Michigan Institute for Plasma Science and Engineering (MIPSE)

University of Michigan & Michigan State University

5th ANNUAL
GRADUATE STUDENT SYMPOSIUM

October 8, 2014

2:00 – 7:00 pm

1200 EECS

North Campus, University of Michigan

1301 Beal Avenue

Ann Arbor, MI 48109-2122

University of Michigan
Ann Arbor, MI

Michigan Institute for Plasma Science and Engineering (MIPSE)

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Schedule

1:45 – 2:25	**Registration, poster set-up**
2:25 – 2:30	Prof. Mark J. Kushner, Director of MIPSE ***Opening Remarks***
2:30 – 3:15	**Poster Session I**
3:15 – 3:30	Cookies + soda
3:30 – 4:30	**Special MIPSE Seminar:** **Prof. Gottlieb Oehrlein,** University of Maryland ***Low-Temperature Plasma Surface Interactions: Nanoscale Graphitic Film Formation, Atomic Layer Etching & Atm. Pressure Plasma Jet Modification of Biomolecules***
4:30 – 5:00	Refreshments (box lunch + coffee, tea)
5:00 – 5:45	**Poster Session II**
5:45 – 6:30	**Poster Session III**
6: 45 – 7:00	***Best Presentation Award* Ceremony**

mipse

Michigan Institute for Plasma Science and Engineering

Wednesday
October 8, 2014
3:30 pm
Room 1200
EECS building

Prof. Gottlieb S. Oehrlein

University of Maryland

Low-Temperature Plasma Surface Interactions: Nanoscale Graphitic Film Formation, Atomic Layer Etching & Atm. Pressure Plasma Jet Modification of Biomolecules

Control of plasma-surface interactions is essential for successful application of low temperature plasmas to materials processing. We briefly review three examples of recent from our laboratory: First, formation of an ultrathin (~1nm) delaminated graphitic layer by two-step plasma processing of methacrylate-based polymer that utilizes the interaction of VUV photons and ion bombardment in low pressure plasmas with the polymer. Second, use of low pressure plasma surface interaction mechanisms aimed at achieving atomic precision in etching materials in the semiconductor industry. We show that by employing steady-state Ar plasma in conjunction with periodic injection of a defined number of C_4F_8 molecules and synchronized plasma-based Ar^+ ion bombardment 1/10 of a nanometer precision in etching of SiO_2 is possible. This is due to the temporal variation of the chemically enhanced etch rate of SiO_2 for Ar^+ ion energies below 30 eV as a function of fluorocarbon surface coverage. Third, studies of plasma-surface interactions related to application of a non-equilibrium atmospheric pressure plasma jet (APPJ) for modification of model polymers and biomolecules will also be discussed. Measurements of the changes in surface chemistry and biological activity of biomolecules exposed to the APPJ plume/effluent in a controlled environment clarify how jet chemistry and interaction of plasma with the environment impact the consequences of APPJ-biomaterial-surface interactions.

About the Speaker: Gottlieb S. Oehrlein joined the Department of Materials Science and Engineering and the Institute for Research in Electronics and Applied Physics at the University of Maryland, College Park in 2000. He received his Vordiplom in Physics from Würzburg University, Germany, and his Ph.D. in Physics from the State University of New York, Albany in 1981. He then joined IBM's Research Division in Yorktown Heights, N.Y. as a Research Staff Member where he worked on Plasma Science and Technology for Nanofabrication. From 1993 to 2000 he served as a Professor of Physics at the State University of New York, Albany. His research has been focused on the use of non-equilibrium plasma for advanced materials processing and development of the science required for the control of the interaction of plasma with surfaces.

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Abstracts
Poster Session I

Particle Lists and Monte Carlo Collisional Dynamics on GPUs *

Charles Bardel [a], John Verboncoeur [a], Min Young Hur [b] and Hae June Lee [b]

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Modeling collisional plasma systems with particle-in-cell (PIC) is utilized to model the statistical nature of the plasma. Additional accuracy in simulations requires more particles and grid locations which can easily become computationally prohibitive. However, implementing the Monte Carlo portion of PIC with the Null Collision Method [1] reduces the number of collisional probabilities necessary to calculate particle dynamics. Graphical Processing Units (GPUs) increase performance speed-up of over 140x on FDTD [2]. For example, a two-dimensional GPU model for PIC has a speed-up of nearly 30x [3] over serial CPU. PIC codes have two fundamental data-structures: (1) mesh (FDTD cell) and (2) particles. The current version of the PIC code [3] with the chosen particle list data structure may negatively affect the total performance of the algorithm. This research examines three different versions of data management of the particles to determine the effect on performance: (1) statically sized interleaved cell particle lists, (2) unmanaged particle list, and (3) dynamic particle list for each cell. The primary interest of this research, however, is to determine which of the sections of the algorithm are most impacted and have the strongest effect: particle push, particle boundary conditions, deposition of particle charge to the grid, or Monte Carlo Collisions. Previous experiments on GPU focuse on random sparse access to particles, which is the worst-case scenario for memory-bandwidth on GPUs. This is evident in the MCC section, while the other sections of the code are expected to have effects related to moving information from the structured field data to the particle list data.

* This work supported in part by an AFOSR Grant on the Basic Physics of Distributed Plasma Discharges.

References

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[3] M. Y. Hur, I. C. Song, and J. Verboncoeur, Computer Physics Communications
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High Repetition Rate Relativistic Electron Beam Generation from Intense Laser Solid Interactions

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Relativistic electron beams have wide-ranging applications in medicine, materials science, and homeland security. Recent advances in short pulse laser technology have enabled the production of very high focused intensities at kHz rep rates. Consequently this has led to the generation of high flux sources of relativistic electrons - which is a necessary characteristic of these laser plasma sources for any potential application. In our experiments, through the generation of a plasma by focusing a 5 x 10^{18} W/cm^2, 500 Hz, Ti:Sapphire laser pulse onto a fused silica target, we have measured electrons ejected from the target surface having energies in excess of an MeV. The spectrum of these electrons, as well as the spatial divergence of the resulting beam, was also measured with respect to incident laser angle, prepulse timing and focusing conditions. The experimental results are compared to particle in cell simulations.

Preliminary Observations of Channel Interaction in a 100 kW-Class Nested Channel Hall Thruster*

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Nested-channel Hall Thrusters have been identified as a means to increase the power level of Hall thrusters while maintaining a compact device form factor. Following the lead of the 10-kW class proof-of-concept X2 two-channel NHT [1], the Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan, in collaboration with the Air Force Office of Scientific Research and NASA, have developed and fired the X3 [2], a three-channel NHT capable of discharge powers up to 200 kW. It has been operated to up to a maximum total discharge power of 61 kW.

Similar to what was observed with the X2, the X3 displayed certain behavior when operating multiple channels simultaneously [3]. Of particular interest is the fact that the propellant necessary to maintain current density during multi-channel operation is lower than the sum of the necessary flow rates of the channels operating alone. This significant propellant savings is illustrated in Figure 1.

Additionally, the so-called "breathing mode" frequency (that at which the discharge current oscillates) of simultaneously-operating channels tends to synchronize. This trend indicates significant channel interaction, though the exact mechanism is still unknown. Figure 2 shows a plot of the breathing modes of all three channels of the X3 operating simultaneously at 61 kW total discharge power.

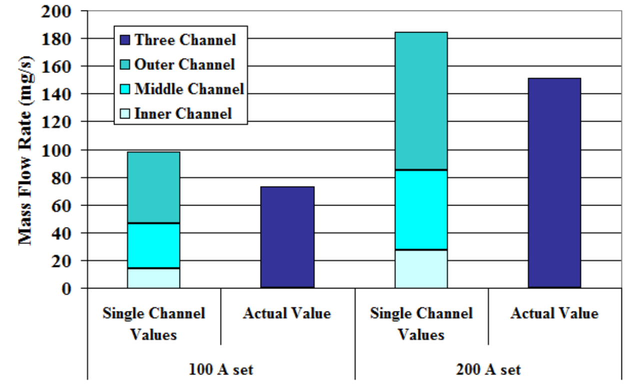

Figure 1 – Mass flow rates for various operating conditions, illustrating that the total mass flow rate necessary to maintain current density in the three-channel mode was significantly less than the sum of the single-channel mass flow rates.

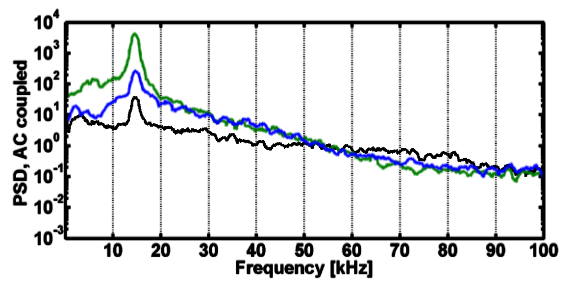

Figure 2 –Power spectral densities of the discharge current of each channel of the X3 operating simultaneously at 61 kW total discharge power illustrate the synchronization of the breathing mode oscillation.

* This work is supported by a NASA Space Technology Research Fellowship and by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1256260. Additional funding was provided by Michigan/AFRL Center of Excellence in Electric Propulsion (MACEEP) FA 9550-09-1-0695.

References

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The X2 Nested Channel Hall Effect Thruster: an Inner Channel Simulation*

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Traditionally, Hall thrusters are built with a single annular channel. However, the idea of nesting multiple channels was recently explored by the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan. First the 10 kW class X2 dual channel thruster was developed by Liang [1] followed by the 100-kW class X3 triple channel device developed by Florenz [2].

Both configurations have shown performance gains when operating multiple channels simultaneously as opposed to independent single channel tests. The unexpected improvements were more significant than could be explained by variations in the facility background pressure [1]. This indicates that a beneficial form of coupling between the channels is taking place, and in order to better understand this phenomenon a series of simulations will be performed.

The initial stage is focused on simulating the X2 single channel operation independently to validate the approach by comparing to experimental measurements. The next stage will be to create a dual channel simulation and concentrate on the channel interaction.

Currently the third revision of the hybrid code HPHall [3] is being used. It models ions and neutrals as particles, while a fluid approach is used for the electrons.

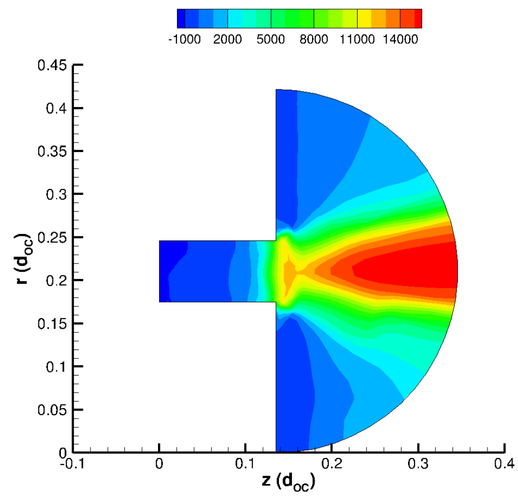

Figure 1 – Axial ion velocity contours (m/s).

For the current test conditions, thrust is matched to within 10% of the measured value. Electron temperature and plasma potential comparisons will follow for the same test conditions. A contour plot of the axial ion velocity is shown in Figure 1.

* Work supported under a NASA Space Technology Research Fellowship, grant number: NNX13AL51H

References

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Time Resolved Studies of Steam Discharges *

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It is commonly known that contaminated water may be sterilized through the use of atmospheric pressure, nonequilibrium discharges. The interaction of these plasmas with the discharge gas and treated liquid, or even just the liquid, creates a collection of quickly oxidizing species that mineralize and break down contaminants.

Like their gas counterparts, steam discharges have been shown to break down contaminants in liquid water with a minimized effect on the pH of the liquid. This work examines the time resolved optical emission spectroscopy of these discharges as a method to investigate the various production mechanisms of the chemical species involved in the sterilization process (such as hydrogen peroxide).

* This material is based upon work supported by the National Science Foundation (CBET 1033141 and CBET 1336375) and the National Science Foundation Graduate Student Research Fellowship under Grant No. DGE 0718128.

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Electrostatic Particle Based Modeling for Simulation of Strongly Coupled Plasmas

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This work focuses on the development of new modeling and simulation tools for studying strongly coupled plasmas (SCP) which differ from traditional plasmas in that their potential energy is larger than kinetic energy. The standard quasi neutral plasma model does not account for two major effects in SCP: 1) Change in the permittivity for modeling electromagnetic waves. 2) Impact on relaxation of charged particles undergoing Coulomb collisions with weakly shielded long range interactions. These objectives require the development of: (i) Electrostatic particle based models based on particle in cell (PIC) and boundary integral treecode (BIT) methods (ii) Electromagnetic particle based models based on PIC and new implicit particle methods based on treecodes (iii) Continuum models with long range correlations incorporated through fractional derivatives in time. BIT is a mesh free method offering advantages in simulating resolved SCP with boundary conditions, whereas resolved PIC necessitates a prohibitively fine mesh when including boundary conditions. A treecode algorithm reduces operation count for full Coulomb interaction from $O(N^2)$ to $O(N \log N)$. The particles are divided into a hierarchy of clusters and particle-particle interactions are replaced by particle-cluster interactions evaluated using multipole expansions. Treecodes using monopole approximations and a divide-and-conquer evaluation strategy have been very successful in particle simulations. With an ongoing interest in optimizing their performance, BIT is an ideal method for studying strongly coupled electrostatic plasmas consisting of $\sim 10^8$ atoms. In this context BIT can be used to simulate a one to one representation of the ultra cold SCP, each particle representing a physical particle, naturally resolving long range interactions. Our current work includes studying oscillations and expansion in SCP, and comparison with experimental work.

* This project is supported by an AFOSR Basic Research Initiative on Ultra Cold Plasmas

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Current Crowding in Thin Film Electrical Contacts*

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Electrical contact problems account for 40 percent of all electrical/electronic failures, ranging from small scale consumer electronic devices to large scale military and aerospace systems [1]. Making good contacts remains the major challenge for using materials with exceptional mechanical, electrical, and thermal properties in electronics, including carbon nanotubes (CNT) and graphene. It is essential to understand contact resistance and the crowding of current flow lines, which leads to enhanced localized heating. This presentation summarizes recent advances on the modeling of electrical contacts. Both horizontal [2] and vertical [3] thin film contacts are considered, exhibiting very different spreading resistance and current crowding behaviors. Scaling laws are constructed for a large range of material properties and geometrical aspect ratios. Our exact field solution of the general contact model accounts for both interface resistance and spreading resistance [4]. The results are compared with the widely used lumped-circuit transmission line model (TLM). The regimes dominated by the specific contact resistance or by the spreading resistance are identified and compared with experimental data.

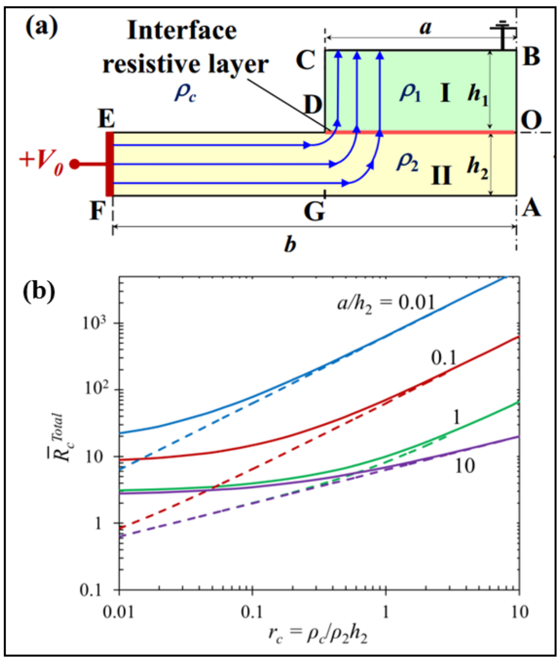

Figure 1a shows the general model for electrical contact. An infinitesimally thin resistive interface layer is sandwiched between two regions I and II. Figure 1b shows the normalized total contact resistance (sum of interface resistance and spreading resistance) for the Cartesian geometry of Fig. 1a, calculated from both our exact field solution and TLM. It is clear that TLM breaks down if the interface resistivity $\rho_c \rightarrow 0$.

Figure 1 - (a) Electrical contact. An infinitesimally thin resistive interface layer is sandwiched between Regions I and II. (b) The normalized total contact resistance for Cartesian thin film contacts in (a), as a function of normalized interface resistivity $r_c = \rho_c/\rho_2 h_2$, for various a/h_2. The solid line is for our exact field solution, the dashed line is for TLM [4].

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PumpKin: A Tool to Find Principal Pathways in Plasma Chemical Models*

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The growing interest in plasma chemistry significantly increases the complexity of chemical models. Recent kinetic models of atmospheric chemistry [1] or of industrial applications [2] contain thousands of chemical reactions and species. Here one should take into consideration that different species have different lifetimes, reaction rates depend on externally applied electric field as well as on temperature. As a result, researchers and engineers are faced with the problem of evaluating very complex models. In some cases, it is necessary to reduce the chemical reaction system to a more compact set of chemical pathways, which will have fewer reactions and fewer species. Besides the practical and/or computational reasoning, this reduce complexity is very important for understanding the mechanisms of production and destruction of certain key species. For example, such techniques have been successfully applied in atmospheric chemistry to investigate ozone destruction [3].

In the present work we have developed the software PumpKin (pathway reduction method for plasma kinetic models) to find all principal pathways (i.e. the important reaction sequences) in a given chemical reaction system. The user first solves the full chemical reaction system, but does so only once. The output is later used as an input for PumpKin. PumpKin analyzes the full chemical reaction system, and automatically determines all significant pathways in the system with a rate above a user-specified threshold.

As the problem is rather general, many different fields (atmospheric chemistry, oceanography, biological systems, genetics, plasma physics, combustion physics etc.) have their own tools and methods to deal with this problem. A general method to gain insight into a dynamical system is sensitivity analysis [4], which determines the response of the system to perturbations of individual parameters. However, it cannot determine complete pathways like, for instance, the catalytic ozone destruction cycles.

Our approach is based on the algorithm described in Ref. [5] which from the basic idea of forming pathways by connecting shorter ones. Here are the key elements:

a) We assume the reaction rates are known, and then we calculate the rate of each pathway.
b) If a newly formed pathway includes sub-pathways, we do not delete it, but split it into its sub-pathways. Then its rate is fully distributed onto the sub-pathways in order to conserve the total flux of reactants and products.
c) We delete pathways with small rates in order to avoid an excessive number of pathways.

The PumpKin package (www.pumpkin-tool.org) is written in object-oriented C++ language. The current version 1.1 of the code reads input files having formats produced by the zero-dimensional plasma kinetics modelling platforms ZDPlasKin and Global_Kin.

* The work is supported by STW-project 10751, ESF grant 5297 and project FQM-5965.

References

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Study of the Feasibility of an EEDF Driven Rare Gas Metastable Laser: Application of a Kinetic Global Model*

Guy Parsey [a], Yaman Güçlü [b], John Verboncoeur [a], Andrew Christlieb [a]

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(b) Max-Planck Institute (yguclu@msu.edu)

Motivation for the rare gas laser (RGL) was instigated by a similarity between the excited level structures of alkali metals used in a diode-pumped alkali laser (DPAL) and those of metastable excitations of noble gas species. First presented experimentally by Han and Heaven, transition probabilities, upper state radiative lifetimes, lasing wavelengths, pressure broadening coefficients and ionization potentials are extremely similar between the DPAL and RGL pumping transition.[1] However, rare gas metastables have the benefit of being chemically inert and gaseous without heating. The RGL use an electric discharge to maintain the metastable species densities, analogous to heating for the alkali vapor, while both focus on optical pumping to induce lasing with a three-level scheme. We propose using a modified electron energy distribution function (EEDF) to either modify RGL efficiency characteristics or to drive the optical gain process.

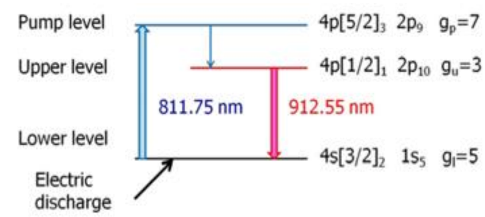

Figure 1 – Line diagram of Argon excited levels used in the lasing process.[2] Thick arrows mark pumping and lasing transitions.

Using our general-purpose kinetic global modeling framework (KGMf), we present a study on the effect of the EEDF on the Argon RGL reaction kinetics with an emphasis on determining if lasing can be achieved without optical pumping. We first model the optically driven system to create a gain efficiency baseline and verify the implemented intensity driven laser model against the simulation work presented by Demyanov et. al.[2] With a comparative baseline, we then look at the effectiveness of using a microwave induced EEDF to either modify optical driven RGL characteristics or maintain the lasing state population inversion without a driving laser. Two argon models are used, a pure Ar system and a second doped with helium to drive collisional relation to the upper lasing level. The physical system will be assumed to be similar to that proposed by Han and Heaven.

* Supported in part by the Air Force Research Laboratory and an MSU Strategic Partnership Grant

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Analysis of a Disk-on-Rod Traveling Wave Amplifier*

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For many high power microwave (HPM) devices, the focus on power usually leaves bandwidth neglected. The disk-on-rod traveling wave tube (TWT) aims to fill the demand for high power and large bandwidth. The high power is provided by an annular electron beam, which has a higher limiting current than a pencil beam due to increased cathode surface area. The high bandwidth is a result of using the disk-on-rod slow wave structure (SWS), as high bandwidth is intrinsic to TWTs. The system is schematically shown in Fig. 1.

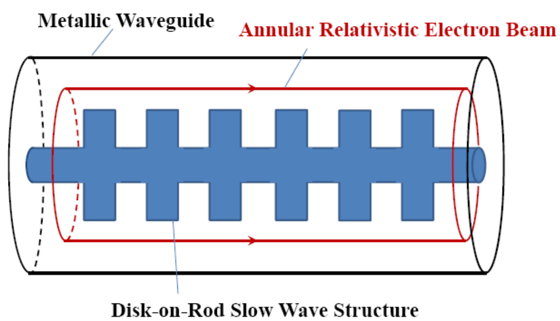

Figure 1 – Diagram of HPM device, including annular beam and disk-on-rod slow wave structure

Traditional TWT metrics are derived anew for the disk-on-rod TWT with an annular beam to allow for comparison to existing tubes. The Pierce gain parameter C is calculated by two different methods; a traditional approach that calculates the interaction of the beam and the dominant circuit mode, and an exact formulation of the space-charge wave on the SWS [1][2]. Both methods agree, and as a consequence of using the two methods, the Pierce space charge parameter QC can be calculated. This is the first time that QC is rigorously derived for a complex slow wave structure. Table 1 shows values of C and QC that are competitive with conventional TWTs.

I [A]	J [A/m^2]	C	QC	β_i (QC = 0) [m^{-1}]	β_i (QC ≠ 0) [m^{-1}]	Operating Parameters	
0.5	2842.1	0.012	0.056	1.070	0.990	V [kV]	123.847
1.563	8881.4	0.018	0.082	1.565	1.393	β_{01} [m^{-1}]	100
6.25	35525.7	0.029	0.130	2.484	2.048	f_{01} [GHz]	2.832
25	142102.6	0.046	0.206	3.943	2.821	R_{beam}[cm]	2.8
50	284205.3	0.057	0.260	4.968	3.145		

Table 1 - Values of C, QC, and the spatial amplification rate β_i for the given operating parameters

In addition to the Pierce parameters, the disk-on-rod TWT cold- and hot-tube dispersion relations have been found analytically. The cold-tube dispersion compares quite well to a numerical simulation using HFSS. We are simulating the device performance using a PIC code to compare with the analytic theory.

* Work supported by AFOSR and L-3 EDD

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Investigation of the Electrothermal Instability on Planar Foil Ablation Experiments*

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The electrothermal instability (ETI) has recently been of interest on magnetized liner implosion experiments due to its ability to seed the destructive magneto-Rayleigh-Taylor instability on imploding metallic surfaces [1-2]. ETI occurs whenever electrical resistivity has temperature dependence; when resistivity increases with temperature, as with solid metal liners or foils, ETI forms stratified structures perpendicular to current flow. High-wavenumber striations have been observed on laser shadowgraph images of ablating foil plasmas on the MAIZE 1-MA linear transformer driver at the University of Michigan [3].

The MAIZE linear transformer driver was used to ablate 400-nm aluminum foils with current pulses of approximately 600 kA at a charging voltage of +/- 70 kV. Shadowgraph images of the aluminum plasmas were taken for several shots at various times within approximately 50 ns of start of current. Fourier analysis was used to extract the approximate wavelengths of the instability structures forming on the plasma-vacuum interface. Surface metrology of pre-shot foils was performed to provide a comparison between surface roughness features and resulting plasma structure. The transition from early-time, large wavenumber structures to later, low wavenumber structures is examined.

* This work was supported by the U.S. Department of Energy. S.G. Patel and A.M. Steiner were supported by NPSC fellowships funded by Sandia National Laboratories. D.A. Yager-Elorriaga is supported by NSF fellowship grant DGE 1256260.

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Results of a Supersonic, Single-mode, Shockwave-driven Kelvin-Helmholtz Instability Experiment*

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The Kelvin-Helmholtz instability is a hydrodynamic process that causes mixing at an interface with shear flow. It is prevalent in many high-energy-density systems such as fusion research, core-collapse supernovae, and protoplanetary disks. Although it is common to simplify the Euler equations by assuming incompressibility, this assumption does not account for the inhibited growth rate found in supersonic flows. Here we present the first laboratory observations of single-mode, compressible Kelvin-Helmholtz instability growth.

This experiment was performed at the OMEGA-EP facility utilizing three beams stitched into a 28 ns square pulse to sustain a shockwave in a low-density foam. The shockwave generated shear along the interface between the foam and a high-density plastic, seeded with a precision-machined, single-mode, sinusoidal perturbation. The system was diagnosed using x-ray radiography with a spherically bent crystal.

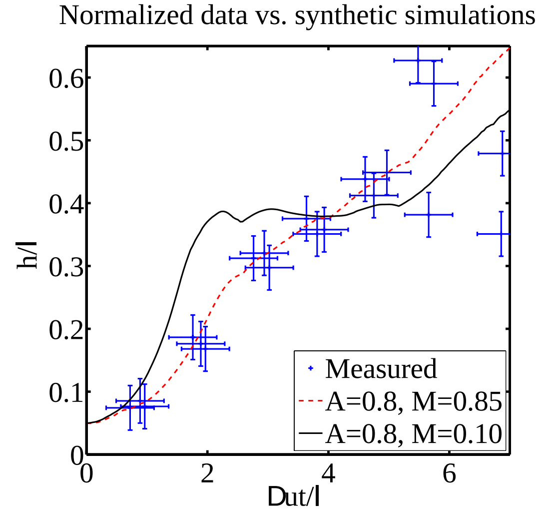

Figure 1 – Normalized experimental data fit against theoretical predictions with (dashed red) and without (solid black) significant compression.

* +This work is funded by the U.S. Department of Energy, through the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0001840, the National Laser User Facility Program, grant number DE-NA0000850, and the Laboratory for Laser Energetics, University of Rochester by the NNSA/OICF under Cooperative Agreement No. DE-FC52-08NA28302.

Accretion Shocks on Young Stars: A Laboratory-Astrophysics Investigation*

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We intend to present results of a laboratory-astrophysics investigation of accretion shocks at the surface of young stars.

We have scaled a stellar accretion shock to an OMEGA experiment by creating a plasma jet (representing the accreting material) and colliding it with a solid block (representing the surface of the young star). Understanding the structure of accretion shocks will allow researchers to more accurately calculate accretion rates.

Magnetic fields are thought to play crucial role in this phenomenon, and therefore we conducted our experiments with imposed magnetic fields of 0 T, 3 T and 7 T. These fields are be imposed by MIFEDS (Magneto-Inertial Fusion Electrical Discharge System) devices, which are custom-designed for each experiment by LLE. We used proton radiography to image the magnetic field distortions in the experiment.

* This work is funded by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0001840, and by the National Laser User Facility Program, grant number DE-NA0000850.

The Long Term Effects of Random DBD Streamers on Thin Liquid Layers over Tissues*

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Atmospheric DBDs are used in treatment of human tissue, such as wounded skin and cancer cells, due to their ability of producing a variety of reactive oxygen and nitrogen species (RONS). The plasma treatment often lasts from several seconds to minutes and consists of 100s to 10,000s pulses, depending on tissue conditions, such as wound area, depth and contamination.[1] The tissue is rarely dry. Instead, the tissue is often covered by a thin liquid layer, mostly water with dissolved gases and proteins, such as O_{2aq} ('aq' denotes aqueous species) and alkane hydrocarbon (denoted as 'RH_{aq}'). The long term effects of plasma exposure, including accumulation of radicals accumulation and acidification of the liquid, are extremely important in these applications. In this presentation, we report on a computational investigation of DBDs in contact with a 200 µm thick liquid layer covering tissue. The model we used is *nonPDPSIM*, a 2-dimensional model in which Poisson's equation, electron temperature equation and transport equations for charged and neutral species are solved. The liquid layer is treated identically to gas as a partially ionized substance with higher density and designated permittivity. Water is allowed to evaporate into gas with a source given by its saturated vapor pressure. The rate of transport of gas phase species into the liquid is given by Henry's law.

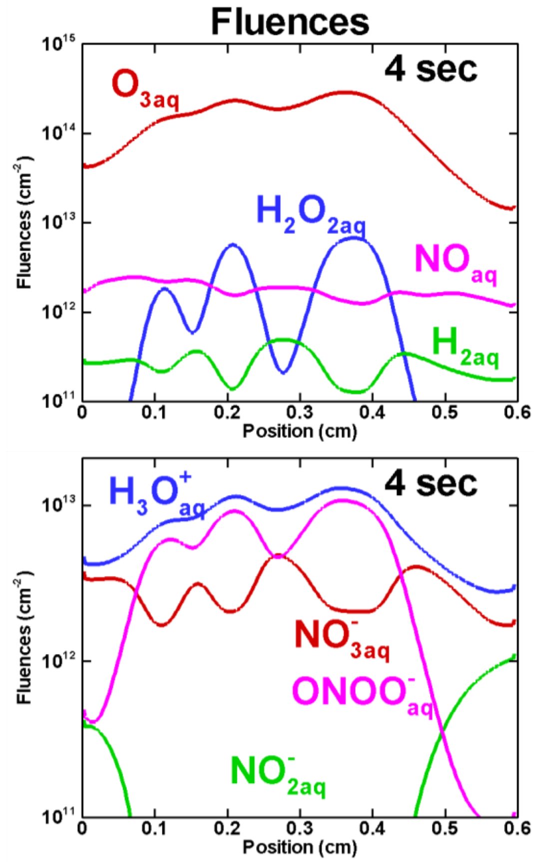

Figure 1 – Fluences of reactive species received by the underlying tissues.

The DBDs are operated with 100 randomly located pulses of -18kV at 100 Hz followed by minutes of afterglow. The randomness of streamers striking the liquid layer significantly reduces nonuniformities. The fluences of reactive species onto the underlying tissue are shown in Fig. 1. $H_3O^+_{aq}$ dominates the positive species while $ONOO^-_{aq}$ and $NO_3{}^-_{aq}$ dominate negative species. $ONOO^-_{aq}$ slowly converts to $NO_3{}^-_{aq}$. The dominant RONS in the liquid are O_{3aq} and H_2O_{2aq}. O_{3aq} is generally uniform. H_2O_{2aq} has significant peaks determined by where the streamers strike on the liquid layer. For liquids with RH_{aq}, ROS are largely consumed, leaving $R\bullet_{aq}$ (alkane radical) to reach the tissue.

* Work was supported by DOE Office of Fusion Energy Science (DE-SC0001319) and the National Science Foundation (CHE-1124724).

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Measurements of Laser Generated X-ray Spectra from Irradiated Gold Foils*

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In many HED systems high intensity x-rays can be used to measure plasma properties such as density and temperature. These diagnostic X-rays are typically produced by irradiating a metal foil with high-intensity lasers (I >1e13W/cm^2), which heat the foil and cause it to act as a quasi-continuum x-ray source for radiography or absorption spectroscopy. As this emission is quasi-continuous and the transmission of x-rays through a material varies with photon energy, a well-characterized x-ray source is vital. Therefore, in order to optimize diagnostics reliant upon x-rays, it is necessary to gain a better understanding of how the x-ray emission from these targets varies over time and varying beam energy. We will present experimental results studying the effect of beam energy and pulse length on M-band and sub-keV x-ray emission generated from a 5um thick gold disk using time-resolved spectroscopy.

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Development and Validation of a Quasi-one-dimensional Particle-in-cell Code for Magnetic Nozzle Simulation*

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A novel quasi-one-dimensional (Q1D) particle-in-cell (PIC) code for kinetic simulation of magnetic nozzles is developed and validated.[1] Two dimensional effects are included through quasi-1D algorithms which include virtual displacements of magnetized particles from the axis of symmetry and cross-sectional area variation based on the assumption that magnetized particles follow magnetic field lines and the conservation of magnetic flux. The Boris algorithm is modified to capture the Lorentz force effects in an axisymmetric quasi-1D coordinate system.[2]

Validation test cases were selected to demonstrate the ability of this code to capture the important physics of magnetic nozzles. These simulations included modelling of two stream instabilities[3], Landau damping[3,4], source and collector sheaths[5], and magnetic mirrors. Results from these simulations illustrate the ability of the code to capture plasma instabilities and oscillations, complex potential structures, and magnetic mirror physics, which are necessary to study magnetic nozzles in a novel way from a kinetic perspective. Figure 1 shows the results of a magnetic mirror simulation in which the code accurately captures the loss cone of a magnetic mirror.

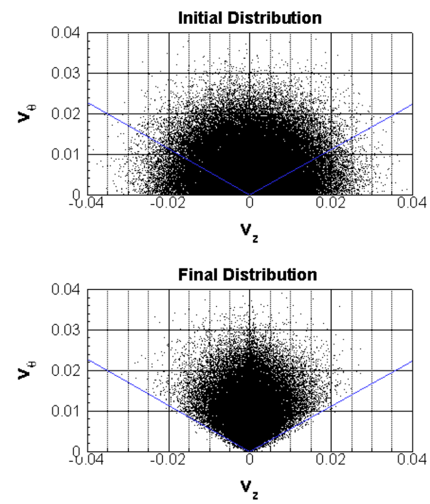

Figure 1 – Magnetic mirror particle velocity distribution comparison with analytical loss cone (blue).

* This research is funded by a NASA Office of the Chief Technologist Space Technology Research Fellowship.

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Multipactor Modelling Using an Averaged Version of Furman's SEY Model*

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Multipactor is a resonant phenomenon in which an electromagnetic field causes a free electron to impact a surface, resulting in the surface emitting one or more secondary electrons. If the surface geometry and electromagnetic fields are appropriately arranged, the secondary electrons can then be accelerated and again impact a surface in the bounding geometry. If the net number of secondary electrons participating in multipactor is non-decreasing, then the process can repeat indefinitely. This phenomenon is of considerable practical interest in the design and operation of radio frequency (RF) resonant structures, windows, and supporting structures.

The formation of multipactor is strongly dependent upon the secondary electron yield (SEY) of a surface, and the emission velocities of the emitted electrons. Two SEY models are popular within different technical communities: Vaughan's model [1] is a relatively simple model that popular in the radio frequency (RF) and microwave source industry; this model does not include SEY contribution from low-impact energy electrons, nor does it specify emission process (energy, angle, number of electrons, etc.). Furman's model [2] is a more sophisticated model which is popular in the particle accelerator community; this model includes SEY contribution from low-impact energy electrons, and the model stochastically specifies the emission process, thus requiring a Monte Carlo simulation in practice.

Recent work has suggested that multipactor formation can be very sensitive to low impact energy electrons and the SEY in this region [3]. Therefore, we are interested in capturing the SEY contribution from low-impact energy electrons, but without the computational cost of a full Monte Carlo simulation using Furman's model. This research presents a modified version of Furman's SEY model, which preserves the net SEY at all impact energies, but uses a pre-computed average emission velocity instead of a stochatic emission process, thereby avoiding the cost of a Monte Carlo simulation. Respectable agreement between multipactor predictions is demonstrated using Furman's full model and the averaged model in a notional coaxial geometry.

* Research supported by U.S. Air Force Office of Scientific Research (AFOSR) grant on the Basic Physics of Distributed Plasma Discharges, and a MSU Strategic Partnership Grant.

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A General Study of Absolute Instability in Electron Beam-Circuit Interactions*

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Oscillations in traveling wave amplifiers are generally caused by either an external or internal feedback process. The external feedback is provided by reflections at both ends of the interaction region. If the amplitude of the reflected signal reaches a certain level such that the loop gain exceeds unity, the wave amplification processes become regenerative and consequently oscillations take place. The internal feedback is a result of the dispersiveness of the unstable medium. Under certain conditions, the wave may grow locally without propagating axially out of the system. As a result, large amplitude waves can simply grow from noise level perturbations. Unlike those caused by end reflections, oscillations produced by internal feedback processes may occur in tubes that are perfectly matched at the input and output, and these oscillations are called absolute instability [1].

This paper provides a first study of absolute instability in a coupled-cavity traveling wave tube (TWT). The interaction of the circuit mode and the beam mode (Fig. 1) may excite absolute instability at the lower band edge (A) and at the upper band edge (B). In the vicinity of A and B, we approximate the circuit mode by a hyperbola in the (ω, k) plane. We next apply the Briggs-Bers criterion [1] to study absolute instability at these band edges. A threshold current for onset of absolute instability is observed at the upper band edge, but not the lower band edge. The nonexistence of absolute instability at the lower band edge (A) is mathematically similar to the nonexistence of absolute instability that we recently demonstrated for a dielectric TWT. The existence of absolute instability at the upper band edge (B) turns out to be mathematically similar to the existence of absolute instability in a gyroton-traveling wave amplifier [2]. These interesting observations will be discussed, and the practical implications will be explored.

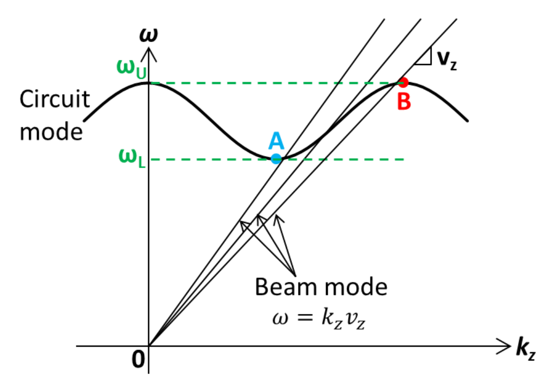

Figure 1 – Dispersion relation of TWT in the (ω, k) plane. Lower and upper band edges are noted at points A and B respectively.

* This work was supported by AFOSR, ONR, and L-3 Communications Electron Devices.

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Dual Frequency Capacitively Coupled Discharge Sustained in Cl_2

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The effect of the control parameters of both the high and low frequency sources on a dual frequency capacitively coupled discharge sustained in Cl_2 is systematically investigated using a hybrid approach consisting of a particle-in-cell/Monte Carlo simulation [1] and a volume averaged global model [2]. The high frequency current density is varied from 20 to 80 A/m^2, the low frequency current density is varied from 1 to 4 A/m^2, the driving high frequency is varied from 27.12 to 100 MHz, and the driving low frequency is varied from 1 to 13.56 MHz, while the discharge pressure is kept at 10 mTorr.

As the high frequency current increases, the electron heating is enhanced in the sheath region and is diminished in the bulk region, showing a transition of the electron heating from the drift-ambipolar (DA) mode [3] to the α mode. The DA heating mode is unique to electronegative discharges. This mode mainly originates from a strong drift electric field in the center of the discharge and an ambipolar field at the sheath edge due to local maxima of the electron density in the electropositive edge region of the discharge. (See Fig. 1.)

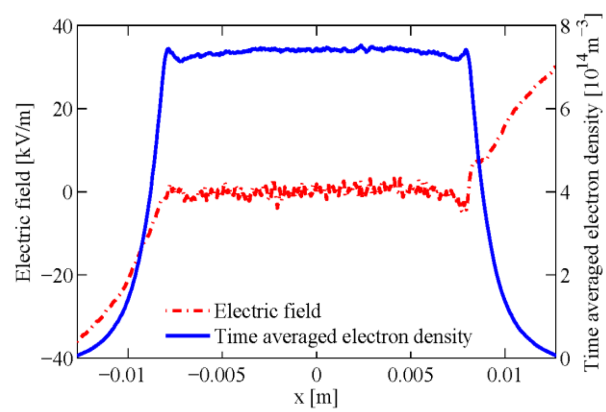

Figure 1. The profile of the instantaneous electric field (left scale) when the left sheath is expanding and the right sheath is collapsing and the time averaged electron density (right scale) for a dual frequency parallel plate capacitively coupled chlorine discharge at 10 mTorr with a gap separation of 0.0254 m. (Other conditions: J_{hf} = 40 A/m^2, f_{hf} = 27.12 MHz, J_{lf} = 1 A/m^2 and f_{lf} =2 MHz.)

The fluxes of Cl_2^+ ions and high-energy Cl_2 molecules reaching the surface decrease with increasing driving high frequency since the average sheath potential is approximately inversely proportional to the driving high frequency. The electron heating rate, the fluxes of Cl_2^+ and Cl^+ ions reaching the surface and the average sheath potential show little dependence on the driving low frequency, while the profile of the ion energy distribution evolves from a broad bimodal profile to a narrow single-peak profile as the driving low frequency increases. This trend corresponds to the transition of the discharge from the intermediate frequency regime to the high frequency regime.

* Work supported by the Icelandic Research Fund Grant No. 130029-051.

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Plasma Dynamics of Microwave Excited Microplasmas in a Sub-Millimeter Cavity*

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Capacitively coupled microplasmas in dielectric cavities are widely used as compact sources of energetic species, such as plumes of ionized gas, or VUV photons. Such sources have many applications ranging from surface treatment to VUV lighting sources to radical production. In these devices, the wall mediated dynamics are important to the uniformity and confinement of the plasma, due to their large surface-to-volume ratio.

In this paper, plasma dynamics in microwave excited microplasma VUV lighting sources are computationally investigated using a 2-dimensional hydrodynamic model. Radiation and electron energy transport are addressed using Monte Carlo techniques. The microplasmas are operated in pure rare gases or mixtures of rare gases at 1-20 Torr, with widths of ≈1 mm and lengths of ≈1 cm, excited by 2.5 GHz microwave power of 2-10s Watt and a flow rate of several sccm.

Normal operating conditions produce a peak electron density of 10^{13} cm^{-3} in argon gas. The plasma dynamics were found to have characteristics that resembled both classic normal and abnormal glows. Like a normal glow, the plasma would not fill the cavity at low power, and would expand to fill the cavity as power increases. The current density, however, increases with increasing power, and in this regard, the plasmas operate as an abnormal glow. The cavity is overfilled by the plasma expansion at high power, at which time a plasma plume is formed. The plume from the cavity flows into pressures as low as a few mTorr. These plasma dynamics are sensitive to gas mixture. The scaling of plasma confinement and VUV production as a function of aspect ratio, power and gas mixture will be discussed.

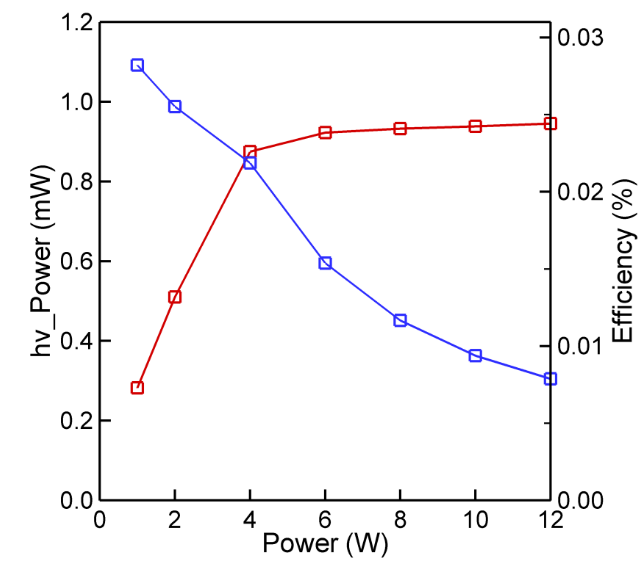

Figure 1 – Photon Flux Power and Power Efficiency Produced from Ar Microplasma.

* Work supported by Agilent Technologies.

Kinetic Simulation of Trapped Particle Bunching Instability in Electron Plasma Waves*

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The bunching instability of particles trapped in electron plasma waves is studied using a 1D+1V (one-dimension in physical space and one-dimension in velocity space) Vlasov simulation, in which the collisionless Vlasov equation is solved directly to obtain the velocity distribution functions (VDFs). Instabilities due to the trapped particles in nonlinear plasma waves plays an important role particularly in laser plasma interactions where the incident laser light can interact with the plasma waves [1].

Trapped particle bunching instability, also known as the negative mass instability [2], may occur when the trapped particle bounce frequency is a decreasing function of wave-frame energy. Assume there is a set of particles on the same energy level. Through Coulomb repulsion, the trailing particles will be shifted to a lower-energy orbit, where the bounce frequency is high, by those leading and vice verse. This results in bunching of trapped particles.

A measure of particle bunching is defined for the first time and used to extract the growth rate from numerical simulations. In addition, the general theory of trapped particle instability in 1D is revisited and a more accurate description of the dispersion relation is obtained. Excellent agreement between numerical and theoretical predictions of growth rates of the bunching instability is shown over a range of parameters [3].

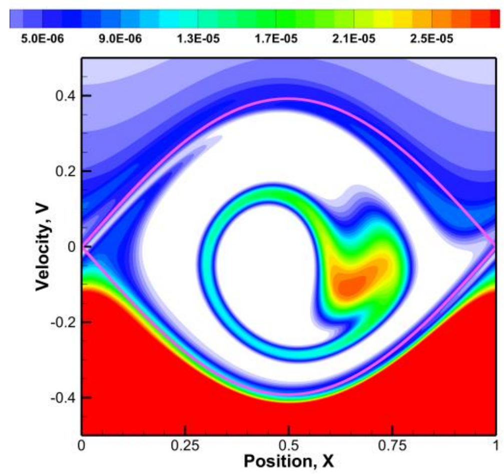

Figure 1 – Example of particle buching in the wave frame of a moving potential well at $\omega_{pe}t$ = 1200. Pink line shows the separatrix.

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Where did Earth's Post-Midnight High Energy Plasmasphere Go?*

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The Van Allen Probes Helium Oxygen Proton Electron (HOPE) instrument measures a high energy tail of the thermal plasmasphere that has strong MLT dependence in the near Earth space. In our study, we statistically analyze a 16 month period of HOPE data, looking at quiet times with a Kp index of less than 3. The high energy plasmasphere tail is the upper 5% of plasmasphere energies, consisting of ions between 1 - 10 eV. We calculated plasma densities over this energy range and see that there is strong depletion in O+ and H+ from 1-4 MLT and a similar but less dramatic density decline in He+. Our results are compared with the Van Allen Probes Electric Fields and Waves (EFW) instrument space craft potential to rule out spacecraft charging. We conclude that the post-midnight ion disappearance is due to diurnal ionospheric temperature variation and charge exchange processes.

* Work supported by the NSF.

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Metallic Beam Development with an ECR Ion Source at Michigan State University (MSU)*

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Electron Cyclotron Resonance (ECR) ion sources have been used at MSU to provide metal ion beams to the coupled cyclotron facility (CCF), and in the future, for The Facility for Rare Isotope Beams (FRIB). The challenges of metallic beam production with ECR are in production, efficiency, stability and contamination. Future facilities such as FRIB will add the challenge of intensity. We report development of two rare earth metals and the conversion from the oxidized state into metal.The enriched isotopes of ^{144}Sm, and ^{176}Yb are commonly available in the sesquioxide form which is unsuitable for use in our standard ovens. We report here results from the off-line chemical reduction of samarium, and ytterbium oxides into metal. We were able to demonstrate efficiencies of up to 90 % throughout the conversion process. The samples were then run on our ECR ion sources to confirm the products of the reduction. In addition we report the development of cadmium metal by passing vapor though over 3/4 m of heated stainless steel tubing and observed 4.3 eμA of Cd^{20+} with an average consumption of 1 mg/hr.

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Plasma-Assisted CVD Grown Single Crystal Diamond for Swift-Heavy Ion Beam Detectors

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Diamond is an attractive candidate for thermal, optical and detector applications due to its numerous superior material properties. Application of diamond for high energy radiation detector has become a growing field of interest in the last few decades. In this particular study, single crystal diamond is investigated for its application as a swift, heavy ion beam detector. The nature of interaction of ions with materials depend on the ion's nuclear charge and energy. Diamond is expected to offer very high radiation tolerance compared to other contemporary semiconducting materials.

Single crystal diamond is grown at Michigan State University (MSU) by microwave plasma assisted chemical vapor deposition (MPACVD) system. Detection performance of the diamond is studied with an eventual objective of understanding the degradation mechanism and lifetime of the detectors under swift heavy ion beams. The single crystal diamond is first mechanically polished followed by chemical-mechanical polishing and/or plasma-assisted etching to reduce surface roughness and mechanical-polishing induced damage. Next the material properties of the diamond are characterized by birefringence, UV-VIS and FTIR (Fourier Transform Infrared spectroscopy) measurements. The detector is constructed by growing top and bottom electrode using sputtering/e-beam evaporation of metal electrode material. The detection performance is studied using swift heavy ion beam generated at the National Superconducting Cyclotron Laboratory (NSCL), MSU. Initial observations of the diamond detectors under 120 MeV/u $^{124}Sn^{45+}$ beam are presented here. Further characterization of detector will be carried to understand charge collection efficiency (CCE) and transient current response.

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Magneto-Rayleigh-Taylor Growth and Feedthrough in Cylindrical Liners*

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Cylindrical liner implosions in the Magnetized Liner Inertial Fusion (MagLIF) concept [1] are susceptible to the magneto-Rayleigh-Taylor instability (MRT). In MagLIF, a pulsed power machine (such as the Z-machine at Sandia National Laboratories) is used to drive a large axial current, initiating the implosion of a metal cylindrical liner onto a pre-heated (~ 250 eV) and pre-magnetized (~ 10 T axial field) fusion fuel. During the implosion process the exterior surface of the liner is initially MRT unstable while the fuel/liner interface is stable. As the fuel becomes sufficiently compressed the liner begins to stagnate and the inner surface becomes MRT unstable (as the acceleration direction has changed). Initial MRT growth on the outer surface of the liner may also feedthrough to the inner surface and provide a seed for the latter's MRT growth during the stagnation phase. Maintaining liner integrity against MRT is key to the success of Mag-LIF.

To characterize MRT we solve the linearized ideal MHD equations, including the presence of an axial magnetic field and the effects of sausage and kink modes. The eigenmode solution, using appropriate equilibrium profiles, allows an assessment of the local MRT growth rate and of the instantaneous feedthrough factor during the entire implosion process once the initial surface perturbation is assumed.

We compare our analytic results to 2D HYDRA simulations of seeded liners [2] including an axial magnetic field and fill gas. Shock driven liners display enhanced feedthrough with large wavelength seeding ($k_z\Delta < 5$) on the outside surface. HYDRA simulations show this growth to be consistent with Richtmyer-Meshkov instability. Such growth also remains extremely robust even in the presence of a large axial magnetic field ($B_z > 100$ T). To better compare with analytic theory for feedthrough, a quasi-isentropic compression pulse was developed which has successfully shown the possibility of feedthrough reduction due to a compressed axial magnetic field.

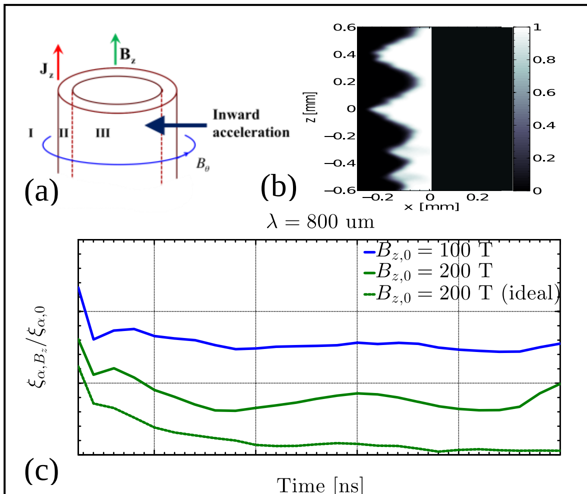

Figure 1 – (a) Sharp boundary model of a liner implosion. (b) Comparison of MRT evolution from 2D HYDRA and experiment [2]. (c) Inner surface growth as a function of time for an isentropic pulse. Increasing axial magnetic field helps stabilize inner surface.

* This work was supported by DoE and NSF.

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Temperature Dependence of Boron Doping Efficiency

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Microwave Plasma Assisted Chemical Vapor Deposition (MPACVD) of semiconducting, boron-doped, single crystal diamond (SCD) has been an area of significant recent research interest. Due to its superlative properties, such as a wide bandgap, high breakdown voltage, and high electron and hole mobilities, diamond is a potentially exceptional semiconductor. Diamond would be particularly well suited for extreme electronic applications, especially high-temperature and high-power devices, such as vertical Schottky Barrier diodes. The realization of vertical diode structures requires the ability to reliably produce heavily doped ($> 10^{20}$ cm^{-3}), free standing (> 200 μm thick) *p*-type substrates, however doping issues continue to be a limitation in this field. In our previous work [1] we have shown that the substrate temperature during growth has a significant effect on the defect morphology. The gas to solid phase boron incorporation doping efficiency was also shown to be temperature dependent. In examining the effect of the growth rate, the ratio of the boron concentration in the gas phase to the flux of carbon incorporated into the solid diamond phase was shown to be a more predictive measure of the resulting boron concentration than the gas phase boron to carbon ratio that is more commonly reported.

This work expands upon our previous efforts to grow heavily doped high quality diamond for high power electronics applications. Films are deposited on high pressure high temperature SCD substrates in MPACVD bell-jar reactor with plasma feedgas mixtures including hydrogen, methane, and diborane. We report on the results of growth experiments, and additionally discuss the effect of the flow rate and the substrate stress on doping efficiency, growth rate and defect formation. Samples are characterized by FTIR, birefringence and activation energy measurements. We report strategies for defect reduction while simultaneously increasing the boron doping efficiency and sample growth rate.

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Experimental Investigation of the Effects of an Axial Magnetic Field on the Magneto Rayleigh-Taylor Instability in Ablating Planar Foils*

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Experiments are underway to study the effects an axial magnetic field on the magneto Rayleigh-Taylor instability (MRT) in ablating planar foils on the 1-MA LTD at the Michigan Accelerator for Inductive Z-pinch Experiments (MAIZE) facility at the University of Michigan. For these experiments, 300 kA of current was discharged over ~100 ns into a 400 nm thick, 1 cm wide Al foil. Using helical return current posts, a peak axial magnetic field of 7.5 T was generated for 300 kA drive current. A 775 nm Ti:sapphire laser was used to shadowgraph the foil in order to observe instabilities that occurred during foil ablation. Early stages of the discharge showed smaller wavelength instability structures characteristic of the electrothermal instability while later stages, when the plasma interface decelerated due to increasing magnetic pressure, showed longer wavelength structures characteristic of MRT. The shadowgraphs showed new structures and asymmetries that were not previously present in earlier experiments without an axial magnetic field at UM.[1,2]

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Effective Quantum Potentials for Atomic, Molecular and Scattering Processes in Dense Plasmas*

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Molecular dynamics simulations of electron-ion systems are prone to the so-called “Coulomb catastrophe” which is due to the infinitely deep Coulomb potential of the ion-electron interaction without any stabilizing effect in a classical framework. Quantum mechanically this is forbidden by the Heisenberg Uncertainty Principle. In addition, many electron systems need to satisfy the Pauli Exclusion Principle as well. Fermion Molecular Dynamics [1] accommodates the two effects in a quasi-classical treatment through momentum-dependent potentials that exclude the regions of phase space forbidden by quantum principles. The extent of exclusion is determined by a set of parameters which need to be chosen carefully to include the quantum effects specific to the system. Initial attempts to determine these parameters were ad-hoc [2] followed by accurate calculation of the Heisenberg parameters for few electron systems [3]. The results so far do not suffice to study plasmas where multi-electron effects are important in atomic processes. We report the first attempt to accurately determine the Heisenberg and Pauli parameters for a set of atoms. The parameters are found to be correlated with parabolic/elliptic form for all the atoms we studied. The results so far suggest that this formulation could be related to quantum mechanical treatment in some limiting cases.

* Work supported by Air Force Office of Scientific Research

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Experiments on the OMEGA EP Laser to Study the Material Dependence of the Two-plasmon Decay Instability*

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Lasers interacting with under-dense plasmas drive laser-plasma instabilities (LPIs), which can convert a non-negligible fraction of the laser energy into hot electrons (>50 keV). In direct-drive ICF implosion experiments, these hot electrons can preheat the fuel, thereby reducing compression efficiency. Additionally, hot electrons interacting with high-Z materials in the target chamber can produce high-energy x-rays that interfere with diagnostics. Therefore, understanding the production of hot electrons in laser-produced plasmas is important to control and mitigate these effects.

For long-scale-length plasmas, two-plasmon decay (TPD) is a major LPI responsible for generating hot electrons. The convective gain of the instability is proportional to the length scale of the plasma electron density and inversely proportional to the electron temperature. Therefore, it has been predicted and demonstrated by preliminary experiments that hot electron production can be controlled through varying these parameters by increasing plasma Z [1,2]. Additionally, TPD may be saturated by further decay processes that depend on ion-acoustic wave damping, and therefore, plasma Z [3].

We have performed experiments on the OMEGA EP laser to thoroughly study the Z-dependence of the TPD instability, through varying the material with which the lasers interact. Hard x-ray diagnostics were used to measure hot electron production and optical diagnostics were used to measure plasma density profile for each material. Preliminary results will be presented, showing the general Z-dependence of hot electron production and electron density scale lengths.

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Minor Ion Heating by Low-frequency Alfvén Waves: Thermal Motion vs. Non-thermal Motion

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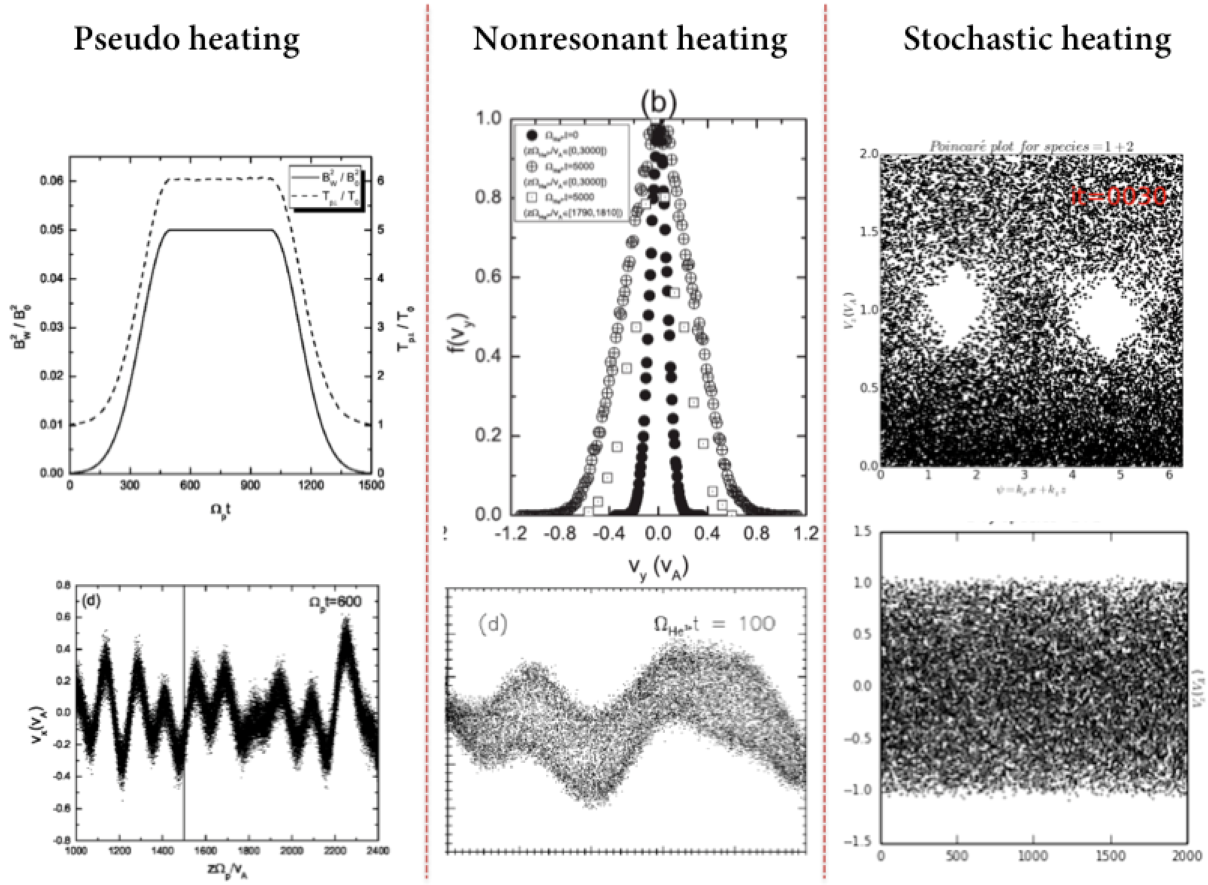
Minor ion (such as He++) heating via nonresonant interaction with spectra of linearly and circularly polarized Alfvén waves (LPAWs and CPAWs hereafter) is studied. The obtained analytic solutions are in good agreement with the simulation results, indicating that newborn ions are heated by low-frequency Alfvén waves with finite amplitude in low-beta plasmas such as the solar corona. In the presence of parallel propagating Alfvén waves, turbulence-induced particle motion is clearly observed in the wave (magnetic field) polarized directions. After the waves diminish, the newborn ions are heated, which is caused by the phase difference (randomization) between ions due to their different parallel thermal motions. The nonresonant heating is dominant in the direction perpendicular to the ambient magnetic field. Besides, the threshold-dependent stochastic heating is also studied.



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Recent Models on Classical, Ballistic, and Quantum Diodes

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A diode is a two-terminal electronic component with an asymmetric charge transfer characteristic, with low resistance to current flow in one direction, and high resistance in the opposite direction. This unidirectional behavior offers the fundamental function of signal rectification. We present our recent efforts on the modeling of diodes, in classical, ballistic and quantum regimes.

For classical vacuum diode [1], we found that the Langmuir-Blodgett solutions for the space charge limited current density, for both cylindrical and spherical diodes, may be approximated by $J_{approx} = (4/9)\varepsilon_0\sqrt{2e/m}(E_c^{3/2}/\sqrt{D})$ over a wide range of parameters, where E_c is the surface electric field on the cathode of the diode *in vacuum*, and D is the anode-cathode spacing.

The emergence of new materials with long charge mean free path, such as graphene, stimulates the development of a new concept, namely, ballistic geometric diode [2]. Recently, we developed an analytical model [3] to calculate the current rectification of an asymmetric two-dimensional ballistic constriction structure (Fig. 1a). We show the conditions at which the I-V asymmetry may be maximized for various aspect ratios (Fig. 1b). The analytic theory is verified by Monte Carlo simulations.

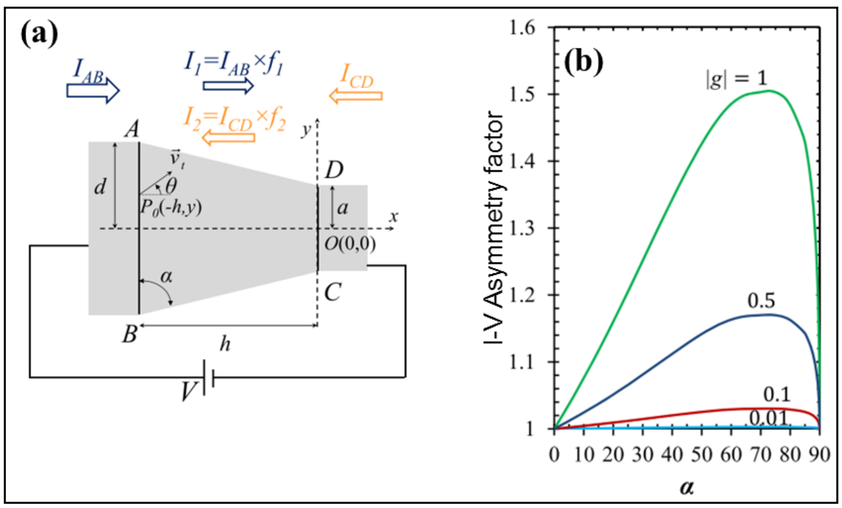

Figure 1 - (a) 2D funnel-shaped ballistic diode. Current entering the interface AB(CD) is I_{AB} (I_{CD}), the probability for charge carriers at AB(CD) that can be transported to CD(AB) is f_1 (f_2). (b) I-V asymmetry factor as a function of the angle α, for various incident charge carriers velocity distributions labeled by $|g|$ [3].

When two electrodes of the diode are separated by an insulator of nanoscale thickness, current can flow between them by quantum tunneling. Our recent modeling efforts on tunneling conductivity will also be presented.

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Dielectric Barrier Discharges in Humid Air*

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Atmospheric pressure dielectric barrier discharges (DBD) in air readily produce reactive oxygen species (ROS) and reactive nitrogen species (RNS). These species are particularly relevant in biological systems where both direct treatment of cells and treatment with plasma-activated water has produced promising results for antimicrobial effects, wound healing, and cancer treatment [1].

Plasma activated water can retain some reactive species on the time-scale of days, which is particularly relevant for biological systems [2]. Other media have been shown to increase diffusion of certain molecules across the cell membrane, which could be tailored to improve drug delivery [3]. In the emerging field of plasma medicine, quantifying and controlling the type and amount of these species delivered to the substrate by a plasma torch is essential to its reliability and effectiveness. In therapeutic applications, too much of a particular species may induce apoptosis of healthy cells, but too little would make the treatment ineffective against cancer cells or bacteria [1].

In many applications, the interaction of plasma with substrate causes evaporation of water, increasing the humidity of the air within the plasma in addition to natural ambient humidity. The production of key reactive species is influenced by humidity in argon plasma jets in air [4]. Humidity can often be difficult to control experimentally, and it is essential to understand how this variable affects the fluxes of reactive species onto the substrate.

In this paper, results from a numerical study of DBD discharges in humid air using GlobalKin are discussed. The global model generates the spatially averaged time evolution of species, which can be modified into a 1-D model. This is achieved by using a plug-flow approach, in which time integration of a 0-D plug of gas is mapped to position by computing its flow velocity. The major simplifying assumption in this model is that radial variation of minor species which react on surface can be represented using fundamental mode diffusion. The model includes the capability of including the experimental circuit, or the power deposition as a function of length. Changes in the gas temperature are calculated from electron collisions and chemical reactions, and an acceleration of the flow due to expansion is included [5]. The produced ROS and RNS in a DBD in humid air are quantified and discussed using this method.

The long-term goal is to extend the analysis a 2-D model using nonPDPSIM, and compare with experimental results by Peter Bruggeman et al.

* Work was suppoted by DOE Office of Fusion Energy Science (DE-SC0001319) and the National Science Foundation (CHE-1124724).

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Efficient Experimental Methods that Enable the Control of High Pressure Microwave Discharges*

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High pressure microwave discharges (> 150 Torr - one atmosphere) have been the focus of numerous recent experimental investigations such as microwave plasmoid/ microwave fireball investigations [1], microwave plasma assisted combustion [2] and microwave plasma assisted gas reforming, and also recent commercial applications such as CVD diamond synthesis [3]. In each of these experiments discharge control and the coupling efficiency become very important as the pressure is increased.

Microwave plasma assisted chemical vapor deposition of diamond at high pressures (150-400 Torr) is one high pressure microwave discharge application that is now being commercialized throughout the world [4]. Thus, in this poster the diamond synthesis application will be used as an example of how high pressure microwave discharges can be efficiently utilized in a commercial material synthesis setting.

Experimental methods and coupling technologies that have been developed to enable CVD diamond synthesis in the high pressure regime will be described. A versatile, mechanically internally tuned reactor technology has been developed [5] and is employed to synthesize single crystal diamond (SCD). High power density (~200-500W/cm^3), high pressure (150-400 Torr), CH_3/H_2, stable discharges are produced via efficient coupling. These discharges have gas temperatures of 2500-4000K and electron densities of $5x10^{11}$ to 3x 10^{12}/cm^3. SCD is synthesized without the formation of detrimental, dusty plasmoids [1,6]. The discharge is located in good contact with the substrate and the plasma substrate boundary layer is controlled as the input power, pressure, gas flow rate, gas mixture, substrate temperature etc. are all independently varied. Microwave coupling efficiencies of greater that 90% are easily achieved over the entire experimental input variable range, and once the optimum synthesis process conditions are identified, coupling efficiencies greater that 98% are achieved.

In this poster, the experimental procedures are described that enable a high microwave coupling efficiency and an efficient CVD SCD growth process. The presented experimental reactor performance measurements provide insight into the SCD growth process optimization of high pressure microwave discharge applications. Using the same reactor technology, diamond synthesis process control strategies will be presented.

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Simulating a 5 kW Class Hall Effect Thruster

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While a 5kW class Hall Effect thruster has undergone extensive ground testing, there are currently no thruster simulations available in the literature. Limited thruster geometric properties and magnetic field characteristics are available as simulation input parameters. In this work, a preliminary model is created using HPHall. HPHall is a hybrid code; it models higher velocity electrons as a quasi-1D fluid and heavier species using a particle-in-cell (PIC) method.[1] Overall, the results of the simulation qualitatively agree with experimentally observed behavior in the thruster, but the quantitative results indicate that macroscopic properties including thrust, discharge current, and ion current do not yet agree with the expected measured properties. Additional plasma properties such as average ion velocity and average electron density exhibit expected qualitative trends within the channel. Model discrepancies may be due in part to the fact that Hall thruster results are sensitive to magnetic field topology, and the simulated topography may differ slightly from experiment.[2] Additionally, the simulation domain may not yet be large enough to capture the thrust occurring outside of the thruster channel.

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Plasma Jet Interaction with Wet Cells *

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The use of atmospheric pressure plasma jets in plasma medicine has been studied extensively in recent years. Encouraging results have been seen in wound treatment, surface sterilization, deactivation of bacteria, and even treatment of cancer cells. However, the primary source of the benefits from treatment using the plasma jet with cells is still debated. One proposal is that the reactive oxygen and nitrogen species produced from the interaction of the plasma jet effluent are key signaling molecules. Another is that the electric fields produced by the voltage source cause electroporation of the cell membrane and promote cell death in that process. Both have shown to be effective treatment methods and the use of atmospheric pressure plasma jets couples them effectively.

In this presentation, results from a computational investigation of the interaction of atmospheric pressure plasma jets with tissue are discussed. The computer model used in this investigation, *nonPDPSIM*, solves Poisson's equation, transport equations for charged and neutral species, electron energy equation and Navier-Stokes equations for the neutral gas flow. The electrical effects of an atmospheric pressure plasma jet sustained in He/O_2=99.8/0.2 into humid air on a cell structure beneath a layer of 200 µm water were investigated. The water layer represents the biological fluid typically covering tissue during treatment. Three different voltage configurations were analyzed – two that produce a plasma effluent that touches the surface of the water layer and one that does not touch. The magnitude of the electric field on the cell membrane during the short duration pulse is above the accepted threshold for electroporation during the touch configuration.

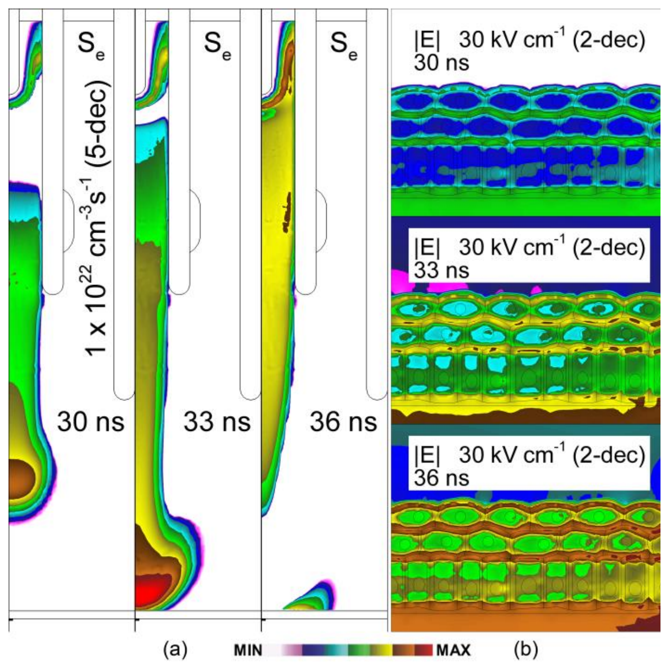

Figure 1 - Atmospheric pressure plasma jet interacting with cells beneath a water layer. (a) Electron impact source for -15 kV touching case. (b) Electric field on cellular scale.

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Ring-Shaped Distributions of Quasimonoenergetic Electron Beams Generated via Density Discontinuities in a Two-Stage Gas Cell*

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Ring-shaped angular distributions of quasimonoenergetic electron beams were consistently generated using a two-stage gas cell with opposing gas flow between the stages. These structures were generated using both ionization injection (2.5% N2 mix/He gas in the 1st/2nd stage) and self-injection mechanisms (pure He gas in both stages). The shape of these "electron halos" observed on a magnet spectrometer scintillating screen (Fig. 1) suggests that they have a monoenergetic energy distribution, with an average maximum ΔE/E of 11 % and energy of 200 MeV. The average angular spread was found to decrease with increasing acceleration length in the gas cell. The average charge contained in these electron halos is on the order of several pC. Interferometric density measurements showed that these electron halos have only appeared when the density in the 1st stage is higher compared with the second. In addition, attempts to create these halos using a similar two-stage gas cell where the gas input into both stages came from the same direction proved to be unsuccessful. It is postulated that these halo-like structures are formed as the laser crosses a steep density perturbation, similar to a hydrodynamic shock, created from the opposing gas flows between the gas cell stages. Such well-defined angular distributions of monoenergetic electrons may prove useful for plasma-based X-ray sources.

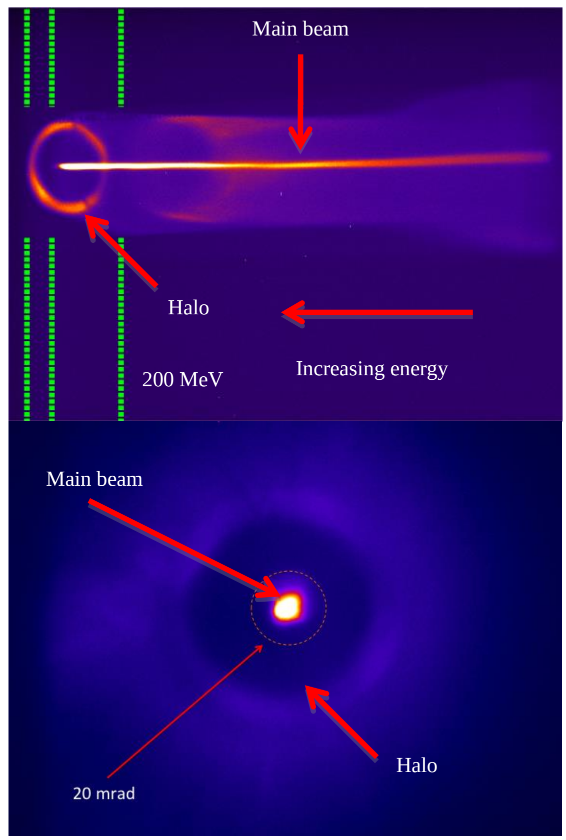

Figure 1 – (Top) Dispersed electron beam with ring-shaped "halo" observed on a magnet spectrometer scintillating screen. Note: The horizontal axis shows the energy dispersion of the electron beam (with higher energires towards the left of the image) after passing through a 0.8 T magnet. The superimposed green dashed lines denote energies separated by 200 MeV. (Bottom) On-axis image of electron beam with halo showing a ~10 mrad divergence for the main beam and ~40 mrad divergence for the electrons in the halo.

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Insights to Etching Process Control through 3-Dimensional Profile Simulation*

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Plasma assisted etching is a necessary process for pattern transfer in microelectronics fabrication. In prior technology nodes, 2-dimensional feature profile models served very well to help optimize features and connect reactor scale properties to feature scale critical dimensions (CDs). The current technology nodes utilize 3-dimensional structures such as FinFETs and Tri-Gate transistors, whose optimization is considerably more difficult and not well represented by 2D profile simulators. For example, etching of 3D structures typically require longer over-etch to clear corners, which then places additional challenges on selectivity to maintain CD.

In this paper, we report on development of a 3-dimensional profile simulator, the Monte Carlo Feature Profile Model (MCFPM-3D). The MCFPM-3D builds upon the two-dimensional MCFPM modeling platform and uses the same reaction mechanism as the 2D model. The MCFPM-3D uses a rectilinear mesh in 3 dimensions having fine enough resolution that, for example, circular vias can be resolved as shown in Fig. 1. Each cell within the mesh may represent a different solid material or a mixture of materials. The model addresses reaction mechanisms resulting in etching, sputtering, mixing and deposition on the surface to predict profile evolution based on fluxes of radical, ions and photons provided by an equipment scale simulator. In these studies, energy and angularly resolved fluxes are provided by the Hybrid Plasma Equipment Model (HPEM). For demonstration of the MCFPM-3D capabilities, Ar/Cl_2 plasma is used for Si over SiO_2 substrate etching. Phenomena such as aspect ratio dependent etching, micro-loading and bowing will be discussed.

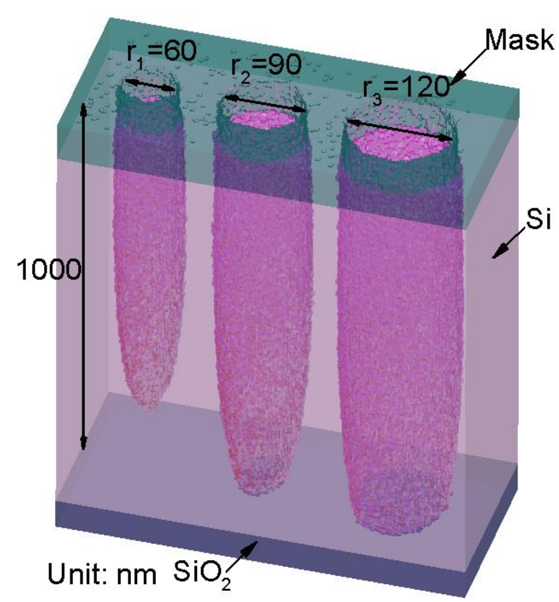

Figure 1 – MCFPM-3D simulation of plasma etching of vias with different radii (120/90/60 nm). Process conditions are 20 mTorr, Ar/Cl_2=80/20, 200 sccm flow. Vias with a higher aspect ratio (smaller radius) have a slower etch rate.

* Work was supported by the Semiconductor Research Corp., NSF, DOE Office of Fusion Energy Science and LAM Research.

Direct Comparison of Full-Scale Vlasov-Fokker-Planck and Classical Modeling of Megagauss Magnetic Field Generation in Plasma near Hohlraum Walls from Nanosecond Pulses*

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Here, we present 2D numerical modeling of near critical density plasma using a fully implicit Vlasov-Fokker-Planck code, IMPACTA, with an implementation of a ray tracing add-on package. This allows to model inverse brehmsstrahlung heating as a laser travels through a plasma by solving the ray tracing equations. In certain situations, such as those at the critical surface at the walls of a hohlraum, magnetic fields are generated through the crossed temperature and electron density gradients (the Biermann Battery effect). These magnetic fields are 0.3 MG in strength and the strong heating also results in magnetization of the plasma up to $\omega\tau \sim 5$.

Simulations were performed with and without magnetic field generation. In the case without magnetic field generation, the heat flows from the laser heating region are generally isotropic. Including magnetic fields causes the heat flow to form jets into and along the wall due to the Righi-Leduc effect. The heating of the wall region causes steeper temperature gradients. This effect results in a positive feedback mechanism for the Biermann Battery field generation rate resulting in nearly twice the amount of field generated in comparison to the case without magnetic fields over 1 ns. Additionally, inverse brehmsstrahlung heating modifies the distribution function such that it results in a 10% increase in the Biermann Battery field generation rate derived from assuming a Maxwellian distribution.

The heat conduction, field generation, and the calculation of other transport quantities, is performed ab-initio due to the nature of the Vlasov-Fokker-Planck equation set. In order to determine the importance of the kinetic effects in the IMPACTA modeling, we perform direct comparison with a classical (Braginskii) transport code with hydrodynamic motion (CTC+) using the same heating profile as calculated from the IMPACTA ray-tracing.

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X-Ray Imaging of Ultrafast Magnetic Reconnection Driven by Relativistic Electrons

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Magnetic reconnection events driven by relativistic electrons are observed between two high intensity laser/plasma interaction sites. The two laser focuses were on average 20um FWHM containing 50TW of power each, delivered with a split f/3 paraboloid onto copper foil targets at a focused intensity of 4x10^18 W/cm^ 2. A spherically bent k-alpha X-ray Bragg crystal was utilized to image the interactions, and by motorizing one half of the paraboloid vertically the focal separation was varied between 0-200um. While these k-alpha images demonstrated a ring structure surrounding a single focus (due to electrons returning from vacuum to the front of the target surface), splitting the focuses revealed the rings of either spot interacting and enhancing between the two foci, evidencing magnetic reconnection driven by the relativistic electron currents. Imaging the transversely propagating electrons with a filtered LANEX screen demonstrated relativistic currents with spatial non-uniformities potentially directly originating from reconnection events, and varying target geometries were used to investigate the resulting effects on the spatial electron profiles. At present PIC simulations are being conducted to better understand and attempt to reproduce the measured electron outflow dynamics.