Michigan Institute for Plasma Science and Engineering (MIPSE)

Proceedings

9th ANNUAL GRADUATE STUDENT SYMPOSIUM

November 14, 2018

2:00 – 7:00 pm

North Campus, University of Michigan

1301 Beal Avenue

Ann Arbor, MI 48109-2122

University of Michigan and Michigan State University

Schedule

2:00 – 2:40	**Registration, poster set-up**	EECS atrium
2:40 – 3:30	**Poster session I**	EECS atrium
3:30 – 3:45	**Refreshments** (box lunch + coffee, tea)	1005 EECS
3:45 – 3:50	**Prof. Mark J. Kushner**, Director of MIPSE ***Opening remarks***	1005 EECS
3:50 – 4:50	Special MIPSE Seminar: **Dr. Svetlana Starikovskaia** Laboratory of Plasma Physics, CNRS, France ***Kinetics of Nanosecond Discharges at*** ***High Specific Energy Release***	1005 EECS
5:00 – 5:50	**Poster session II**	EECS atrium
5:50 – 6:40	**Poster session III**	EECS atrium
6:40 – 6:55	**Poster removal**	EECS atrium
6:55 – 7:00	***Best Presentation Award*** **ceremony**	EECS atrium

Poster Session I

Poster Session II

Poster Session III

Dr. Svetlana Starikovskaia

Laboratory of Plasma Physics, CNRS, France

Kinetics of Nanosecond Discharges at High Specific Energy Release

Recent progress in solid-state high power electronics has produced compact and reliable high voltage nanosecond (ns) generators for research and industry. High-voltage pulses 5-10 kV in amplitude and a few tens of ns in duration are capable of producing highly non-equilibrium low temperature plasmas over a wide range of pressure – 0.1 Torr to 15 bar. In these transient plasmas, reduced electric fields up to kTd (1 Td = 10^{-17} V cm^2), are typical at the propagating discharge front that initially produces the plasma. Behind the front the electric field stays high, hundreds of Td, producing high densities of excited states and radicals. This results in the high efficiency of ns discharges as a trigger for chemically active systems. At deposited energies of 0.5-1 eV/molecule, high rates of energy relaxation produce fast gas heating – thousands of K during tens of nanoseconds. Excitation densities can become so high that collisions of excited species with ions, other excited species and radicals become important. A review of plasma parameters in ns discharges, from fast ionization waves (FIWs) at low pressure to filamentary nanosecond surface dielectric barrier discharges (nSDBDs) at tens of bars will be given. Modifications of discharges leading to high energy release will be discussed, as well as their consequences for plasma diagnostics and potential applications.

About the Speaker: Dr. Svetlana Starikovskaia received the Ph.D. in Plasma Physics and Chemistry in 1993 from the Moscow Institute of Physics and Technology where she was also Senior Scientist and Professor. During this time, Dr. Svetlana Starikovskaia became one of the youngest Doctors of Science (D.Sc.) in Russia, receiving the Russian Federation Presidential Award for Young Doctors of Science. She is now Senior Researcher (Directrice de recherche) in the CNRS Laboratory for Physics of Plasma, French National Academy of Science. Her research interests include nanosecond pulsed discharges and fast ionization waves; kinetics of gases and plasmas at extreme thermodynamic nonequilibrium; kinetics of excited species and their influence of chemically nonequilibrium media and interaction of nonequilibrium plasmas with living cells. Dr. Starikovskaia is internationally recognized for her research in plasma assisted combustion for which she has written several review papers. Dr. Starikovskaia has authored more than 70 articles.

Abstracts

Development of a Mobile Electric Propulsion Demonstration for STEM Outreach*

Katherine Wolff, Sarah E. Cusson, Marcel P. Georgin, Veronika Bayer, Kirsten Reid, Catherine Budd, Abigail Huff, Kaelan Oldani, Nora Shapiro, Benjamin A. Jorns, and Alec D. Gallimore

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Public outreach is critical to recruit the next generation of engineers and scientists as well as correct misconceptions about the engineering discipline. In particular, outreach for plasma sciences and engineering is challenging as the ideas and technologies are removed from everyday life. In response to this need, the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan is developing a mobile-demonstration platform to bring advanced propulsion technology into high school classrooms in the greater Ann Arbor area to build interest in plasma science and engineering. This platform features the first thruster developed at PEPL, the PEPL-70, in action such that the next generation of students can begin to understand and experience this plasma technology. Figure 1 shows the demonstration in action. To build this demonstration unit, the Michigan Advanced In-Space propulsion Engineering (MAISE) team was formed from student members of the Women in Aeronautics and Astronautics club (WAA) to restore the initially defunct PEPL-70 to its former capacity and improve upon the design, to then be ignited for large audiences. The MAISE team was split into three different sub-teams to fulfill this task: Hall thruster refurbishment, vacuum facility design, and control system design. The thruster sub-team theoretically modeled the magnetic field, conducted simulations, characterized flow uniformity, and installed the cathode. The chamber team designed and built a small vacuum test facility that incorporated side and end viewing windows and mounted on a mobile cart, while still meeting necessary pressure and flow rate requirements. The controls team determined the current and voltage needs of the different components of the PEPL-70, developed an ignition sequence, and created a LabVIEW graphical interface with dials and data displays on a touchscreen computer for the audience to see. Additionally, the team is developing a presentation and poster to maximize the effectiveness of the outreach event. Current work on this project includes switching the controls of the power supplies from manual to remote, constructing a deflecting paddle to visualize the thrust the device produces, and converting the plasma oscillations to that of the audible frequency level, so participants can "listen" to the PEPL-70.

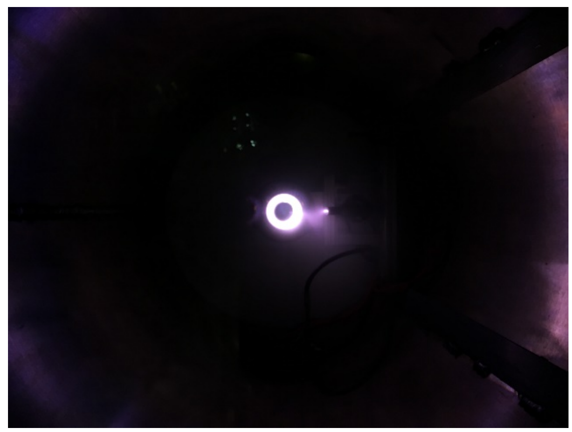

Figure 1 - PEPL 70 thruster in operation in the MAISE chamber.

*This work was funded by the Michigan Institute for Plasma Science and Engineering and the University of Michigan College of Engineering.

Two Dimensional Tunneling Resistance Transmission Line Model for Parallel Carbon Nanotube Contacts*

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Contact resistance and current transport through the contacts between individual carbon nanotubes (CNTs) are important, as CNT fibers contain a very large number of such junctions and contacts; and on a macroscopic level, their properties, especially the electrical conductivity, are not well understood. In this study, we used lumped circuit Transmission Line Model (TLM) to get a self-consistent analysis of contact resistivity, current and voltage distribution across parallel contacts formed between two closely spaced CNTs or CNT and other metals (Fig. 1a). Electric tunneling effect between similar/dissimilar contacting members separated by a thin insulating gap was included in our model using Simmon's formula [1, 2]. The properties of CNT contacts are examined in detail for various input parameters (i.e. input voltage, work function, dimension of the contact, sheet resistance and distance between the contact electrodes). The results give insights on the macroscopic contact resistivity and current distribution across such contacts.

Figure 1(b) shows the normalized (with respect to the input current) contact tunneling current density from CNT 1 to CNT 2 in a parallel CNT-CNT contact, for different contact lengths L. The tunneling current density profile is symmetric along the contact length. Due to current crowding effects, the maximum current density occurs at the contact edges.

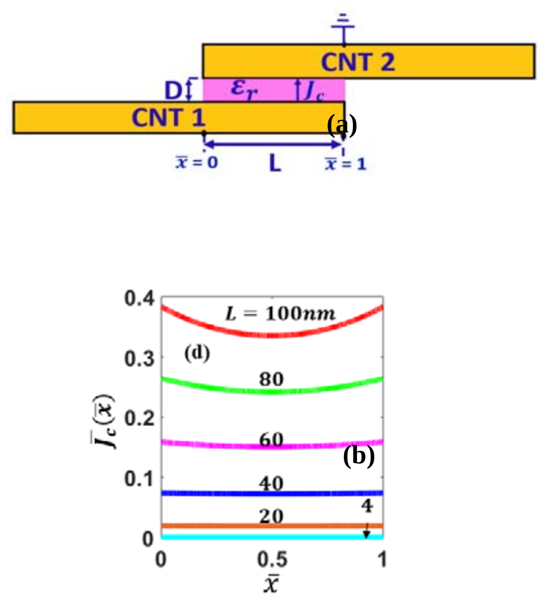

Figure 1 – (a) Parallel contact between two CNTs. A thin (in nm) resistive interface layer of permittivity ε_r and thickness D is sandwiched between them. (b) Normalized (with respect to the input current) tunneling current density from CNT 1 to CNT 2 through the interfacial layer, as a function of $\bar{x} = x/L$, where L is the contact length. Here, the insulator layer is vacuum, with ε_r = 1, electron affinity = 0, and D = 0.5 nm, and L varies from 4nm to 100nm. Work function of CNTs = 4.5 eV, and input voltage = 1V across the two contact ends.

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

References

[1] J. G. Simmons, J. Appl. Phys. 34, 1793–1803 (1963).
[2] P. Zhang, Sci. Rep., 5, 9826 (2015).

Effect of Background Pressure on Ion Acceleration in an Electron Cyclotron Resonance Thruster*

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Electrodeless thruster designs offer several advantages over traditional Electric Propulsion (EP) devices such as Hall effect thrusters and gridded ion thrusters. The absence of electrodes, thermionic emitters, and multiple power supplies enables simpler designs, lower thruster mass, and the use of alternative propellants. To date, however, these thrusters have been unable to match the performance of mature EP technologies, with typical thrust efficiencies lower than 7% [1].

Recent experiments at National d'Etudes et de Recherches Aérospatiales using Electron Cyclotron Resonance (ECR) heating in a magnetic nozzle have shown great improvements over previous electrodeless thrusters operating at similar power levels. Their work showed thrust efficiencies above 10% at specific impulses over 1000 seconds while operating at 30 watts [2]. However, their experiments also showed that thruster performance was extremely sensitive to testing conditions, with measured efficiency decreasing by 70% as background pressure is raised from 1×10^{-5} to 5×10^{-5} Torr-Xe [3].

In the experiment presented here, the ion velocities in the acceleration region of an ECR thruster are measured using laser induced fluorescence as background pressure is varied from 8×10^{-7} to 2×10^{-5} Torr-Xe. It is found that the acceleration potential decreases by 20% as background pressure is increased. This effect cannot be explained by collisionality in the plume, as the ion mean free paths in this region are greater than 1 meter for all conditions tested. It is proposed that the decrease in acceleration potential is caused by leaky microwave fields exciting a plasma external to the main discharge region. This plasma robs the thruster discharge of power, thus decreasing the thruster performance.

Figure 1 – ECR thruster firing in low background pressure conditions

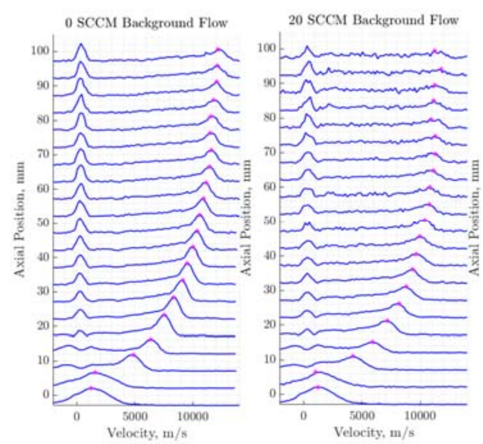

Figure 2 – Ion VDFs along the thruster axis for two background pressure conditions

* This work was supported by NASA Space Technology Research Fellowship grant 80NSSC17K0157.

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[2] T. Vialis, J. Jarrige, A. Aanesland, and D. Packan, J. Propul. Power **34**, 1323 (2018).
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Time-Dependent Helical Magnetic Field Effects on Cylindrical Liner Ablations*

P. C. Campbell, T. M. Jones, C. Wagner, S. M. Miller, J. M. Woolstrum, N. B. Ramey, A. P. Shah, N. M. Jordan, Y. Y. Lau, R. M. Gilgenbach, and R. D. McBride

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Instabilities such as the magneto Rayleigh-Taylor (MRT) and general magnetohydrodynamic (MHD) instabilities such as the m=0 “sausage” and the m=1 “kink” instabilities (where m is the azimuthal mode number) form during cylindrical liner implosions and ablations. The effects of adding a time dependent helical magnetic field on the MRT instability using a dynamic screw pinch have been shown in simulation [1]. We have modeled and fabricated several helical return current paths to set up such a field configuration, with the axial magnetic field component of 10 T for peak currents of 550 kA. Simulation results on the expected magnetic field profile as well as experimental measurements of the magnetic field values achieved for the return current paths will be presented as well as a comparison of the instabilities seen for the various return current paths.

* 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.

References

[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.

An Experiment to Observe Photoionization Fronts in the Laboratory*

H. J. LeFevre [a], W. J. Gray [b], J. S. Davis [a], P. A. Keiter [c], C. C. Kuranz [b], and R. P. Drake [b]

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An experiment at the Omega-60 laser investigates radiation front propagation in a regime where the radiation transport is non-diffusive yet the initial target is many mean free paths in extent. The atomic physics at the front is such that photoionization is the dominant heating mechanism there. This type of front is relevant to star-forming regions and the age of reionization of the universe. In the experiment, a thin Au foil irradiated with a laser energy flux of ~10^14 W/cm^2, creates soft x-rays source that are incident on a N gas cell. The N is doped 1% Ar to enable absorption spectroscopy measurements. We will show preliminary results from upcoming experiments.

* Supported by the U.S. DOE, through the NNSA-DS and SC-OFES grant number DE-NA0002956, and NLUF grant DE-NA0002719, by the Laboratory for Laser Energetics under Cooperative Agreement No. DE-NA0001944 and by LLNL under subcontract B614207.

Construction of the BLUE Linear Transformer Driver System at the University of Michigan*

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The University of Michigan has received four linear transformer driver (LTD) cavities, which were previously a part of the Ursa Minor experiment at Sandia National Lab. As such, the stack has been somewhat facetiously deemed the Bestowed LTD from the Ursa Minor Experiment, or BLUE. BLUE will be capable of delivering up to 8kJ of energy in a ~200ns, ~200kA pulse for high-power microwave and Z-pinch experiments. Currently, the cavities are fully disassembled, and located within a newly-built concrete wall for high-energy photon and neutron shielding. Based on our existing LTD system, MAIZE, we have begun to consider the charging and triggering sub-systems for BLUE. Our ambitious goal is to rep-rate the entire system as fast as 10Hz, though this may only prove possible with lower voltage and/or lower total capacitance. We are considering dual, ambipolar 100kV, 12kW Spellman power supplies to minimize charging time.

Pulse shaping on LTDs has been explored briefly at Sandia [1]; eventually BLUE may have this capability by staggering the trigger pulse or mismatching capacitors. Adding pulse shaping capability would widen the range of applications for BLUE; however, we are focusing on getting the cavities up and running first.

We have also considered transforming BLUE into a relatively new driver architecture known as an impedance-matched Marx generator, or IMG [2]. An IMG is very similar to an LTD but does not require the ferrite cores, which can represent a significant fraction of an LTD cavity's weight. We are carefully evaluating other possible issues to determine the feasibility of an LTD-IMG transition with BLUE.

Figure 1 – Components of the BLUE LTD system within concrete shielding

* Work supported by the U.S. Office of Naval Research through the Young Investigator Program.

References

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[2] Stygar, W. A., LeChien, K. R., Mazarakis, M. G., Savage, M. E., Stoltzfus, B. S., Austin, K. N., Breden, E. W., Cuneo, M. E., Hutsel, B. T., Lewis, S. A., McKee, G. R., Moore, J. K., Mulville, T. D., Muron, D. J., Reisman, D. B., Sceiford, M. E., and Wisher, M. L. *Impedance-matched Marx generators*. United States: N. p., 2017. Web. doi:10.1103/PhysRevAccelBeams.20.040402.

Optimization of Lightly Boron Doped Diamond Growth by Microwave Plasma-Assisted CVD for Electronic Applications.

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Single Crystal Diamonds (SCDs) have an extraordinary mechanical, thermal, optical, and electrical properties ideal for the application on electronic devices. High quality SCDs are currently being produced in MSU by Microwave Plasma-Assisted Chemical Vapor Deposition (MPACVD) using a 2.45 GHz microwave resonant cavity system. In this reactor Ultra High Purity (UHP) levels of process gases (H_2, O_2 and CH_4) are used and diborane (B_2H_6) is employed as the boron doping source. A constant temperature of approximately 800^{o}C and a process pressure of 90 Torr were applied.

The incorporation of boron in the gas phase during the deposition process determines the p-type diamond doping level [2]. The boron can also affect the morphology and structure of the diamond films [3]. In order to improve the quality of the deposited p-type boron diamond, oxygen is added as an additional processing gas in low amounts of less than 1% [1]. It acts as a more aggressive etchant of non-diamond bonded carbon and it helps to decrease the incorporation/growth of defects as well as decrease the nucleation of new defects.

This present study demonstrates that it is possible to control the growth rate (Fig.1) of the lightly boron doped epilayer by varying the oxygen concentration in the total gas flow. Also, AFM measurements have shown that low roughness surfaces (Fig. 2) can be obtained after growth without the need of applying a polishing process.

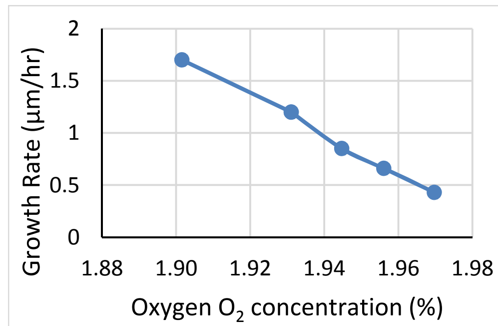

Figure 1 - p^- epilayer growth rate vs O_2 concentration.

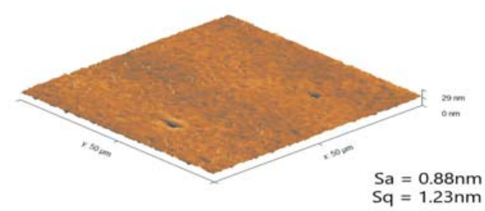

Figure 2 - AFM Measurement after p-epilayer growth (50x50µm area)

* Work supported by DARPA

References

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[2] S. N. Demlow, R. Rechenberg and T. Grotjohn, Diam. Relat. Mater., 49 (2014)
[3] R. Ramamurti, M. Becker, T. Schuelke, T. Grotjohn, D. Reinhard, G. Swain and J. Asmussen, Diam. Relat. Mater., 17 (2011)

Multiple Species Laser-driven Ion-shock Acceleration*

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Using 2-D OSIRIS particle-in-cell simulations, laser-driven ion-shock acceleration of a multi-species plasma is explored. We perform simulations consisting of over-dense plasmas of electrons, protons, and C^{6+} at several densities, to obtain a generalized picture of shock propagation in a system consisting of multiple particle species. These results are relevant to high-intensity laser-driven shocks using gas jets with multiple ion species such as methane, or exploded plastic targets.

* This material is based upon work supported by the Department of Energy under Award Number DE-SC00012327. The authors would like to acknowledge the OSIRIS Consortium, consisting of UCLA and IST (Lisbon, Portugal) for providing access to the OSIRIS 4.0 framework. Work supported by NSF ACI-1339893.

Impact of Neutral Density on the Acceleration Region in a Magnetically Shielded Hall Thruster*

Sarah E Cusson, Ethan T. Dale, Benjamin A. Jorns, and Alec D. Gallimore

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The influence of the cathode flow fraction and facility background pressure on the acceleration region of a Hall thruster is experimentally characterized. The location of the acceleration region is measured using laser induced fluorescence on the H9 Hall thruster for six different facility background pressures and four different cathode flow fractions. Results show that when the facility pressure is increased from 7.1×10^{-6} to 3.0×10^{-5} Torr-Xe, the acceleration region shifts inward 1.6 ± 0.5 mm. Similarly, when the cathode flow fractionis increased from 7% to 15%, the acceleration region shifts inward 0.9 ± 0.5 mm. This experiment leads to two conclusions. First, introducing neutral in the cathode region can directly affect the accelerating mechanism in the thruster. Second, changing the cathode flow fraction affects the channel of the thruster in a similar manner as the background pressure. This similarity may be explained by local changes in the neutral density. Calculations of this parameter shows that the increase in neutral density in the proximity of the acceleration region is similar due to both effects. This provides correlational evidence linking the role of neutral density to the acceleration region shift.

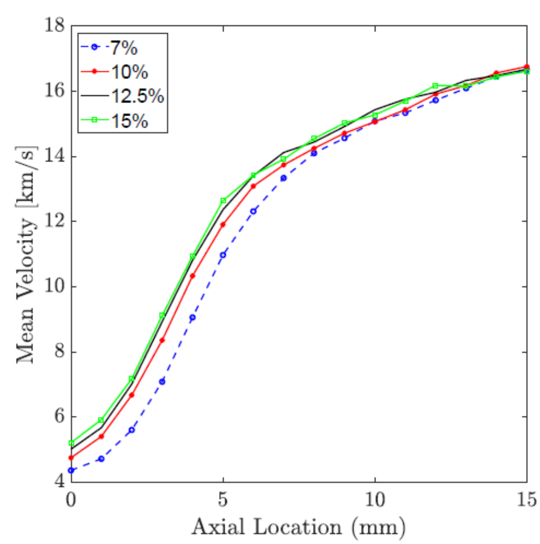

Figure 1 - Mean velocity versus position for the cathode flow fraction sensitivity study. The results show that as cathode flow fraction is increased, the acceleration region shifts inward.

*Portions of this work were funded by NASA Space Technology Research Fellowships NNX15AQ43H and NNX14AL65H.

Optimizing Transient Behavior of a High-Low Pulsed Power Inductively Coupled Plasma*

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Inductively coupled plasmas (ICPs) are widely used for etching in semiconductor device fabrication. Pulsed power with up to 10s kHz pulse repetition frequencies (PRFs) are commonly used for the high power density it provides during the pulse-on period and the unique chemistry during the pulse-off period. The highly attaching halogen gases used in the etching process often results in low electron densities during the pulse-off period, producing instabilities, E-H transitions and ignition delays when power is applied. In this work, to mitigate these instabilities, a low-level power is maintained during the "pulse-off" period to limit the minimum plasma density, therefore improve the transient plasma behavior.

In this work, an ICP sustained by 1-5 kHz pulsed power using Ar/Cl_2 gas mixtures at tens of mTorr were computationally and experimentally studied. The computational tool used is 2-D Hybrid Plasma Equipment Model (HPEM). The experimental results are mainly Langmuir probe measurements such as electron density (n_e) and temperature (T_e). The comparison between the experimental and computational results will be discussed.

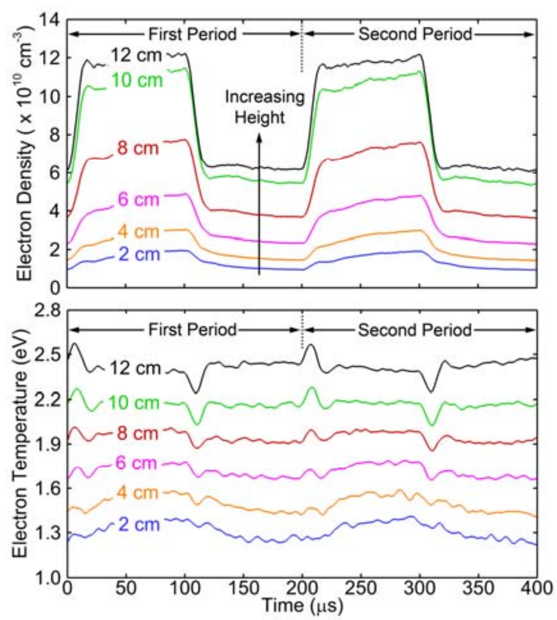

Figure 1 – The electron density and temperature at mid-radius of the wafer at different heights from the substrate.

Due to the finite transit time of the charge species and the decay of the power density from the power source to the substrate, both T_e and n_e are expected to be spatial dependent. This is evident in both the computational and experimental results. A few centimeters above the substrate, only weak fluctuation of T_e and n_e could be observed when pulsed power was applied. The model predicts that within the skin-depth, T_e spikes to a high value during the low-to-high power modulation and a low value during a high-to-low power modulation, which could be explained by the longer relaxation time of n_e compared to the ramping time for the power change. The effects of the power, pressure, PRF and the duty cycle of the pulse profile on the bulk plasma properties will be discussed.

* Work supported by Samsung Electronics, National Science Foundation and the DOE Office of Fusion Energy Science.

High Flow Argon through Cascaded Arc for Use as a High Pressure Gas Target Isolator*

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The so-called Plasma Window is a DC cascaded arc whose function in this study is to limit the flow of gas from a high pressure chamber, called the gas cell here, (around 300 torr) to a low pressure chamber (around 0.1 torr). This ability to limit gas flow makes it an attractive option for use with a gas charge stripper of a high intensity heavy ion accelerator, such as the upcoming Facility for Rare Isotope Beams (FRIB) at MSU.[1] The reduction in gas flow is caused by the high gas temperature in the channel, greatly enhancing viscosity.[2] Additionally, a choked flow condition is expected to contribute as gas exiting the channel reaches supersonic conditions. In order to accommodate the ion beam's passage through it, the plasma channel through which the ion beam travels would ideally be no smaller than 10 mm in diameter. This study looks at Ar plasma properties of a plasma channel of 6 mm diameter, and will subsequently be compared to results for a plasma window with 10 mm diameter channel. Measurements were conducted using the plasma window test stand at the National Superconducting Cyclotron Lab (NSCL).

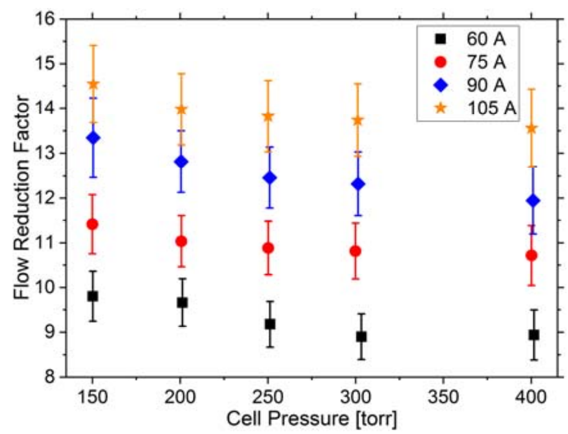

Figure 1 – The plasma window reduces the gas flow rate at a given pressure from what it would be without arc. The ratio of these is strongly dependent upon arc current, and shows a weaker dependence upon the gas cell pressure.

The arc pressure and current can both be adjusted, to establish a wide range of operating conditions to study. A primary figure of merit concerning the utility of the plasma window in this context is the gas flow reduction factor which represents, at a given cell pressure, the ratio of gas flow without arc to that with arc. This is shown in Figure 1 where it is clear that arc current strongly impacts the flowrate reduction, and cell pressure affects it to a lesser degree. Spectral analysis is used to determine electron temperature, through Boltzmann line method, and electron density, through Stark broadening analysis. The Ar plasma is characterized by an electron temperature of roughly 1.7 eV and 2.5×10^{16} cm^{-3}. Also measured is the floating potential of each metal plate along the length of the cascaded arc. Results and implications of these measurements will be presented and discussed.

* This work was supported by NSF Award PHY-1565546.

References

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Estimation of the Auroral Ionospheric Conductance in Global MHD Models

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The interaction of the Earth's intrinsic magnetic field with the solar wind plasma produces a myriad of magnetospheric current systems, some of which like the field aligned currents close through the ionosphere and the upper atmosphere. The closing of these currents and their effect on the ground is heavily influenced by the height-integrated electrical conductivity or conductance of the ionosphere. Since the prediction of these current systems during space weather activity greatly affects the prediction of geomagnetically induced currents, which have detrimental effects on electrical power grids and oil pipelines, the accurate estimation of the ionospheric conductance, especially in the auroral region, is a necessity for modern space weather predictive models. In the following study, we present initial validation results from the updated empirical conductance model in the University of Michigan's Space Weather Modeling Framework (SWMF, *Toth et al. 2005, 2012*) and describe the initial computational layout towards estimating the ionospheric conductance using a first principles-based method. In updating the existing empirical conductance model, we used one year's worth minute-resolution auroral conductance data derived from the assimilative mapping method of ionospheric electrodynamics (Ridley et al. 2004) to draw an inverse exponential relationship between the field aligned currents and the ionospheric conductance for any given location. Using the updated conductance model, we show new validation results following the same analysis techniques used in the GEM Challenge (*Pulkkinen et al. 2013*). We find that space weather predictions of ground magnetic perturbation significantly, especially during stronger driving of the solar wind.

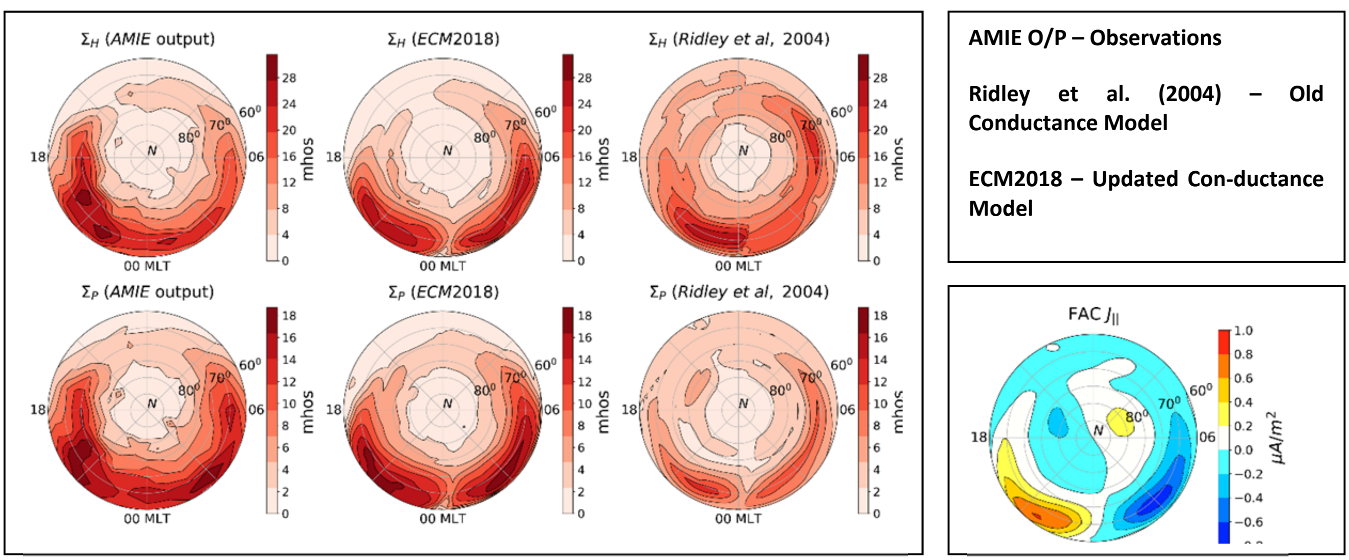

Figure 1 - Comparisons between the updated and older conductance model run in the SWMF for the same event (Halloween Storm of 2003) and compared against AMIE observations.

* Work supported by US Department of Energy, NSF PREEVENTS Program and NASA Earth and Space Science Fellowship Program.

Ultrafast Probing of Non-Equilibrium Plasmas Using LaserWakefield-Accelerated Electron Bunches*

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We explore the predominant physics behind the generation and evolution of an optical-field ionized plasma using electron bunches produced from a laser-plasma accelerator. The delay between the pump pulse and when the electron probe passes through the generated plasma has a direct effect on the measured energy of said electrons. Thus, we can use these electron bunches as a diagnostic to understand the dynamics of these non-equilibrium plasmas with picosecond temporal resolution. We employ particle-in-cell codes, including collisions and ionization, to model the plasma's electric fields that cause such an effect. We then simulate electrons passing through these electric fields at various points in its evolution and compare with experimental results.

* Work support in part by the NSF under grant 1535628 and the DOE under grant DE-SC0016804.

Relativistic Laser-solid Interaction: From Near-infrared to Mid-infrared*

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There has been growing interest in the physics and application of mid-infrared laser-plasma interaction. The ponderomotive potential in laser-plasma interactions increases with longer laser wavelength, so there may be significant differences in the physics of x-ray and electron generation and other phenomena driven by mid-infrared lasers. In this work, we report the results of experiments performed with millijoule, 40 fs, 2 μm laser pulses generated by an optical parametric amplifier (OPA) which are focused onto metallic and silicon targets. We characterized the hard x-ray source and electron source produced via 2 μm, 1.3 μm and 800 nm driving laser. Hard x-ray source size, energy conversion efficiency, emission of k-alpha relative to bremsstrahlung and electron temperature are studied and compared from near-infrared to mid-infrared.

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Benchmarking Ultra-Nano-Crystalline Diamond (UNCD) as a Field Emission Source for Accelerator Applications

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UNCD with high electron doping has been investigated recently as an efficient field electron emission source due to its high potential advantages for industrial, medical and scientific applications [1-3], such as hard X-ray and THz radiation and medical isotope production, wakefield acceleration, time-resolved electron microscopy, and some others. UNCD can be grown on bulk metal substrates and directly incorporated into normal conducting or superconducting electron radiofrequency injector and has both high charge and low emittance (i.e. high spatial emission coherence) [2, 4].

Due to limited amount of experimental database, we still know little about emission stability and intrinsic UNCD stability under extremely high electric fields (~100 MV/m) when UNCD is operated inside a MW RF injector over extended periods of time. Our limited knowledge also results in the lack of understanding (and therefore the absence of synthesis strategies) whether UNCD emissivity and emission coherence can be further improved.

To gain more insight into technological and application aspects of UNCD field emission sources, we are further benchmarking basic characteristics in a 2 MeV L-band RF injector based beamline at the Argonne Wakefield Accelerator called Argonne Cathode Test-stand (ACT). At MIPSE 2018, we will be presenting experimental microscopy and spectroscopy and beam dynamics results shedding light onto advances and limitations of the UNCD field emitter, namely, 1) life time and degradation mechanisms of the UNCD material, and 2) longitudinal and transverse phase spaces the electron beam produced in the 2 MeV accelerator.

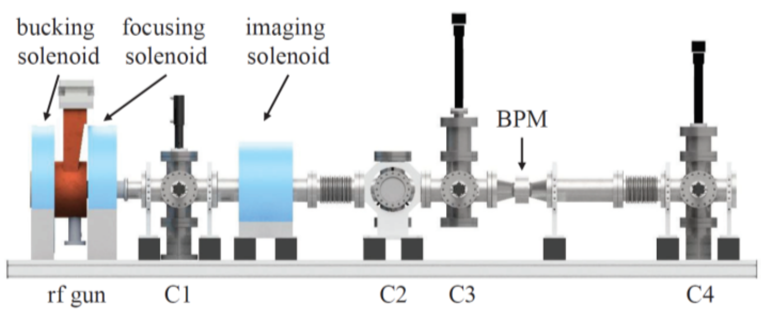

Figure 1 – Layout of the upgraded ACT. C1: Faraday cup and YAG phosphor beam imaging station; C2: In-vacuum laser mirrors; C3: Station containing collimators, slits, and YAG phosphor for high resolution imaging; C4: Auxiliary station that has Faraday cup, USAF target, and YAG station.

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Plasma Waves in Hollow Cathodes*

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Hollow cathodes are plasma devices that are commonly used in electric propulsion systems to source current and neutralize ion beams. Although these systems have extensive flight history for missions orbiting the earth, new interest in electric propulsion for deep space missions has required an improved understanding of the fundamental physics of these devices to accurately predict lifetime through numerical models. An open question for cathodes regards the presence of an instability that occurs at low flow rates and is characterized by large plasma potential fluctuations that can substantially increase the erosion rate of the device. This instability has been studied experimentally but was limited to single point probe measurements or measurements of fluctuations in global properties. [1] As a result, we do not know how the potential fluctuations evolve in the plume. More recently, numerical simulations have been able to capture fluctuations that are qualitatively similar to those observed experimentally, but we still do not know the dominant processes involved in the growth of the instability. [2]

In this work, we expand on past experiments by measuring plasma fluctuations in the plume of a hollow cathode along the axis of the discharge, providing spatially resolved information about the propagation and growth of those modes in the plasma. We analyze the growth rate of the higher frequency plane waves and find that they are well described by a saturated model for ion acoustic waves. Figure 1 shows the measured growth rate as a function of frequency and position along the discharge centerline. Above a cutoff frequency, we find that the growth rate is independent of frequency. We then developed a model for saturation, curve fit the data, and showed that the model captures the trends observed in the data. This work is beginning to shed some light on the evolution of these erosive waves in the cathode discharge.

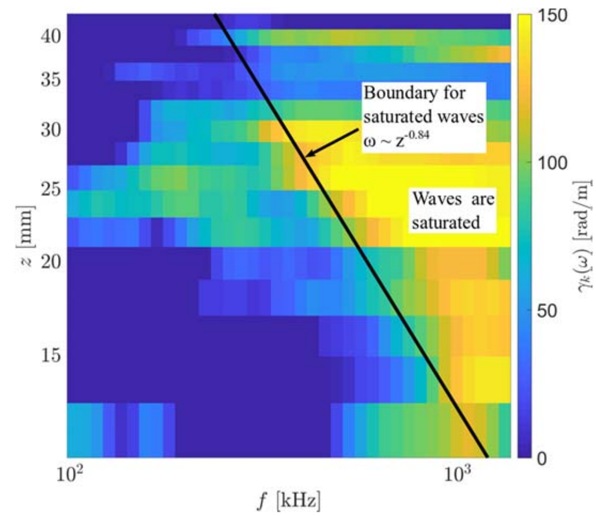

Figure 1 – Measured growth rate as a function of position and frequency. Higher frequencies are saturated and are bounded by a lower cutoff that depends on position. The curve fit is in agreement with a simple model for the saturation of wave energy.

* This work is funded by the NASA Space Technology Research Fellowship grant number NNX15AQ37H

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Investigation Particle Emission from Surface of Electrolyte in a DC Atmospheric Pressure Glow with Liquid Anode*

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Self-organization patterns observed on anode liquid surfaces in atmospheric pressure DC glow discharge represents both a mysterious and beautiful plasma physics phenomenon [1-3]. The mechanism underlying self-organization of plasmas in this context is still poorly understood. Recently, as observed with certain electrolytes under self-organization conditions, luminous particle emission from the liquid anode has been observed as shown in figure 1. High-speed camera analysis was used to map the 2D trajectories of these particles in order to analyze forces experienced by the particles during flight and to assess the initial launch velocity, which gives insight into the mechanism for launch. The size range and composition of the particles were analyzed by using a scanning electron microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDX) diagnostics respectively. The particle temperature during its glowing trajectory was measured from an infrared (IR) camera as well. This work provides not only insight into injection particle dynamics but also the energetics associated with self-organization pattern formation.

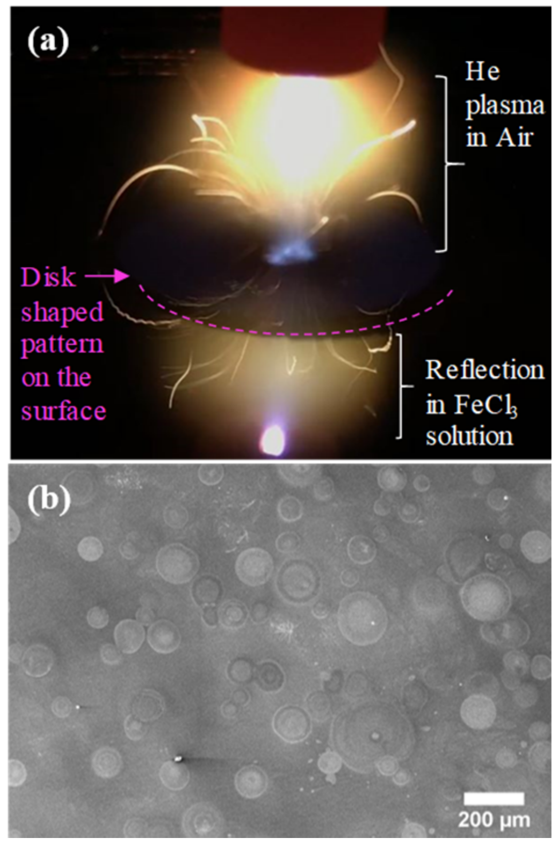

Figure 1 – Particles emitted at 100 mA from $FeCl_3$ solution (a) and a SEM image of collected particles after their impaction to a silicon wafer surface (b).

* Work supported by U.S. Department of Energy with an award DE-SC00-18058.

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Plasma Etching of High Aspect Ratio Oxide-Nitride-Oxide Stacks*

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Increasing demand for large capacity in semiconductor memory chips is now being met by 3-dimensional vertical structures. Fabricating these structures requires plasma etching through hundreds of stacked layers resulting in extremely high aspect ratio (up to 100) vias. The stack typically consists of alternately deposited SiO_2 and Si_3N_4 layers which serve as the sacrificial material and gate dielectric respectively. Combining the high aspect ratio and hybrid materials, the etching of oxide-nitride-oxide (ONO) stacks faces both traditional (e.g., aspect ratio dependent etching, bowing and charging) and new challenges (e.g., mixing layers, line edge striation and tapered etch front through several layers).

In this paper, we report on results from a computational investigation of the etching of ONO stacks using tri-frequency capacitively coupled plasmas (TF-CCPs) sustained in $Ar/C_4F_8/O_2$ mixtures. The reactor scale modeling was performed using the Hybrid Plasma Equipment Model (HPEM) from which the neutral and ion fluxes and energy and angular distributions (EADs) to the wafer surface were obtained. The feature scale modeling was performed using the 3-dimensional Monte Carlo Feature Profile Model (MCFPM) with a newly developed polymer mediated fluorocarbon etching mechanism for oxide and nitride.

During the etching of the ONO stack, the etch front quickly evolves into tapered profile that persists deep into the feature. The etch rate generally decreases with increasing aspect ratio (AR) due to limited transport of radicals and ions. As the etching in fluorocarbon containing plasmas occurs through a finite thickness of polymer layer, the etch profile is significantly affected by the polymer thickness on the surface, which is determined by the balance between the polymer deposition and removal processes. As the polymer etch probability by O atoms, $CF_x(s) + O(g) \rightarrow COF(g)$, increases from 0.005 to 0.05, or equivalently, the fluxes of O atoms increases by 10 times, there is more bowing in the etch profile at low ARs. This profile allows more radicals and ions to reach deep into the feature, which removes sidewall waviness and increases the diameter of the holes at high ARs.

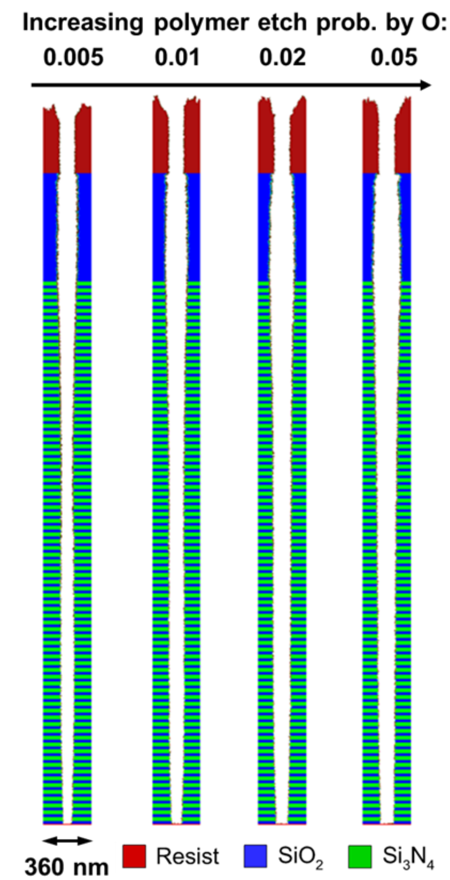

Figure 1 - Final etch profile of ONO stack with 10% over etch using fluxes and IEADs from a TF-CCP reactor. Operating conditions: $Ar/C_4F_8/O_2$ = 75/15/10, 25 mTorr, 500 sccm, 80/10/5 MHz power = 0.4/2.5/5 kW.

* Work supported by the Samsung Electronics Co., Ltd., the DOE Office of Fusion Energy Science and the National Science Foundation.

Experimental and Computational Exploration of the Effects of Non-Uniform Applied Axial Magnetic Field on Z-Pinch Imploding Cylindrical Foils*

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We use X-pinch radiography and PERSEUS [1], an extended magneto-hydrodynamic simulation code developed by Seyler et al., to explore the effect that an applied non-uniform axial magnetic field has on a z-pinch imploding cylindrical liner as compared to a uniform magnetic field. The effect of magnetic field geometry is of importance to inertial confinement fusion efforts being explored at Sandia National Laboratories on the Z-machine, which uses z-pinch cylindrical liners to compress fusion fuel. We present results of cylindrical foils imploded on the MAIZE facility at the University of Michigan, a 1-MA, 100-ns rise time pulsed power machine, as well as results from simulation work using PERSEUS, to compare several relevant physics results concerning the low density material surrounding the imploding liner.

* This research was supported by the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764.

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Substrate Holder Design Parameters for Single Crystal Diamond Deposition via Microwave Plasma Assisted CVD

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The electrical, mechanical, and thermal properties of Single Crystal Diamond (SCD) make it a promising material for next generation electronic devices. Further research and development in diamond device fabrication is currently in need of higher quality and larger area diamond substrates. SCD subtrate fabrication is based on homoepitaxial growth by Microwave Plasma-Assisted Chemical Vapor Deposition (MPACVD) with hydrogen and methane used as the process gas. This study is focused on exploring the design of the molybdenum substrate holder used in the system for diamond deposition. The main component of the sample holder design is the inclusion of a recessed region which places the diamond in optimum exposure to the plasma discharge region. This study shows a summary of current efforts and recent results in adjusting several parameters including deposition temperature, recessed pocket dimensions relative to the diamond substrate, diamond seed size/placment, and adjustment of microwave cavity dimensions.

The present study is based on empirical data from previous works [1-6] and recent results such as analysis of defect densities in grown layers by etch pit counting, birefringence measurements and micro-XRD mapping of grown SCD substrates.

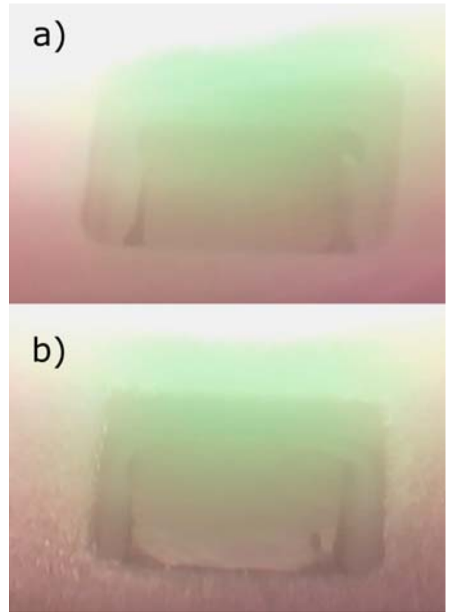

Figure 1 – (a) SCD substrate with initial dimensions of 4.8mm x 4.8mm x 1.1mm placed in the sample holder during the initial stages of the deposition. (b) Same sample after a 30h growth process, measuring 5.2mm x 5.2mm x 1.9mm.

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Evolution of Perturbed Interfaces Subjected to Transient Accelerations *

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In phenomena ranging from the expulsion of stellar core elements during supernova explosions to the degradation of the ignition hot spot during inertial confinement fusion implosions, interfaces separating plasmas of different densities undergo large, transient accelerations.[1,2] Depending on the respective signs of the acceleration and density gradient, interfacial perturbations may be Rayleigh-Taylor unstable and thus experience significant growth (see Figure 1). Although Rayleigh-Taylor analysis is well established for small-amplitude, incompressible, and constant-acceleration situations, predicting perturbation growth when departing from these conditions is both more challenging and more relevant to actual high energy density applications and experiments.[3,4]

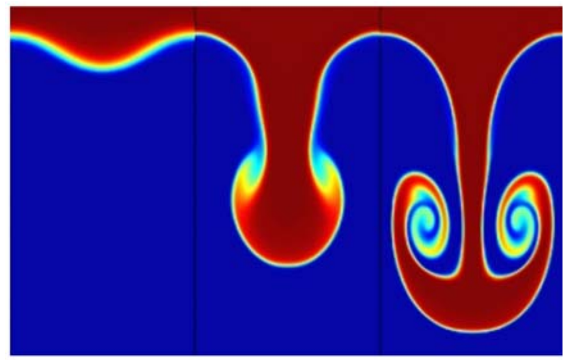

Figure 1 – The evolution of the Rayleigh Taylor instability begins with an interfacial perturbation (left). An unstable, accelerated interface will develop a bubble and spike configuration as the fluids interpenetrate (middle). At late times, the evolution of the interface is highly nonlinear and leads to the formation of "roll-up" patterns (right).

Our objective is to investigate interfacial perturbation growth driven by transient accelerations with substantial density changes. Such conditions are chosen to mirror what is observed during supernovae explosions and inertial confinement fusion experiments, where typically a blast wave passes through an interface separating two plasmas of different densities. Analysis based on one-dimensional gas dynamics is used to quantify the acceleration and dilatation experienced by such interfaces, which are incorporated into existing one-dimensional models to characterize perturbation growth at early and late times. Another key result of the analysis is the prediction of the system of waves generated by the impingement of a rarefaction wave onto a plasma interface, which is an especially important result for the analysis of systems involving multiple interfaces. All modeling results are compared to simulations performed using an in-house, high-order accurate hydrodynamics code.

* This work is supported by the LLNL under subcontract B614207.

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Growth and Propagation of the E x B Electron Drift Instability in a Hall Effect Thruster: Experiment Compared to Theory*

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Hall thrusters are a form of crossed-field plasma device commonly employed for in-space electric propulsion. A strong magnetic field confines the lighter species of the plasma, electrons, which ionize the propellant, while an applied electric field accelerates the ions downstream. Ideally, the electrons would be confined by the magnetic field, serving as an efficient ionization source. However, it has been found experimentally that electrons can cross field lines in these devices at rates orders of magnitude higher than can be explained by classical collision effects. To date, no self-consistent model has been developed for this anomalous electron transport. This lack of understanding about Hall thruster plasma dynamics precludes predictive modelling and forces designs to be validated with lengthy and expensive physical testing.

The prevailing theory to explain anomalous electron transport supposes that a strong azimuthal plasma instability develops in the Hall thruster that can knock electrons across magnetic field lines. The instability is known as the E X B electron drift instability (EDI), due to the plasma turbulence gaining energy from the electrons' high E x B drift velocity. Many models indicate that the plasma oscillations have frequencies in the low megahertz and with wavelengths on the order of a millimeter or smaller, but recent 1D kinetic simulations and experimental results point towards the EDI developing at much larger wavelengths and frequencies. The lack of consensus for the form of the EDI must be resolved.

In this work an advanced wave measurement technique is used to study the spatial evolution of plasma waves in Hall thruster plumes. Two closely spaced probes are setup to measure high frequency oscillations in plasma density. By performing a Fourier analysis on the time varying density signal the frequency and amplitude of various plasma waves can be resolved. Taking the cross-correlation of two the closely spaced probes also yields the phase lag of a plasma wave traveling past the probe tips. Knowing the separation between the probes allows the conversion from phase to wavelength as a function of frequency. By quickly injecting the probes through the plume the collected signaled can be separated into position bins and a spatial map of plasma oscillations is generated.

The results show a clear spatial evolution of the plasma turbulence in the Hall thruster's plume. Very close to the Hall thruster, where the EDI is thought to originate, the probes show high frequency plasma waves concentrated in distinct resonance peaks as predicted by many simulations. Further away from the face of the Hall thruster the high frequency waves lose strength and give way low frequency and large wavelength oscillations similar to the predications of recent kinetic models. Future simulation efforts must include a domain large enough to resolve these observed low frequency oscillations.

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Experiments to Understand the Interaction of Stellar Radiation with Molecular Clouds*

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Enhanced star formation triggered by local hot and massive stars is an astrophysical problem of interest. Radiation from the local stars act to either compress or blow apart gas clumps in the interstellar media. In the optically thick limit (short radiation mean free path), radiation is absorbed near the clump edge and compresses the clump. In the optically thin limit (long radiation mean free path), the radiation is absorbed throughout, acting to heat the clump. This heating explodes the gas clump. Careful selection of parameters, such as foam density or source temperature, allow the experimental platform to access different hydrodynamic regimes. A stellar radiation source is mimicked by a laser-irradiated, thin, gold foil, providing a source of thermal x-rays around 100 eV. The gas clump is mimicked by low-density CRF foam. We plan to show the initial experimental results from the second shot day of this platform in the optically thick limit.

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Particle Method for the Vlasov-Poisson System

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We present a 1d1v Lagrangian particle method (LPM) for the Vlasov-Poisson system in which the electric field is obtained by summing pairwise particle interactions rather than the usual particle-in-cell (PIC) approach. The aim is to achieve higher accuracy and less noise than PIC, while still providing an efficient representation of phase space using an adaptive particle distribution and treecode acceleration. We compare our LPM with a standard PIC code and an Eulerian Vlasov code for several test cases including the two stream instability and Landau damping.

Time Dependent Physics of Single Surface Multipactor by Multiparticle Monte Carlo Simulations*

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This work investigates the time dependent physics of the single surface multipactor by Monte Carlo (MC) simulations [1, 2]. We consider a system with large number of macroparticles. The number of macroparticles is held fixed throughout the simulation. Upon impact of each macroparticle onto the surface, the charge and mass in that macroparticle and the normal electric field to the dielectric surface are updated according to the secondary electron yield.

We observe that for the single frequency mode of the rf electric field acting parallel to the surface, the normal surface field saturates at the lower multipactor susceptibility boundary with a temporal oscillation at twice the rf frequency. The temporal relationship between the fields normal and parallel to the surface traces a closed curve in the ac saturation state. The shape of the curve depends on the amplitude of the rf envelope. These observations agree with previous works of H.C. Kim and J.P. Verboncoeur [3].

For the dual frequency mode of the rf electric field, the saturation level and oscillation pattern of the normal electric field changes from those of the single frequency mode. These changes are due to the modification of the rf envelope and the susceptibility boundaries [4] of the dual frequency mode. We have studied a square wave rf field as well, resolving the corresponding normal field profile at different rf frequencies.

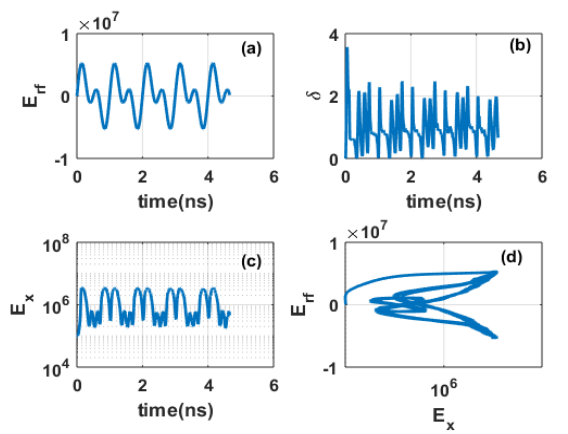

Figure 1 – Dual frequency mode of multipactor in a dielectric: (a) Instantaneous total rf electric field, E_{rf},(b) secondary electron yield, δ, with the average δ_{avg}=1 for saturation, (c) normal electric field, E_x, and (d) the trajectory of the electric field (E_x, E_{rf}), with both fundamental and 2nd harmonic rf field of magnitude $3MV/m$, fundamental rf frequency $f = 1GHz$, relative phase of the second carrier, $\gamma = 0$.

*Work supported by AFOSR MURI Grant No. FA9550-18-1-0062, and in part by an MSU Foundation Strategic Partnership Grant.

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Numerical Investigation of Radiation Heat-fronts*

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When a cold body is exposed to an intense source of radiation, its temperature equilibrates with the source by the propagation of a nonlinear heat front. As a result, the surface ablates and a shock is driven through the interior of the body (see Fig. 1). This phenomenon is ubiquitous in astrophysics, for example occurring as a H-II region expands within a giant molecular gas cloud [1]. Understanding the physics of these fronts is also crucial to the success of indirect-drive inertial confinement fusion experiments [2].

Obeying fundamental scaling similarity allows use of results obtained from radiation heat-fronts in the laboratory to form inferences about the astrophysical systems. Such work is being conducted by collaborators at the University of Michigan [3] as well as at Lawrence Livermore National Lab [4]. These experimental campaigns are largely dependent on numerical investigations for predicting measurable quantities, physically explaining key features of observations, as well as assessing the feasibility of designs in certain physical regimes.

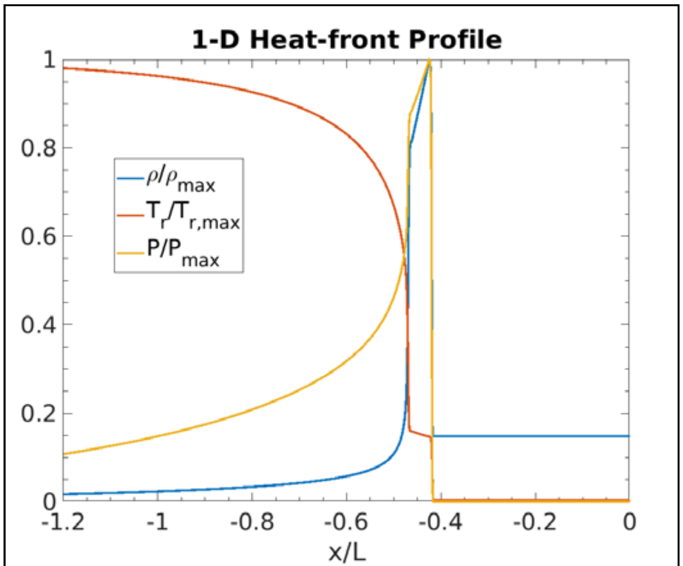

Figure 1 – Simulated 1-D profile of radiative heat front

In this study we use 1-D and 2-D simulations performed using the CRASH radiation hydrodynamics code to provide estimates of shock timing and strength for comparison with observed radiographs obtained from a laboratory-astrophysics experiment. We study ablation features relevant to an apparent bow-shock observed in radiographs of this experiment. We also assess the usefulness of models (e.g. self-similar solutions) in predicting these quantities, which have the potential of making further simulations using different target and drive data unneeded.

* This work is supported by the Lawrence Livermore National Laboratory under subcontract B614207 and was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

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The Mobility of Electrons in a Hall Thruster Simulation*

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A two-dimensional, hybrid-direct kinetic (DK) simulation is used to model the discharge plasma in a Hall thruster channel and near-field plume. The simulation employs a two-dimensional Vlasov solver coupled with a quasi-one-dimensional electron fluid solver and a collision model. Our previous work showed that the simulation was particularly sensitive to boundary conditions for the electron model in the near-anode region of the thruster.[1] After benchmarking and having achieved a stable simulation, the present work focuses primarily on the mobility of electrons.

Wall collisions and turbulent plasma fluctuations are known to enhance the mobility of electrons beyond that due to collisions with heavy particles. This so-called *anomalous mobility* has been the subject of a large body of work, and state-of-the-art computational models account for the phenomenon by augmenting and tuning the electron collision frequency to match experimental measurements.[2]

Due to its Eulerian nature, the kinetic algorithm in this work does not contribute artificial numerical statistical noise to simulation results. The effects of this can be seen in Fig. 1, where the time-varying plasma density in the DK simulation is compared to that in a comparable PIC simulation. Because of the lack of statistical noise in the kinetic algorithm, the DK simulation provides a unique platform in which to quantify the effects that different electron mobility models have on computed quantities of interest, primarily the discharge current and the distribution of plasma properties within the simulation domain.

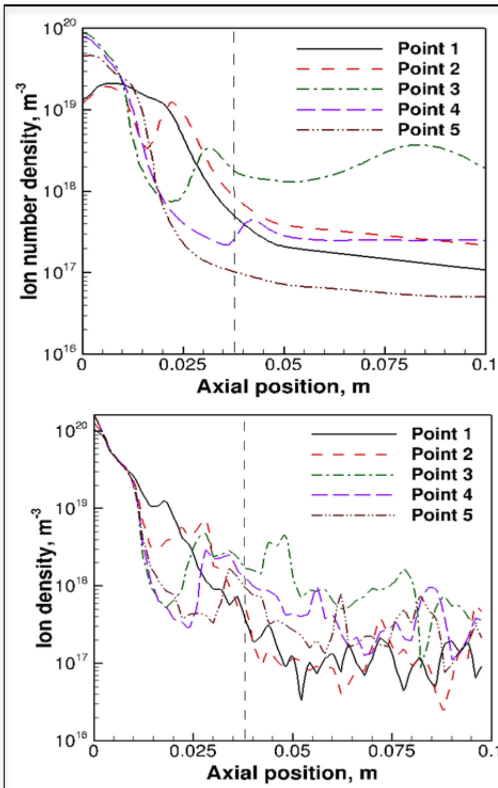

Figure 1 - Comparison of predictions at 5 different time points of ion density: DK (top) and PIC (bottom)

* Work supported by the Air Force Office of Scientific Research Grant No. FA95550-17-0035

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An Analytical Model for Ultrafast Electron Emission Due to Two-color Laser Fields*

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Laser-induced electron emission from solids provides a way to coherently control electron dynamics in ultrashort spatiotemporal scales. It is important to free electron lasers (FELs), ultrafast electron microscopes, x-ray sources, particle accelerators and novel quantum nanocircuits [1-3]. Two-color laser pulses have been used to generate electron emission from a metal nanotip, which offers new flexibility to control the dynamics and distribution of emission electrons due to the interference effect [4].

By solving the time-dependent Schrödinger equation [5], we construct an exact analytical model for the nonlinear photoemission from a metal surface due to two-color laser fields (Fig. 1). Our solution is applicable for arbitrary fundamental and harmonic laser frequencies, laser intensities, phase delays, metal work function and Fermi level. Our single formulation covers various emission mechanisms such as multiphoton absorption, photon-induced over-barrier emission, strong optical field emission, and various combinations of them. We identify the condition for the maximum emission current modulation (Fig. 2) by superimposing a weak harmonic laser on a fundamental laser, showing good agreement with the experimental results [4]. Our results are expected to guide future experiments on ultrafast electron emission.

* Work supported by AFOSR YIP Award No. FA9550-18-1-0061.

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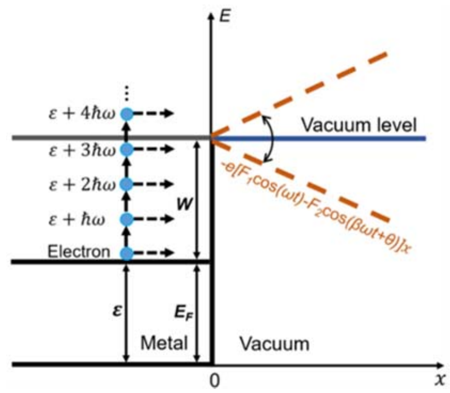

Figure 1 – Energy diagram for electron emission through a wiggling potential barrier induced by two-color laser fields across the metal-vacuum interface at *x*=0. Electrons with initial energy of ε are excited to emit by absorbing photon energy $n\hbar\omega$, with an integer n. The fundamental and harmonic laser fields are $F_1\cos(\omega t)$ and $F_2\cos(\beta\omega t+\theta)$, respectively. E_F and W are the Fermi energy and work function of the metal, respectively.

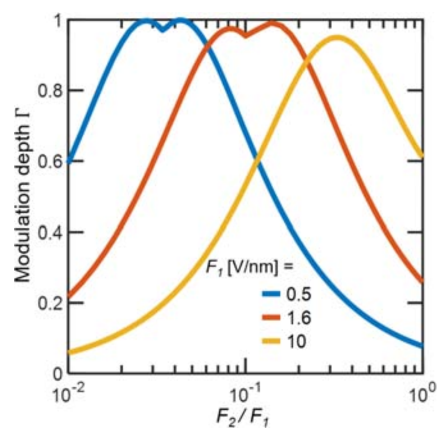

Figure 2 – Current modulation depth Γ as a function of F_2/F_1 for different fundamental laser fields $F_1 = 0.5, 1.6, 10$ V/nm. Here, F_2 is the second harmonic laser field. The wavelength of the fundamental laser is 800nm ($\hbar\omega$ = 1.55 eV). The metal is assumed to be gold with Fermi energy E_F=5.33 eV and the work function W=5.1 eV.

Non-Invasive Characterization of the Hall Thruster Breathing Mode

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An experimental characterization of the Hall thruster breathing mode is performed non-invasively. This investigation provides insight into the successes and failures of zero-dimensional models of this low-frequency instability.[1] Time-resolved laser-induced fluorescence is used to measure the ion velocity probability function, and an in situ electrostatic probe provides a fixed downstream measurement of current density. Moments of the one-dimensional ion Boltzmann equation are solved explicitly for ionization rate, electric field strength, and ion density gradient as a function of time using the experimental data, extending the method of Pérez-Luna et al.[2] Numerical integration is used to yield the ion density profile. Further, fluid equations for the neutral gas are used to estimate neutral density and velocity.

From these experimental measurements it is found that all measured quantities fluctuate over a breathing cycle. The ionization region length also correlates with breathing and its phase offset with ion density fluctuations is quantified, fulfilling several sufficient criteria for a zero-dimensional that predicts growth of the instability. However, the ion density oscillations are not zero-dimensional but instead evolve spatially, proving incorrect a fundamental assumption of many breathing models. The nature of the breathing mode oscillations is reconsidered given these results.

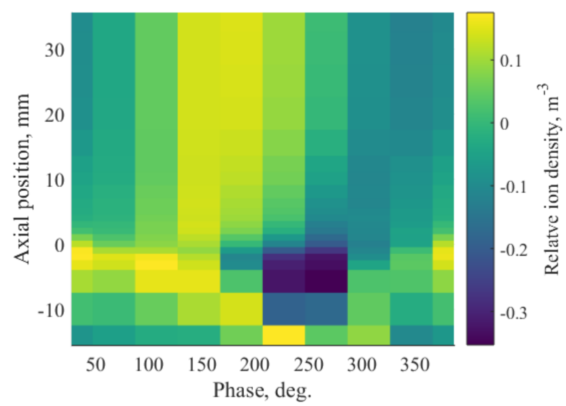

Figure 1 – The ion density normalized by its spatial mean as a function of axial position and breathing phase in a 9-kW magnetically-shielded Hall thruster operating at 300 V, 2.5 kW.

*This work was supported by NASA Space Technology Research Fellowship NNX14AL65H.

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Active Control for High Repetition-rate Laser Wakefield Accelerators*

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Many potential applications of laser accelerator sources require operation at high repetition rate. Here, few-milliJoule pulses are generated at kilohertz repetition rate for wakefield acceleration. A genetic algorithm is implemented using a deformable mirror with the wakefield electron beam signal optimized onto several different masks used as feedback. This procedure allows a heuristic search for the optimal wavefront under laser-plasma conditions that is not known a priori. We are able to improve the electron beam charge and angular distribution by an order of magnitude. These improvements do not simply correspond to finding the 'best' focal spot, as the highest quality vacuum focal spot produces an inferior electron beam. The saved deformable mirror configurations coupled with the use of a Shack-Hartmann wavefront sensor promise to characterize the laser phase front that induces a plasma wave which provides optimal accelerating fields.

* Work supported by the National Science Foundation

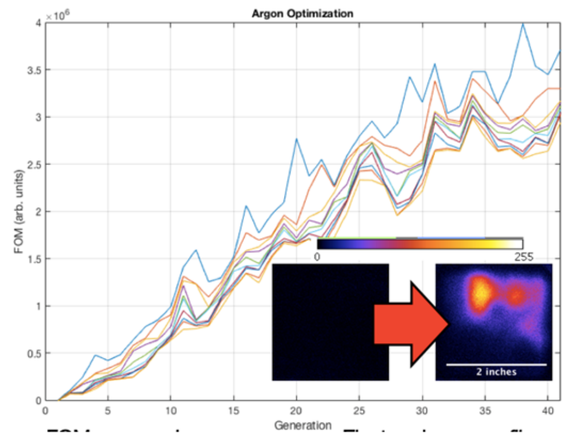

Figure 1 – Figure of merit generation curve for an electron beam generated with a kHz laser outputting milliJoule pulses. The figure of merit used here was a gaussian mask on the phosphor screen. The beam was generated using a jet of argon with 100µm inner diameter. The inset shows the before and after (optimization) image behind the phosphor screen.

Omega 60 Experiments of Rayleigh-Taylor Instability Growth in the Highly Nonlinear Stage: Results and Future Directions*

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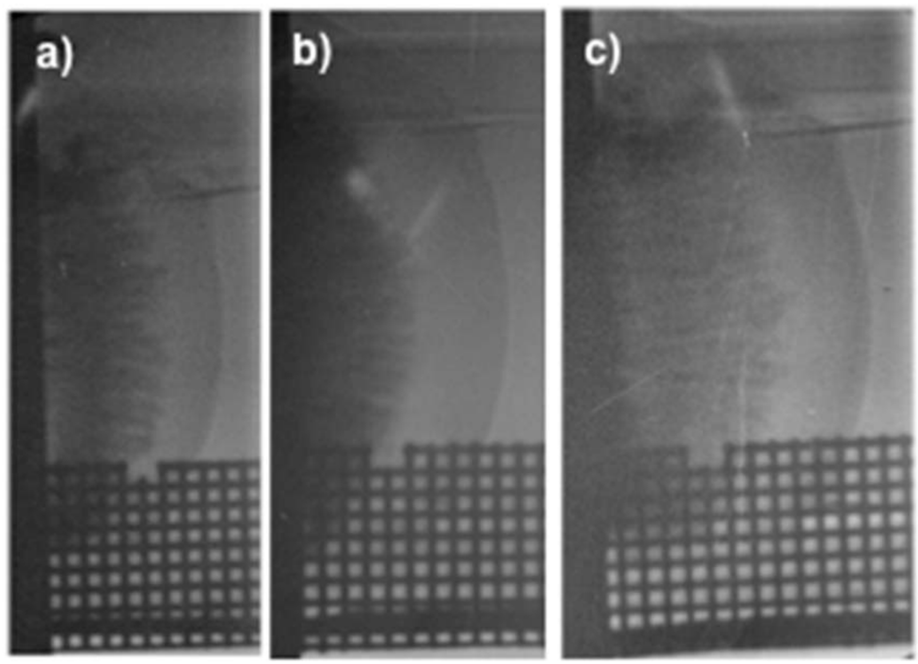

Radiography data of low-Atwood, λ=40 μm targets. a) RID 90385 at 20 ns; b) RID 90381 at 25 ns; c) RID 90382 at 30 ns

The ability to predict the evolution of the Rayleigh-Taylor Instability (RTI) and rate at which two fluids mix is of great interest in high-energy-density physics. Potential flow models predict that mixing due to RTI will reach a terminal velocity (and constant Froude number) [1]. For Rayleigh-Taylor-unstable systems where density contrast of the two fluids is small (low Atwood number), numerical simulations show an unexpected reacceleration of RTI growth and higher Froude number in the late nonlinear stage [2].

To observe or refute the behavior in question, we have conducted a series of experiments at Omega 60 to drive single-mode RTI growth to the latest times possible, for both high- and low-Atwood number systems. Experimental results, comparisons with simulations, and future directions are discussed here.

* This work is funded by the Lawrence Livermore National Laboratory under subcontract B614207, and was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

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Design of a Pulsed-Power Magnetized Plasma Flow Experiment for the Study of Star Formation and Astrophysical Bow Shocks*

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We present the design of two laboratory-astrophysics experiments with the goal of translating research performed at a major (several kJ) laser facility into the pulsed-power laboratory at the Michigan Accelerator for Inductive Z-Pinch Experiments (MAIZE). The experiments are designed to explore the interactions of magnetized plasma flows in astrophysical bow shocks and accretion shocks found in star formation, with a focus in the structure and development of shock instabilities. Appropriate scaling [1] is used to verify relevance of our experiment to the astrophysical phenomena. We will be generating magnetized plasma flows via pulsed-power in the Linear Transformer Drive (LTD) at the University of Michigan, by ablating aluminum wire arrays with currents of up to 1 Mega-Amp. We have designed two different array geometries: a cylindrical wire array (Fig.1 (a)) that will be used to study bow shock interactions against a variety of magnetized targets (conducting wires, electromagnets and permanent magnets), and a conical array (Fig.1 (b)) that will drive a plasma jet into a solid target for the study accretion shocks.

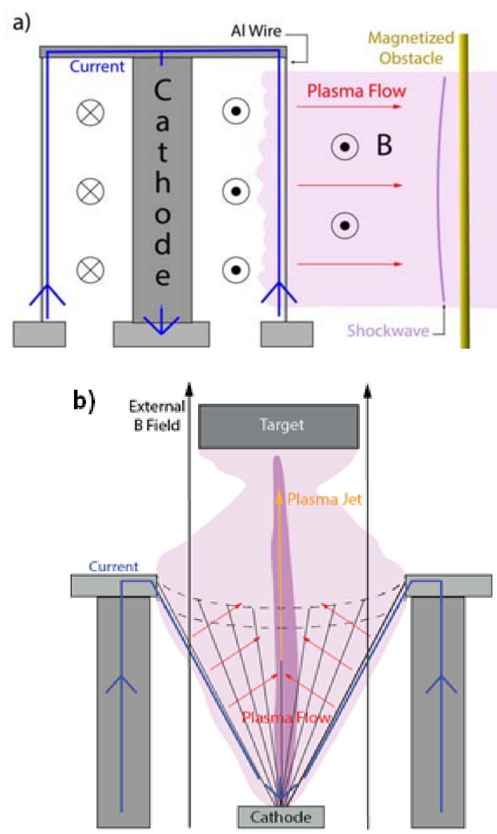

Figure 1 – Schematic illustration of the target array for both experimental configurations: a) cylindrical array, where a magnetized plasma flow is generated outwards, towards a magnetized obstacle. b) conical array, in which a magnetized jet is projected towards a flat target, and an external B-field is applied.

* This work is funded in part by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0002956; as well as the University of Michigan and a Faculty Development Grant from the United States Nuclear Regulatory Commission.

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Comparison of Traditional and Plasma-induced Advanced Oxidation Processes

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Advanced oxidation processes (AOPs) are a category of chemical treatment methods for removing persistent organic pollutants from waters and wastewaters via reactions with highly reactive oxidizing agents, namely hydroxyl radicals. Low-temperature plasmas in contact with water produce chemically reactive environments for the abundant generation of hydroxyl radicals, thus representing a novel advanced oxidation technology. Plasma-derived AOPs hold significant advantages over traditional methods since the oxidizing species are generated through plasma interaction with water molecules, negating the requisite for expensive and often dangerous transport and storage of these reactive chemicals. However, before plasma-induced AOPs can be considered for commercial applications, their cost effectiveness and throughput must be established to be competitive with traditional methods.

In this study, the decontamination performance of plasma-induced advanced oxidation in an underwater dielectric barrier discharge plasma system is experimentally assessed and compared with the traditional hydrogen peroxide and ultraviolet light advanced oxidation process performance. Ethylene glycol and methylene blue are used as model organic contaminants. The decontamination performances of traditional AOPs are simulated, and the model results are compared with the experiments.

* Work supported by NASA

Magnetized Bow Shocks at the OMEGA Laser Facility: Comparing Experimental Observations with Theory and Simulation

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We present analysis of recent experiments studying magnetized bow shocks at the OMEGA laser facility, in which the spatially resolved optical Imaging Thomson Scattering diagnostic (ITS) measured plasma parameters across a magnetized shock front. The bow shock system consists of a relatively slow, low-density plasma flow impinging on the azimuthal magnetic field imposed by a current-carrying wire. The magnetic field is strong enough to oppose the flow and generate a shock. We infer electron number density and temperature from the Thomson scattered spectra, from which we determine the shock standoff distance. The data collected for two different levels of current in the wire suggests that the shock exists farther from the wire for stronger magnetic fields. We compare the inferred shock standoff distances to analytical models and to MHD simulations using the FLASH code.

* 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-NA0002956, and the National Laser User Facility Program and William Marsh Rice University, grant number, R19071, and through the Laboratory for Laser Energetics, University of Rochester by the NNSA/OICF under Cooperative Agreement No. DE-NA0001944.

Laser-wakefield Accelerators for High-resolution X-ray Imaging of Complex Microstructures

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Laser-wakefield accelerators (LWFA) are a new generation of plasma based particle accelerators, capable of producing high-energy electron beams. Within the strong focusing fields of the wakefield, accelerated electrons undergo betatron oscillations, emitting a bright source of x-rays with a source size as small as one micrometer. Non-destructive x-ray phase contrast imaging and tomography of heterogeneous materials can provide insight into their processing, structure, and performance. To demonstrate the imaging capability with LWFA, we have examined an irregular eutectic in the aluminum (Al)-silicon (Si) system. The lamellar spacing of the Al-Si eutectic microstructure is on the order of a few micrometers, thus requiring high spatial resolution. We present comparisons between the sharpness and spatial resolution in phase contrast images of this eutectic alloy obtained via synchrotron x-ray phase contrast imaging on the Swiss Light Source and x-ray projection microscopy via a LWFA source. Our results indicate that betatron x-rays from LWFA can be competitive with conventional synchrotron sources for the characterization of eutetics and, more broadly, complex microstructures.

Interactions Between Water Droplets and Dielectric Barrier Discharge Plasmas*

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Plasma/liquid interactions are of interest for pollution control, water purification, disinfection, and medical treatment. The means of transferring reactivity from the plasma into the bulk liquid, however, is poorly understood. One method to optimize the transfer of reactive species into the liquid is by maximizing the surface-to-volume ratio of the liquid. This is accomplished by plasma activation of aerosols. Dielectric barrier discharges (DBDs) interacting with single water droplets having radii of 5 µm to 20 µm at different discharge frequencies (10 kHz to 1 MHz) were computationally investigated using the plasma hydrodynamics model nonPDPSIM [1]. The reaction mechanism includes 58 gas-phase and 37 liquid-phase species, and over 1,500 reactions.

We found that the droplets, acting as a dielectric at small time-scales, provide electric field enhancement increasing the probability of discharge formation in their proximity (Fig. 1). The densities of species in the aerosol having high Henry's Law constants, h_0, had a strong dependence on the radius of the droplets. This is because the liquid bulk can support high densities of these species, and their densities in the liquid typically do not saturate regardless of droplet diameter. The opposite is true of species with low h_0. The densities of these species saturate in the liquid and do not have a strong dependence on either radius or frequency of the DBD. Higher frequency operation aided in decreasing the time required for saturation by increasing the local gas-phase density, elevating rates of solvation during the pulsing phase.

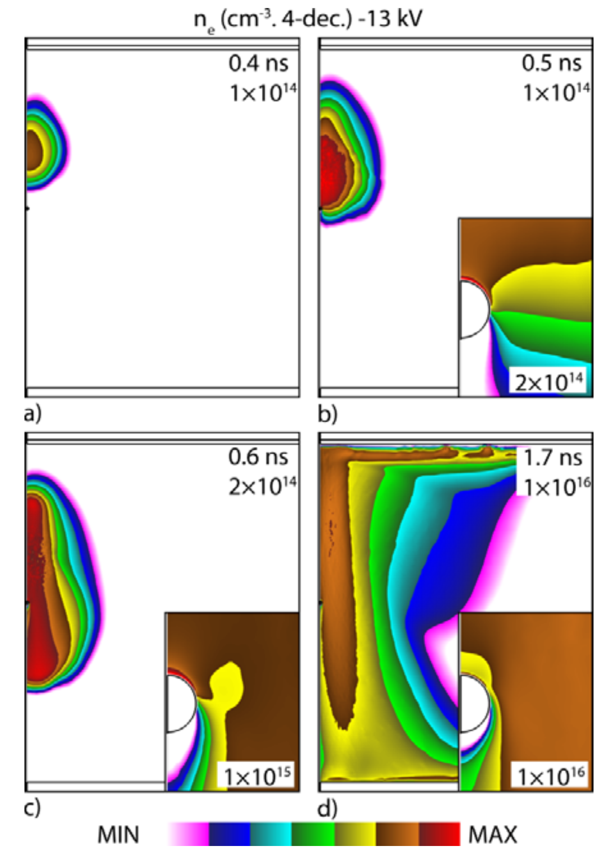

Figure 1 - Evolution of electron density.

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

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Dynamic Evaluation of EEDF with Boltzmann Equation Solvers in the KGMf*

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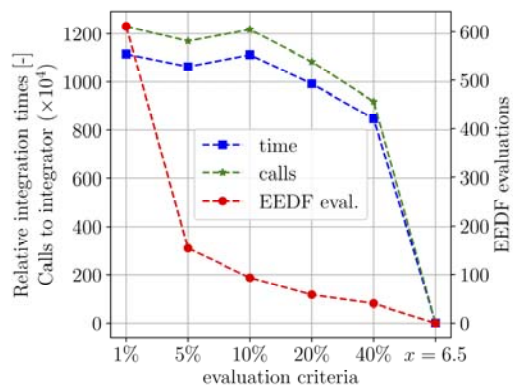

Figure 1 – Computational time versus different EEDF evaluation fequency criteria.

Global models are widely used to investigate macroscopic parameters in various discharge systems, offering fruitful results with simplicity and high efficiency, while including as many microscopic processes as possible.[1,2] One common assumption in a global model is using a predefined electron energy distribution function (EEDF), which depends on a system state and might have significant impact on the rate coefficient of electron impact reactions and further on the plasma properties.

The Kinetic Global Model framework (KGMf) is a volume-averaged simulation tool used to explore complicated plasma chemistry in multi-species systems with a goal to find a set of the most influential reactions.[3] The reduced set of reactions from the KGMf can be used in fluid or particle-in-cell (PIC) simulations to reduce the computational expense. The KGMf is currently developed by coupling it with various Boltzmann equation solvers (BOLOS and MultiBolt), which are used to compute the EEDF self-consistently.[4,5] This improvement enables the KGMf to capture the temporal evolution of the EEDF, which makes simulation results more physically reasonable, however, it results in longer simulation times, as shown in Fig. 1.[6]

To preserve the advantage of the global model, a reduction in EEDF evaluations is possible by automatically adjusting its evaluation frequency. That is to say, one can update EEDF at fixed simulation steps (Δn) or at relative change of system variables: the electron temperature (ΔT_{eff}), the electron density (Δn_e) or the reduced electric field ($\Delta E/N$). The dependence of electron density, electron temperature, and reaction rate coefficients on different EEDF evaluation frequencies in high-pressure low-temperature argon discharges, computed with BOLOS and MultiBolt Boltzmann equation solvers, is presented and discussed.

* Work supported by Department of Energy Plasma Science Center grant DE-SC0001939 and MSU Strategic Partnership Grant.

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Characterization of Plasma Properties in Hollow Cathode Discharge

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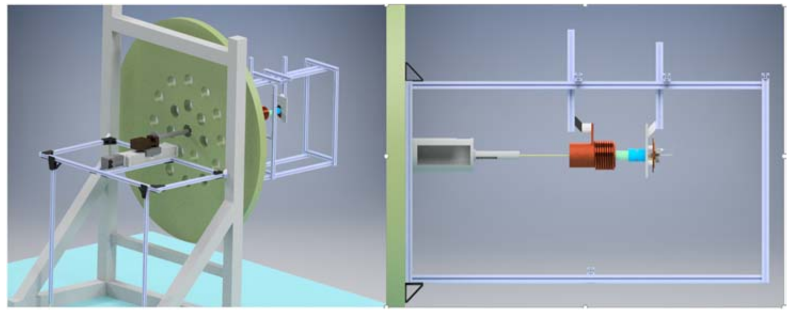

Figure 1 – The experimental setup allowing diagnostic access of fast scanning probes to the cathode interior region. A motion control stage is mechanically coupled to the probe of interest, and the probe transits throught the cathode orifice, obtaining information about the plasma.

An important life limiter in conventional gridded ion and Hall thrusters is lifetime of the hollow cathode assembly. The cathode's lifetime is a function of the barium supply within the insert. While barium can be lost from the cathode via gas phase diffusion, models predict that significant barium recirculation within the insert actually occurs. The recirculation and transport of barium is dependent on plasma conditions prevailing in the hollow cathode. Presented here are plasma measurements made within the hollow cathode under conditions of spot and plume mode operation. Ion acoustic wave spectra are also examined in an attempt to assess recirculating barium concentration within the insert region using krypton as a propellant.

* Work supported by the NASA Space Technology Research Fellowship (NSTRF)

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Proton Radiography of a Highly Asymmetric Laser-driven Reconnection Geometry*

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In experiments performed at the OMEGA EP laser facility at the Laboratory for Laser Energetics, the typical laser-driven magnetic reconnection geometry was adapted such that one high intensity pulse ($I \approx 10^{19}$ Wcm^{-2}) was focused alongside a moderate intensity UV long pulse ($I \approx 10^{14}$ Wcm^{-2}) on foil targets. First, the long pulse ablates a region of the target and misaligned temperature and density gradients in the plasma plume generate an azimuthal magnetic field via the Biermann battery mechanism. After the Biermann field develops, the high intensity pulse arrives on target and produces a relativistic, highly magnetized plasma ($\sigma = B/\mu_0 n_e m_e c^2 \geq 1$) which sweeps across the target surface with velocities near the speed of light. Proton radiography captures the evolution of the strong, impulsive magnetic field generated by the high intensity pulse and its interaction with the relatively slowly evolving Biermann battery fields. Quantitative measurements of the magnetic field dynamics will be presented, as well as 2D and 3D particle-in-cell simulation results.

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Towards Multidimensional Kinetic Modeling of Thermionic Hollow Cathodes*

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Thermionic hollow cathodes are a critical component of two prevalent electric propulsion devices: ion thrusters and Hall thrusters. In these devices, gas supply is fed through a tube and, through the use of low work function inserts and a heating mechanism, a plasma is generated and extracted. Hollow cathodes serve primarily as an electron source; they are used to supply either an ionizing current, a neutralizing current, or both, to the system. Although cathodes have been utilized for decades, their operation and life-limiting processes are still poorly understood.

Existing numerical models of thermionic hollow cathodes largely use the fluid assumption for a plasma [1]. While the results of those studies are satisfactory in the cathode channel, once the plasma expands into the plume, continuum descriptions break down and this treatment is no longer accurate. Processes such as ion acoustic turbulence become important in the cathode plume, driving the electron temperature and plasma potential well above classical values. In order to address the need for a high-fidelity, multidimensional model of a hollow cathode, this work aims to utilize a deterministic kinetic method. In particular, this work draws from the finite volume, hybrid direct-kinetic (DK) method developed by Hara. This approach solves the Vlasov equation in discretized physical and phase space [2]. For the most efficient simulation of a hollow cathode, an axisymmetric (2D2V) formulation in cylindrical coordinates is being developed.

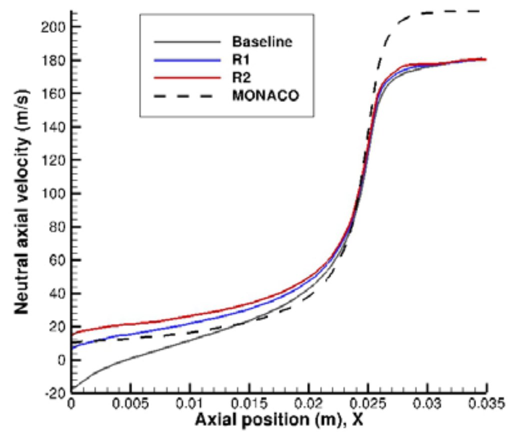

Figure 1 – Solution Grid Dependence

As an initial approach to the problem, a simple neutral particle expansion flow is simulated in the axisymmetric configuration. Preliminary results indicate that the addition of the radius in the flux terms of the finite volume scheme introduce an increased dependence on the grid spacing. Figure 1 demonstrates this dependence, via the axial neutral velocity at the radial midpoint of the channel, through three iterations of grid refinement for this simple case. As a comparison benchmark, the extensively validated direct simulation Monte Carlo (DSMC) code MONACO is used and the results included here. Further work is necessary in order to verify the implementation of the cylindrical coordinate Vlasov equation solver, as well as assessing the effects of grid spacing and boundary conditions on this configuration. In the future, this treatment will then be extended to ions, and an axisymmetric fluid electron model.

* Work supported by the National Defense Science and Engineering Graduate Fellowship

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Low Power Magnetic Nozzle Thrust Performance in the Presence of Non-Idealities*

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Magnetic nozzles have been proposed for a number of electric propulsion devices [1, 2], due to the ability to convert thermal energy within a plasma into directed kinetic energy through an externally applied diverging magnetic field. In an ideal nozzle as the plasma expands in the diverging nozzle section it is initially confined to the magnetic field lines. At a downstream location the plasma detaches from the field lines, generating a net thrust. However, this idealized notion of operation is inconsistent with experimental measurements of some laboratory devices; these devices have demonstrated that non-idealities, including neutral pressure and spatial power deposition effects, can significantly degrade performance.

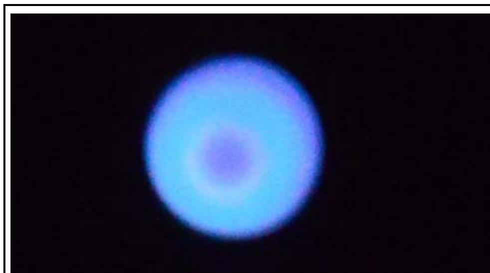

Figure 1 - A front view of the source operating on xenon at ~150 W deposited power and 0.5 mg/s. Note the dim center region.

A miniature radio frequency (RF) magnetic nozzle source is used to investigate non-idealities that impact thrust performance. The source is flexibly designed to operate with multiple plasma liners ranging from 1.25 cm to 2.5 cm in diameter and 1.9 cm in length. The diverging magnetic nozzle is generated by an electromagnet with 149 windings and is capable of producing a peak axial magnetic field of up to ~900 G within the plasma liner. Power is deposited into the plasma at 5-20 MHz via a 3-turn solenoidal antenna by an external RF source. This configuration enables variable capacitor matching for coarse tuning and frequency matching for fine tuning to improve power coupling. Both the RF antenna and the electromagnet are water cooled to improve thermal and power coupling stability.

A suite of electrostatic probes, including a double Langmuir probe, an emissive probe, and a guarded Faraday probe are used to map the properties within the plume. The magnetic field is spatially mapped using a 3-axis gaussmeter. The radial and axial ion velocity trajectories are directly measured using Laser Induced Fluorescence.

These 2D maps of the plasma properties are used to determine if non-idealities are present and the extent of the performance changes due to the non-idealities. The experiment examines source configurations with different magnetic field strengths, neutral gas flow rates, input powers, and plasma liner geometries to identify operating regimes that are conducive to non-idealities to inform future propulsive magnetic nozzle designs.

* This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1256260.

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Deuterium Pinches and Switch Diagnostics for the 1-MA, 100ns MAIZE Pulsed Power Facility*

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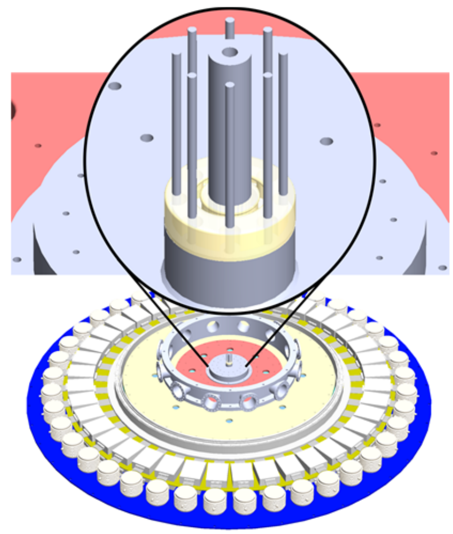
The Z-machine housed at Sandia National Laboratories is instrumental in plasma physics research across a range of applications including inertial confinement fusion. University-scale z-pinch experiments can inform high-value experiments conducted at Sandia. A Dense Plasma Focus (DPF), gas puff z-pinch, and a hybrid of the two are such z-pinches [1]. Specifically, they involve plasma compression resulting in a large number of fusion reactions. Fusion results from micro-pinch instabilities, regions of extremely high pressure and temperature within the plasma which are poorly understood. Hybrid systems (Fig. 1) allow for gas to be puffed into a DPF leading to compressions that allow for a systematic study of micro-pinch phenomena. A hybrid system may also allow us to study shear-flow-stabilized z-pinches on fast (100-ns) time scales. The experimental design is based on simulations run using the Lee model [2], which we recoded in Python. Additional simulations will be carried out using PERSEUS, an extended magnetohydrodynamics code [3]. These simulations will lay the foundations for experimentation on MAIZE.

Figure 1 - Schematic of a hybrid gas-puff and Dense Plasma Focus system integrated onto MAIZE.



We have revamped switch diagnostics on MAIZE, which consists of a set of 40 capacitor-switch-capacitor “bricks”. Discharging each of the capacitors in a brick is carried out by the breakdown of a spark-gap switch, a process that results in emission of light. Monitoring this output light provides information on switch performance and timing jitter– whether a switch fired early, late, or in phase with the other switches. However, examination of 40 switches during each shot with a dedicated photomultiplier tube (PMT) and oscilloscope channel is a resource-intensive process. If the only information required is the pre-fire of a switch, a circuit can be set up that reduces a PMT to a computer bit. With such a circuit, six PMTs can uniquely identify a single pre-firing switch out of 40.

* 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.

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Performance Portable Finite Volume Magnetohydrodynamics for the Exascale Era

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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. [1,2] 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.

* Work supported by Michigan Institute for Plasma Science and Engineering

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X-ray Diagnostic Development for e- beam Driven Warm Dense Matter Studies*

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A platform for characterizing the equation-of-state of the warm dense matter (WDM) regime is being developed on an intense, relativistic electron accelerator.[1,2] An 80-ns (FWHM) electron pulse with a beam current of 1.7 kA and energy of 19.8 MeV deposits energy into a thin, low-Z metal foil heating it to a warm dense plasma. LASNEX hydrodynamic simulations suggest the relatively large scale (~100 μm) WDM lasts 100 ns after the beam pulse providing a background-free measurement window for deploying X-ray diagnostics. The ultimate goal of these diagnostics is to measure the temperature and density of the WDM. Measurements on expanded Al, Ti, and Cu plasma plumes show significant absorption in the visible emission likely due to opacity effects. A modeling effort of these spectra is underway using the ATOMIC suite of codes at Los Alamos National Laboratory (LANL) whose results will ultimately be post-processed using FESTR, a LANL-developed radiation transport code.[3,4] In addition, a 600 kV, 33 J compact Marx generator is being investigated for use as an X-ray source for detector and crystal calibration as well as potentially a backlighter for target radiography. Initial experimental results and interpretation and hardware setups and designs will be presented.

* This work was supported by the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. DE-AC52-06NA25396.

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Nano-wires to Film Transitions During Pulsed-laser Deposition: Role of Ion Distribution

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Tin-doped indium oxide (ITO) is the most commonly adopted transparent conducting oxide due to its high transparency and high conductivity.[1] Furthermore, ITO nano-wires (NW) have attracted interest as components for flexible transparent electronics, gas sensors, and nano-meter scale optoelectronic devices.[1,2] Pulsed laser deposition is increasingly being used for ITO fabrication, with NW vs. film formation most often determined by the use of an inert or reactive atmosphere. Fabrication of both NW and film has been observed in inert atmosphere with increasing pressure, but a mechanism for the transition has not been discussed.[3] We have examined the formation mechanisms of droplets, nano-wires (NW), and films during pulsed laser deposition of tin-doped indium oxide (ITO). We consider the role of an inert gas pressure-manipulated plasma on the transition from vapor-liquid-solid to vapor-solid growth. For the lowest N_2 pressure, liquid indium-tin droplet formation, followed by self-catalyzed vapor-liquid-solid (VLS) growth of nano-wires, is observed. With increasing N_2 pressure, a transition from VLS to vapor-solid (VS) growth of films is apparent. We hypothesize that the source gas pressure influences the metal-oxide stoichiometry across the plasma core. In the presence of N_2, the lightest element, oxygen, is strongly scattered, resulting in a metal-rich plume. As the N_2 pressure is increased, the radial extent of the plasma plume and its metal rich core are reduced. This approach is likely applicable to the formation of a wide variety of metal-oxide nano-wires core-shell structure for nanoscale electronic devices.

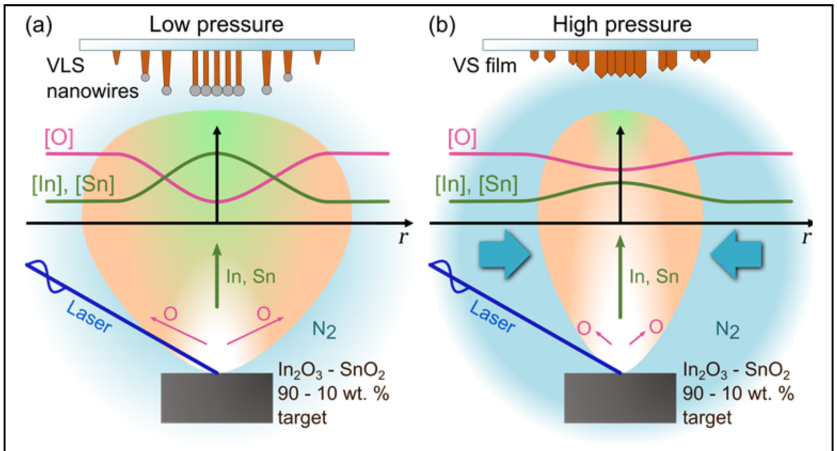

Figure 1 - Schematic drawing of the spatial variation of the stoichiometry of the plasma plume. For lower N_2 pressure, oxygen is scattered by N_2, resulting in a metal rich stoichiometry at the plasma plume core, enabling VLS growth of NW. For higher N_2 pressure, the expansion of the plasma plume is limited, recovering the oxygen-rich stoichiometry to enable VS growth of films.

* Work supported by NSF grant # ECCS-1610362

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Recent Progress on the Harmonic Recirculating Planar Magnetron*

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The Multi-Frequency Recirculating Planar Magnetron (MFRPM) [1,2] is a high power microwave source capable of generating MW power levels, and is novel because it can radiate multiple frequencies simultaneously. The MFRPM is designed to produce 1 and 2 GHz signals, generated by the L-Band Oscillator (LBO) and S-Band Oscillator (SBO), respectively. The MFRPM is the first magnetron to demonstrate harmonic frequency-locking, where the SBO's oscillating frequency locked to the harmonic of the LBO's oscillating frequency. To understand this locking phenomenon, the Harmonic Recirculating Planar Magnetron (HRPM) has been designed. The HRPM prototype is pictured in Figure 1, featuring a frequency tunable LBO and B-Dot ports for frequency sampling within the cavities. Key simulation results will be presented in addition to early experimental data obtained by driving the HRPM with the Michigan Electron Long Beam Accelerator (MELBA-C). MELBA can provide a -300 kV pulse for a duration of 0.3-1.0 μs.

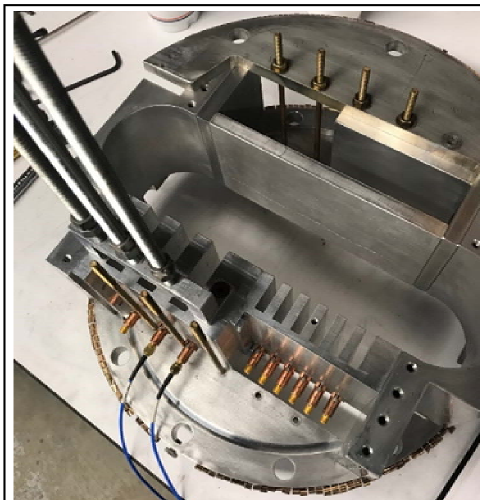

Figure 1 - The fabricated HRPM prototype is pictured.

* Supported by the Office of Naval Research under grant numbers N00014-13-1-0566 and N00014-16-1-2353, a DEPS Fellowship to DP, AFRL for ICEPIC, and L-3T EDD.

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Nanodiamond to Nanographite Conversion During Field Emission

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Vacuum arcs (breakdowns) can form in ultrahigh vacuum when a solid surface is exposed to a high electric field. Breakdowns are one of the main performance limitations for high power microwave devices including accelerator facilities. Electrical breakdowns, despite occurring at microscale, arrest the operation of multi-kilometer accelerators. Therefore, breakdowns are being intensively studied until this very day as underlying physical mechanisms involved are still poorly understood. Indeed, fundamental questions on whether arcs are caused by a heating mechanism (such as resistive heating induced by field emission) or cold mechanism (electro-migration), and whether they are produced due to anodic or cathodic activity are still open.

Since high power devices including accelerators are enclosed RF systems operated with short pulses in GHz frequencies, breakdowns are extremely short-lived and their real time diagnostics is extremely challenging. In recent years though, the DC vacuum diode was used on many occasions as a model system to study plasma discharge and breakdown formation in high and ultrahigh vacuum that are longer lived and therefore easier to detect and analyze.

In the present study, we use a vacuum diode that makes use of ultrananocrystalline diamond (UNCD) cathode to test the hypothesis of the hot cathodic breakdown. Convenience of using UNCD stems from that it has large emission area that is easy to detect and characterize by simple means [1], and because diamond is a temperature sensitive material that has a diamond to graphite transition at about 2,000K.

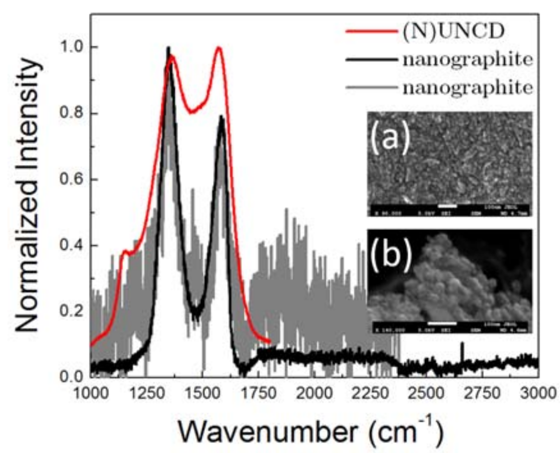

Figure 1 – Raman spectra for graphitic and UNCD sites on the damaged cathode due to electron field emission. Inset (a) Pristine (N)UNCD; (b) Nano-graphite.

Figure 1 shows Raman spectra (532 nm laser probe) and scanning electron microscopy (SEM) images for one of our consumed samples. Undamaged surface areas retained the original UNCD characteristics (red solid line Raman spectrum and SEM image (a)) while at the breakdown locations UNCD was found to convert into nanographite according to Raman and SEM at those locations [2]. Such post-mortem analysis suggests that the formation of nanographite from nanodiamond could only be caused by extremely high temperature inflated by localized field emission current. Our finding supports thermally driven cathodic mechanism of the vacuum breakdown/arc. Our results are also consistent with most recent results from KEK, Japan, where hot emission spots inside an accelerating structure were observed in-situ in real time and were found to be precursors for breakdowns [3].

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Laser Gate Experiment for Reducing Energy Coupling Losses in Magnetized Liner Inertial Fusion (MagLIF)*

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In Magnetized Liner Inertial Fusion (MagLIF), a laser pulse preheats pressurized fuel contained inside of a cylindrical metal tube (or "liner"). This preheating laser pulse must ablate a thin laser entrance window (LEW) to deposit energy into the fuel. Energy losses are thought to occur at the LEW from laser plasma interactions (LPI). To reduce potential energy losses, the LEW could be removed, early in time, before the laser pulse reaches the LEW. This removal concept is referred to as "Laser Gate."[1] One proposed implementation of Laser Gate, is to weaken and then break the LEW by driving an electrical current through a thin wire wrapped around the perimeter of the LEW.[1] The current heats the resistive wire and the LEW perimeter melts. As the LEW breaks, the fuel pressure pushes the LEW away from the contained fuel and out of the laser path. This should reduce fuel-window mixing and LPI in MagLIF. For our initial experiments, we imaged the LEW opening up and away from the laser path. We will report on LEW opening times and our experimental tests of Laser Gate.

* Work supported by DOE NNSA-LRGF (DE-NA0003864), DOE NNSA-SSAP (DE-NA0003764), NNSA-DS / SC-OFES HEDLP (DE-NA0002956), and Sandia National Labs (DE-NA0003525).

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Spectroscopic Investigation of Excited Nitrogen Produced in a Pulsed, Packed Bed Dielectric Barrier Discharge Reactor

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Packed bed reactors (PBRs), utilized as dielectric barrier discharges, have attained interest for their non-thermal and chemically selective properties. PBRs have been implemented in plasma-aided combustion, ozone generation, agriculture, and plasma catalysis. Previous work has shown that the plasma formation and propagation in these systems has occurs as filamentary micro-discharges, surface ionization waves, and restrikes.

In order to understanding the reaction kinetics of micro-discharge formation, a 2-dimensional PBR was designed. The 2D design allows for optical access and diagnostics with iCCD camera imaging and optical emission spectroscopy. For this setup, plasma is generated using a DC, nano-pulsed power supply with zirconia acting as a dielectric aggregate. Measurements will be presented for spatial and time resolved imaging of optical emission and near UV spectra from neutral and ionized states of N_2. Combining this data with results from modeling of the PBR produced by a plasma-hydrodynamic simulation, scaling laws will be discussed to develop methods for optimizing PBRs for chemical selectivity.

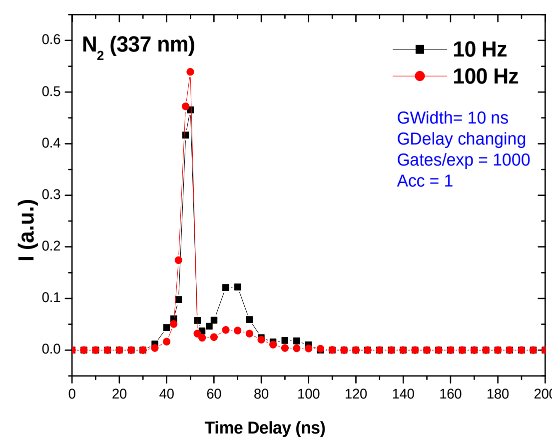

Figure 1 – N_2 emission intensity as a function of time delay from the start of plasma formation. Intensity as a function of discharge frequency is also shown.

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Modeling Atmospheric Pressure Plasma Multi-jet Dynamics*

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Atmospheric pressure plasmas are of interest for medical applications such as wound healing and cancer treatment, and industrial applications such as the functionalization of polymers. Atmospheric pressure plasma jets, which use a rare gas flow into ambient air, are a popular low temperature plasma source, but can treat only a small area at a time. One potential solution to treating larger areas is a multi-jet which branches from a single ionization wave. This device was recently developed by Robert et al.[1] In this paper, results from a modeling study of a pulsed-DC version of this device, and its sensitivity to different geometrical and operational parameters are discussed.

The device consists of a glass tube with a series of 800 μm holes (Fig. 1a). The plasma is driven by a high voltage pulse, initializing a primary ionization (PIW) propagating horizontally inside the tube, and a secondary ionization wave (SIW) propagating out each hole (Fig. 1b). The SIW behavior depends on the hole diameter, voltage polarity, helium flow rate, and distance to the grounded surface below. If the gap between the holes is not sufficient, electrostatic interactions between the SIWs can prevent some from propagating. The mole fraction of helium in the gas plumes must also be sufficiently high, and therefore the SIWs are less consistent at low flow rates.

* Work supported by the Department of Energy Office of Fusion Energy Science (DE-SC000319, DE-SC0014132), the National Science Foundation (PHY-1519117) and the NSF Graduate Research Fellowship Program.

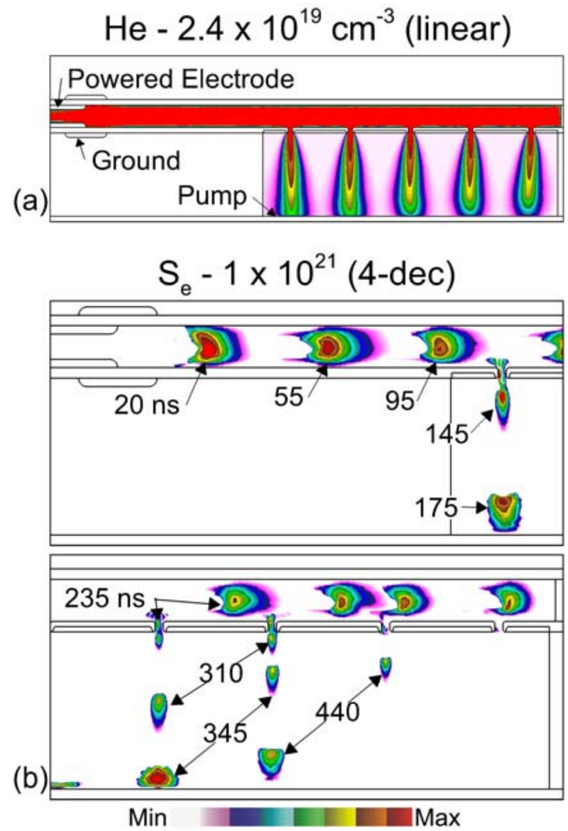

Figure 1 – An atmospheric pressure plasma multi-jet. (a) The device and helium density profile. (b) The electron impact ionization source term. Several different times, indicated in ns, are overlaid to illustrate the ionization wave propagation.

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Low Frequency Instability Detection in a Magnetic Nozzle*

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Magnetic nozzles consist of a diverging magnetic field used to accelerate a plasma via diamagnetic electron drifts to generate thrust. A fundamental gap in our understanding of how these devices work lies in determining when and how electrons ultimately detach from field lines. While multiple theories have been developed to describe this process, the role of instabilities and turbulence has not yet been thoroughly described. This work represents the first spatial map of dispersion plots (Figure 1) and anomalous collisionality estimates on a magnetic nozzle.

At the magnetic field strengths applicable for our magnetic nozzle, ions are largely unaffected by the magnetic field. As such, as pressure and electric field gradients form in the plume, electrons will orbit azimuthally. As they do, they will lose energy to a set of drift-driven instabilities that act as an effective drag on the electrons. The resistive force, which can be modelled by an anomalous collision frequency, contributes to cross field transport and can detach them from magnetic field lines.

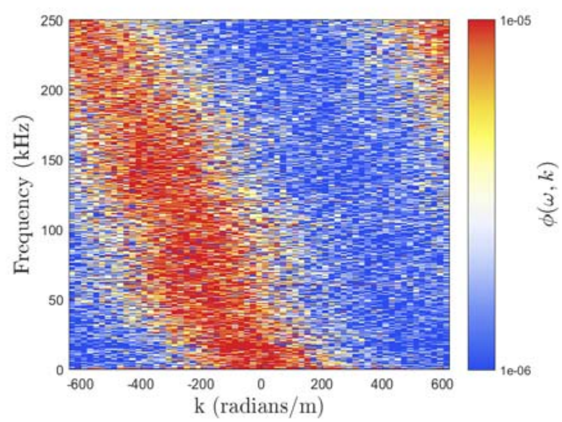

Figure 1 – An example Beall Plot taken in the thruster plume. Drawing a line through the high-intensity region gives the phase velocity under the acoustic wave assumption.

We move a pair of electrostatic probes throughout the plume to measure number density oscillations as a function of frequency and wavenumber. Doing so allows us to generate a Beall Plot (Figure 1), which records potential fluctuations as a function of frequency and wavenumber [1]. Observing the high-intensity trend allows us to estimate a dispersion relation.

In our results, we note that we observe a linear dispersion propagating perpendicular to the magnetic field. We relate these results to those described theoretically as an electron cyclotron drift instability, a wave previously observed in Hall thrusters and understood to contribute to cross-field transport. As per the results of Cavalier et al. [2], in the presence of a finite wavenumber parallel to the magnetic field, this instability reduces to the case of an ion acoustic instability propagating perpendicular to the magnetic field. This limit implies that the phase velocity should be the same as the ion sound speed. We find that the phase velocity indeed takes this value in multiple areas. Finally, under the assumption that these waves are described as the acoustic limit of the electron cyclotron drift instability, we can relate the wave amplitude to an anomalous collision frequency and compare it to classical values to determine if the anomalous collisions are significant relative to classical collisions in detaching electrons.

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Investigation into the Coupling Between Plasma-induced Capillary Oscillations and Streamer Self-organization in Bubbles in Water*

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Discharges in bubbles are of interest in plasma-based liquid activation applications such as water purification. Optimization of production and transport of plasma-derived reactive species rely on understanding of streamer propagation in bubbles in water. Pulsed discharges have been observed to induce capillary oscillations on the bubble interface, which can also lead to sympathetic oscillations in nearby bubbles. [1] Capillary oscillations can alter the geometry of the bubble and affect subsequent streamer propagation, possibly leading to self-organization of streamers inside bubbles. In this study, a 2-D plasma-in-liquid Hele-Shaw-like cell is used to study the plasma-liquid interface region and streamer propagation in air bubbles. [2] Various capillary wave modes are excited on bubble boundary by altering parameters such as excitation frequency and water conductivity. Discharges inside bubbles are imaged using a high-speed camera to assess coupling between capillary oscillations and self-organization of streamers. Additionally, streamer hopping and capillary oscillations coupling between bubbles attached to excited electrode and bubbles in bulk liquid are investigated. This work gives insight into the influence of plasma driven mechanical effects that otherwise lead to the modification of plasma production and propagation modes, ultimately influencing reactive oxygen and nitrogen species' spatial and temporal transport into the bulk liquid. This basic insight may yield understanding on how to improve the efficiency of plasma water purification systems.

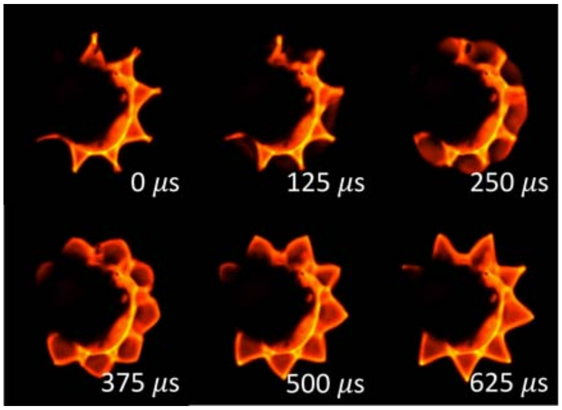

Figure 1 – Spatiotemporal evolution of bubble cavity distortions due to streamer discharge in bubble in water.

* Work supported by DOE DE-SC0001939 and NSF CBET 1336375.

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A Re-examination of Backward Wave Theory for Oscillations on a Helix Traveling-Wave Tube*

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The exact small-signal hot-tube dispersion relation for a thin tape helix traveling-wave tube (TWT) was recently derived [1]. When applied to the forward wave, it gives an exact determination of Pierce's "AC space charge" parameter Q, a quantity which has never been properly evaluated in the literature for a realistic TWT. In addition, this new theory predicts a significant detune of the circuit phase velocity by as much as 2% through a new parameter q. Here, we examine the effect of this new parameter q on the starting current and oscillation frequency according to the classical Johnson's theory for the threshold of backward wave oscillation in a TWT. [2] We found that the threshold current was not appreciably affected by q. The oscillation frequency was shifted, however. An interpretation will be provided. The evaluation of the other parameter Q for the backward wave mode is being examined.

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