser Additive Manufacturing Resins for Pulsed Power Applications

R. Beattie-Rossberg, A. Kuskov, S. Portillo, E. Schamiloglu

Electrical and Computer Engineering

The University of New Mexico

Polycarbonate dielectrics like Lexan and polyetherimides such as Ultem have long been used as dielectrics in Marx generators, Blumlein lines, and in other pulsed power devices. These materials have relatively high voltage hold off and tensile strength, and are typically machined out of raw stock. The principal drawback of these materials is the cost of raw stock, machining time, and the need for higher voltage holdoff capability. Modern High Power Microwave (HPM) sources capable of gigawatt power with a compact footprint require an associated compact pulsed power driver that can hold off 100s of kilovolts for extended periods of time. The smaller volume of these devices, of course, places greater electrical stress on the dielectrics of the device. Photopolymers that polymerize with photons of UV wavelength are the basis for new stereolithographic additive manufacturing 3-D printers. These printers can produce not just prototype dielectric structures, but also fully operational dielectrics ready for use in a high energy pulsed power machine. Such printers have been used to manufacture pressurized spark gap switches for UNM's 10 stage, 10 kJ high energy, high voltage Marx generator. This presentation discusses empirical measurements of voltage hold off, both pulsed and DC, for various photopolymers as well as some initial dielectric permittivity measurements based on Sparameter analysis at low to medium frequencies.

This work is supported by ONR grant # N00014-16-1-2352

FLASHOVER STUDIES IN PRESSURIZED DRY AIR AND TRANSFORMER OIL

Ian Bean, Colin Adams, Thomas Weber

We are developing new, high-voltage, high-current plasma switches, triggers, transmission lines, and other pulsed power infrastructure to replace legacy systems in the Magnetized Shock Experiment (MSX) at Los Alamos National Laboratory. MSX is comprised of several different pulsed power systems of various voltages, currents, pulse energies, and technology bases; all of which will be replaced by a single, modular, proven design. The flashover failure mode has been shown to a factor in the design of these systems and a stand-alone experiment has been conducted in parallel to obtain the required data to properly design these systems. Flashover threshold voltages were measured in a variety of environments, geometries, and materials. The largest time-scale concerned for these systems are the charging systems which must hold for minutes at a time. A broad study has been conducted varying dielectric material, shape, and length between two electrodes exposed to DC voltages up to 100 kV in both a pressurized dry-air environment, and submerged in high voltage oil. Additionally, due to the statistical nature of flashover events data has also been recorded to provide estimates of time constants in all cases so that safety factors could be appropriately extrapolated. This work provides an engineering data set for a large range of flashover conditions common in pulsed power systems.

STUDY ON INSULATION CHARACTERISTICS EVOLUTION OF OIL-IMPREGNATED PAPERBOARD UNDER MECHANICAL STRESS

Yao Xiao[1], Yan-Jie Cui[1], Xi-Ning Li[1], Sheng-Chang Ji[1]
1. School of Electrical Engineering, Xi'an Jiaotong University

I.INTRODUCTION

During the long-term running of transformer, its oil-paper insulation system withstands various stresses of temperature, mechanical stresses and electric fields, which will continue to age. There is much research on electrical aging and heat aging, but few research on aging under mechanical stress.

II.EXPERIMENTAL PLATFORM AND PROCESS

In order to simulate the pressing force of the transformer during steady-state operation and the impact force during short-circuit operation, two kinds of force are loaded on the paperboard: the stress amplitudes are 30MPa, 50MPa, 70MPa, and the loading time is 60s; the amplitude of the force is 50MPa, with frequencies of 5Hz, 10Hz, 15Hz, 20Hz, all lasting 1200 cycles. After that, the loaded paperboard was subjected to strain measurement, confocal microscopy and partial discharge test.

III.RESULTS AND DISCUSSION

According to PRPD, the process of discharge is divided into three stages: initial stage, developing stage, severe stage. With the amplitude of stress increasing or the frequency of stress decreasing, PRPD pattern changes from "turtle" to "rabbit ear". An experiment with compression superimposed multi-layer paperboard shows that the spectral shape transformation is caused by the difference in fiber structure strain at different positions of the pressboard.

The higher the mechanical stress amplitude or the lower the frequency is, as a result, the strain of the insulating paperboard becomes greater, the damage of the fiber structure gets more serious, partial discharge inception voltage and the breakdown time value of the paperboard become lower, and the discharge repetition rate and the maximum discharge amount get higher. The "solid dielectric air gap model" and the "effective time model of stress action" are proposed to explain the above experimental results, respectively.

THE INVESTIGATION OF PLUME CHARACTERISTICS OF A CAPILLARY DISCHARGE BASED PULSED PLASMA THRUSTER

Wang Yanan, Ge Chongjian, Cheng Le, Ding Weidong, Geng Jinyue

Pulsed plasma thrusters (PPT) have great advantage in simple structure, high reliability and low impulse bit and they have been successfully applied to many space missions. However, the low overall efficiency caused by late time ablation (LTA) and particles emission impedes the further application of PPTs. In recent years, the capillary discharge based pulsed plasma thrusters (CDPPT) draw much attention for their great output parameters. Different with the traditional electromagnetic acceleration dominant thrusters, CDPPTs utilize the electrothermal acceleration mechanism which is more effective in low energy level. In this paper, the plume characteristics of a capillary discharge based pulsed plasma thruster have been investigated. First of all, the structure of a capillary discharge based pulsed plasma thruster and experimental platform was illustrated. The plume dynamics of the plasma jet were studied with ICCD camera. By the time-resolved imaging, the turbulent flow process, laminar flow process and transient process were figured out.Then, an optical time of flight (OTOF) method based on a photodiode array was adopted to measure the equivalent velocity of plasma plume. The photodiode signal exhibited a two-peak profile. With the band pass filter applied, the equivalent velocity corresponding to the different part of plasma plume were calculated. The particles species and emission spectroscopy were investigated by the spectrometer. It was found that the single ionized species, C+ and F+ exerted out from the cavity firstly and the neutral particles appear at a lateral time. Moreover, the influences of the discharge energy, cavity length, diameter on the equivalent velocity were studied systemically. Finally, a two component model for calculating the overall efficiency was proposed. Based on the measurement results of the equivalent velocity and ablation mass, the calculation results were discussed. It showed that the results calculated by the typical equation were lower than the actual results.

MEASUREMENTS OF THE CHARACTERISTICS OF PLASMA PLUME GENERATED BY LOW ENERGY SURFACE FLASHOVER

Yunping Zhang[1], Adam Patel[1], Alexey Shashurin[1]
1. Purdue University

Due to their high feasibility and flexibility CubeSats has found increasingly extensive applications in various research fields, and with an on-board propulsion system the capabilities and service lifespan can be significantly enhanced. Electrical propulsion system recommended by its high efficiency and low threat to the primary payload is a promising candidate and usually utilizes an ignitor subsystem to provide the seed plasma and initiate the main discharge. It has been demonstrated in previous work that Low Energy Surface Flashover (LESF) ignitor subsystem can sustain extended operation of the same assembly for $>$1.5 million pulses. Experiments incorporating LESF with models of Pulsed Plasma Accelerator and Vacuum Arc Thruster confirmed the successful ignition by LESF. In this work the characteristics of the plasma plume generated by LESF were investigated by simultaneous measurements of three double Langmuir probes in individual LESF events. The three double probes were positioned at three linear distances from the LESF assembly for the time-of-flight measurements and at three polar angles for the angular distribution measurements. Preliminary results showed that the plasma expansion velocity is $\sim$ 5cm/μs and the plasma plume generated by the LESF is primarily concentrated within 60 degrees above the assembly.

THRUST-TO-POWER RATIO IMPROVEMENT OF MICRO-CATHODE ARC THRUSTER BY ADDITION OF THE MAGNETOPLASMADYNAMIC STAGE

Denis Zolotukhin[1], Keir Daniels[1], Michael Keidar[2]
1. The George Washington University
2. George washington University

Addition of the acceleration stage to the micro-cathode vacuum arc thruster (μCAT) allows increase of the thrust and the specific impulse and finally the overall efficiency of such miniature thruster for CubeSats. In this work, we propose to use a magnetoplasmadynamic (MPD) approach for such improvement.

Significant advantages of the μCAT-MPD approach in comparison with gridded ion acceleration stage is its griddles construction, a design that helps to overcome the loss of ions along the grid cells, with lower voltages on the accelerating electrodes.

In the considered approach, the quasi-neutral plasma, produced by the single μCAT as the first stage, is additionally accelerated by the Lorentz force that is generated with just one additional dc-biased electrode, and one pulsing magnetic coil.

Using a thrust stand for indirect thrust measurements, combined with thrust calculation with experimental values of ion velocity, ion current and erosion rates, together with calculating the powers, dissipating in both stages and magnetic coil, we show that the second accelerating stage based on MPD approach allows improvements not only to the thrust (almost twice, from 9 to 18 μN), but also to the thrust-to-power ratio (in 53%, from 3.2 to 4.9 μN/W) of the low-power (several W) miniature (several cm - size) μCAT, firing at 10 Hz.

Further increase of TPR will require the optimization of the coil current, the accelerating voltage values, and the thruster's electrodes geometry. Since the thrust of the system with MPD stage is proportional to $j \times B$, to improve TPR it is necessary to increase the amplitudes of the current density and the magnetic field in solenoid within the single pulse, for the same values of dissipating power.

The work was supported by a Vector Space Systems and NASA DC Space Grant Consortium, the National Science Foundation, grant 1747760.

TRIPPLE LANGMUIR PROBE DIAGNOSTIC FOR VACUUM ARC THRUSTERS

Marina Kühn-Kauffeldt[1], Marvin Kühn[1], Vincent Andraud[2], Christophe Thibaut[2], Jochen Schein[1]

1. Universität der Bundeswehr München

2. undefinedcole supérieure d'électricité

Vacuum arc thrusters are an interesting technology for generation of uN thrust pulses suitable for position control. The simplicity and compact design due to its solid fuel make it particularly interesting for small satellite applications. By now the limiting factor for the usage of vacuum arc thruster is the reliability of the system which limits the current pule number to about one million. In order to understand how to make the vacuum arc thruster operate reliably for more than 10 million pulses an online diagnostic is needed which allows to evaluate the quality of the thrust and diagnose the failure of the thruster.

The triple Langmuir probe technique is a probe technique which allows an online time resolved measurement of the electron temperature and density in pulsed plasma applications. Thus various information about the vacuum arc inter-electrode plasma and hence the relative thrust change of the system can be deduced.

In this work a triple Langmuir probe system was build according to the requirements of the vacuum arc. Measurements with different cathode materials were conducted in order to evaluate its performance as an online diagnostic tool.

EMBEDDED MINIATURE THRUSTERS WITHIN CARBON FIBER REINFORCED STRUCTURES

Dejan Nikic[1]
1. The Boeing Company

Increased use of carbon fiber reinforced polymers (CFRP) for space applications presents an opportunity of using these structures as a fuel source for thruster operation. Typical CFRP structures used for space applications are designed to handle take-off loading and stresses. This results in an oversized and overweight component in orbit. To take advantage of excess weight an array of electrodes is embedded within and on the surface of CFRP material. Applying high voltage between the electrodes causes the carbon fiber to erode and eject material out of the electrode orifices. Amount of material eroded can be controlled by the supplied current and the duration of the pulses. To maximize the use of material an array of electrodes can cover all of the available surfaces. Doing this also enables rotational control of the spacecraft by firing embedded thrusters on different sides of the spacecraft. Typically 1-4 mN of thrust are possible out of any single electrode orifice and total thrust duration of 10-30 seconds. With approximate size of 10 mm square it is possible to have thousands of electrodes per CFRP panel, depending on size, and with advanced metal electrode printing it would be possible to achieve even tighter packing of electrodes.

MODULAR DESIGN OF A RADIAL SCALED HALL THRUSTER FOR DIFFERENT MAGNETIC CONFIGURATIONS

Alberto Olano Garcia[1], Haibin Tang[1], Junxue Ren[1], Guangchuan Zhang[1]
1. Beihang University

A 100 W radial scaled Hall Thruster has been designed and manufactured using as reference design the D-55 thruster with anode layer (TAL). The magnetic field required is provided by permanent magnets following a modular design in order to compare three different magnetic field configurations: A) nominal, B) orthogonal magnetic field and C) high magnetic field. In Hall Thrusters the magnetic field is used to confine the electrons and create highly ionized plasma. Configuration A and configuration B were chosen to compare two different topographies of the magnetic field with two different magnetic field gradients and to study their influence in the plasma discharge and thruster performance. Both configurations where derived assuming Bohm diffusion as the dominant process in the plasma discharge. If instead of Bohm diffusion it is considered electron-wall collisions as main mechanism in the electron transport then a higher magnetic field is required and in consequence configuration C was designed. These three configurations are intended to provide a better understanding of the influence of the magnetic field in the thruster discharge.

KINETIC MODELING OF ION THRUSTER PLUME PLASMA SURFACE INTERACTIONS

Nakul Nuwal[1], Deborah Levin[2]
1. University of Illinois Urbana Champaign
2. Professor, AE, UIUC

Plasma surface interactions are an important aspect of spacecraft design. The spacecraft surfaces present in the backflow region of the plume can acquire a negative potential, attracting slow moving charge exchanged ions created in the core plume region[1]. The ions accelerating towards the surface can cause surface sputtering on protective coating present on the solar panels. In previous works, semi-kinetic approaches have been used to model plume backflow region[2]. In this work, we will perform a three-dimensional fully-kinetic numerical study of ion thruster plume plasma interactions with spacecraft surfaces where all species are considered as particles and their individual kinetics is resolved.

PIC-DSMC[3] will be used to perform numerical simulations. A hybrid MPI-GPU code, CHAOS[4], will be modified to include effects of charging and used for this work. We plan to present different surface boundaries in the backflow region of the plume and report the macro-parameters, such as ion and electron densities, and the kinetic parameters such as ion energy distribution and plasma-sheath thickness near the surface. Finally, we will estimate surface erosion for the surface using kinetic results and empirical relations[5], and compare those results with traditional plume plasma models.

1.B. Korkut, D.A. Levin, "Three-Dimensional Simulations of Backflows from Ion Thruster Plumes Using Unstructured Grid Refinement", Journal of Propulsion and Power, 2016.

2.F. Cichocki, A. Domínguez-Vázquez, M. Merino, E. Ahedo, "Hybrid 3D model for the interaction of plasma thruster plumes with nearby objects", Plasma Sources Science and Technology, 2017.

3.C.K. Birdsall, "Particle-in-cell charged-particle simulations, plus Monte Carlo collisions with neutral atom, PIC-MCC", IEEE Transactions on Plasma Science, 1991.

4.R. Jambunathan, D.A. Levin, "Multi-GPU PIC-DSMC solver for modeling ion thruster plasma plume and neutralization", AIAA 2018.

5.Y. Yamamura and H. Tawara, "Energy dependence of ion-induced sputtering yields from monatomic solids at normal incidence", Atomic data and nuclear data tables, 1996.

SPLITS - RECONFIGURABLE 5.5 OHM SERIES PULSE FORMING LINES FOR MULTIPLE 300KV PULSE CREATION

Patrick Corcoran[1], David Spelts[1], Douglas Weidenheimer[1], Alannah Myers[1], Norman Link[1], Richard Stevens[1], Naresh Jaitly[1], Doug McGlathery[1], Gregory Dale[2], Mark Crawford[2], Juan Barraza[2]

1. L3 Applied Technologies, Inc.

2. Los Alamos National Laboratory

The Series Pulse-Line Integrated Test Stand (SPLITS) comprises a set of four, 5.5ohm coaxial pulse forming lines that are each capable of producing a -300kV pulse when driving a matched resistive load. The hardware's modular design allows series configurations for driving multiple pulses into a common load. The water filled pulse lines are discharged by SF6 insulated laser triggered gas switches that allow long charge times up to 4 micro-seconds with high precision and high reliability. Such charge time allows them to be charged by either a Marx or pulsed transformer circuits.

The design of the pulse lines and configurability is described. Test results demonstrate single line and series operation, gas switch trigger (jitter and pre-fire rates) and maintenance, pulse shaping ability, and post pulse damping. Simulations made using a circuit model reproduce measured voltages and currents.

This work was supported by Los Alamos National Laboratory.

CONSIDERATIONS FOR IMPROVEMENTS TO THE 25 TW SATURN HIGH-CURRENT DRIVER

Mark Savage[1], Kevin Austin[1], Sean Coffey[1], Peter Jones[1], Nathan Joseph[1], Debra Kirschner[1], John Lott[1], Bryan Oliver[1], Rick Spielman[2], Ken Struve[1]
1. Sandia National Laboratories
2. Idaho State University

The Saturn X-ray generator is a 2.5 megavolt, 10 megampere electrical driver at Sandia National Laboratories. Saturn has been in operation for more than 30 years. A plan is under development to identify key areas of the machine, improvement of which would benefit operational efficiency and reproducibility of the system. Saturn is used to create high-dose, short-pulse intense radiation environments for testing electronic and mechanical systems. Saturn has 36 identical modules driving a common electron beam bremsstrahlung load. Each module utilizes a microsecond Marx generator, a megavolt gas switch, and untriggered water switches in a largely conventional pulse-forming system.

Achieving predictable and reliable radiation exposure is critical for users of the facility. In decades of continual use with minimal opportunities for research, improvements, or significant preventive maintenance, the facility has declined in the number of useful tests executed for customers.

We will show data relevant to present-day performance of Saturn and areas being studied to maximize performance while considering operational efficiency and sustainability.

TECHNIQUE TO DETERMINE INTENSE ELECTRON BEAM PARAMETERS AND X-RAY SPECTRA FROM DOSE-RATE MEASUREMENTS AT DIFFERENT ANGLES*

Bruce Weber[1], Ian Rittersdorf[1], Timothy Renk[2], David Hinshelwood[1], Stephen Swanekamp[1]
1. Naval Research Laboratory
2. Sandia National Laboratories

Electrical parameters (current and voltage) of intense electron beams are often difficult to measure directly in pulsed power experiments, and additional information (electron angles of incidence) is required to determine the photon spectra produced. Measured dose-rates in the far field at selected angles can determine the electron-beam current, voltage, and an effective angle of incidence on the converter package, all as functions of time. This information enables calculation of the far-field photon spectrum as a function of time and polar angle. The axisymmetric 2D Monte-Carlo CYLTRAN code calculates photon spectra escaping the converter package for a range of electron energies and angles of incidence. Spectral attenuation by intervening materials and absorption in CaF2 is calculated using mass attenuation and absorption coefficients. The CYLTRAN results indicate promising angles for dose-rate measurements to optimize the sensitivity to voltage and electron angle. This technique is described for a 2-MV generator, Gamble II, and an 8-MV generator, RITS-6.

*Work supported by the US Defense Threat Reduction Agency

M3: A NEW PULSED POWER MACHINE DEDICATED TO INERTIAL CONFINEMENT FUSION EXPERIMENTS

Luis Sebastian Caballero Bendixsen[1], Thomas Clayson[1], Jamie Darling[1], Nicolas Hawker[1], Paul Holligan[1], James Parkin [1], Oli Hall[1], Simon Hall[1]
1. First Light Fusion

First Light Fusion Ltd (FLF) is a privately funded company researching energy generation using inertial confinement fusion. Efforts are centred around developing both simulation and experimental capabilities. Simulation combined with experimental efforts increase our understanding of electromagnetic launch and novel target physics, with a focus on code validation. Two low inductance pulsed power drivers delivering 1 MA and 3.5 MA have been used for electromagnetic launch.

Machine 3 (M3), is a new low inductance capacitor discharge pulsed power generator designed to store up to 2.5 MJ when charged at +/-100 kV, delivering in excess of 14 MA. The pulser was commissioned in December 2018 with the intention to demonstrate fusion. A complementary suite of machine and experimental diagnostics enhance the understanding of novel target physics and validates Hytrac and Code B, two simulation tools developed by FLF. Rapid feedback enables iteration within experimental campaigns and continuous improvement of engineering designs.

During the conference details of M3 design and construction will be presented. Results on the first of six modules, half the machine, and the full machine will be shown. In addition, the full suite of diagnostics for the machine, electromagnetic launch and target physics will be discussed.

M3 PULSED POWER GENERATOR DIAGNOSTIC SUITE

Luis Sebastian Caballero Bendixsen[1], Thomas Clayson[1], Jamie Darling[1], Nicolas Hawker[1], Paul Holligan[1], James Parkin[1], Jonathan Skidmore[1]
1. First Light Fusion

First Light Fusion Ltd (FLF) is a privately funded company of researching energy generation using inertial confinement fusion. Efforts are centred around developing both simulation and experimental capabilities. Three low inductance pulsed power drivers delivering 1 MA, 3.5 MA and 14 MA are used for electromagnetic launch. Experimental and simulation efforts increase our understanding of electromagnetic launch and novel target physics, with a focus on code validation.

Machine 3 (M3), is a low inductance capacitor discharge pulsed power generator designed to store up to 2.5 MJ when charged at +/-100 kV delivering in excess of 14 MA. The pulser was commissioned in December 2018 with the intention to demonstrate fusion.

World class diagnostic capabilities have been established at FLF, including ultra high-speed imaging ($\sim$ 3 ns exposure), streaked spectroscopy, VISAR and dynamic x-ray radiography. M3 diagnostics include a fibre optic Faraday rotation system, V-dot and B-dot probes. This enhances our understanding of the machine, as well as electromagnetic launch techniques and the target physics. During the conference a detailed overview of both machine and experimental diagnostics will be presented. Along with preliminary experimental results of electromagnetic launch experiments.

ALL-SOLID-STATE BIPOLAR HIGH VOLTAGE NANOSECOND PULSE ADDER WITH OUTPUT PARAMETERS ADJUSTABLE

Yonggang Wang, Yifan Huang, Min Jiang

Nanosecond high voltage pulse generators are widely used in dielectric barrier discharges, plasma jets, corona discharges in water, et al. In this paper, a novel bipolar pulse adder with output parameters adjustable is proposed. Several full bridge MOSFET units are connected in series. And the storage capacitors in each units is charged isolated by a high-frequency resonant power supply. In order to solve voltage unbalance between storage capacitors, a third winding is added to each magnetic core transformer. The mechanism of eliminating voltage difference by third windings is analyzed in theory, and validated by simulation and experiments. Optic fibers, together with gate drivers, are used to drive MOSFETs. Thus, each switch can be turned on or off independently and the rising/falling time of each pulse is adjustable. A 6-stage prototype is implemented in laboratory. The pulse adder can generate 5 kV bipolar pulses with voltage polarity, amplitude, repetition rate, pulse width, and rising/falling time adjustable independently. The experimental results are shown in this paper and discussed at last

THE BEHAVIOR OF PULSED STEEL WIRE DISCHARGES

Maximilian Bigelmayr[1], Petrus Pieterse[2], Dirk Uhrlandt[2]
1. Institut für Elektrische Energietechnik, Universität Rostock, Germany
2. Leibniz-Institut für Plasmaforschung und Technologie e.V., Greifswald, Germany

The objective of this project is the analysis of pulsed capacitor discharges through steel wires with varying geometries. Discharges at high energy density levels produce pressure waves which have numerous application possibilities in industry. Experimental trials are performed using a series LCR configuration (C = 150μF, U = 6kV), with the wire producing the circuit damping. In an effort to predict the optimum wire and circuit dimensioning for maximum energy transfer efficiency, various experiments are performed. Wire lengths ranging from 20mm – 160mm and wire diameters from 0.5mm – 1.0mm are used in addition to modifying the circuit inductance (3 – 15μH). The pulse current and voltage across the wire is measured for each separate wire configuration. This allows the computation of the absorbed energy within each individual wire-plasma as well as the power. An analysis of the electrical resistance behavior of these wire-plasmas are performed to find the time independent specific resistance characteristic for various wires. A time independent fit function is used to relate the specific resistance to the wire energy density.

It was possible to discover a coupled system of differential equations, using a semi-physical model, which in turn allows the computation of the pulse current during discharges. Furthermore, a general method was found to compute the discharge behavior of arbitrary wire dimensions. The known circuit parameters as well as the time independent resistance is used to numerically solve the differential equation system through the implementation of an adaptive Runge-Kutta method. This new model may help to plan, design and construct experimental and industrial pulsed wire discharge systems. By using these methods, one is capable of predicting the current, the wire voltage, the capacitor voltage, as well as the energy distribution and efficiency for pulsed steel wire discharge systems using known circuit parameters and arbitrary wire geometries.

Author Index