Michigan Institute for Plasma Science and Engineering (MIPSE)

University of Michigan & Michigan State University

6th ANNUAL
GRADUATE STUDENT SYMPOSIUM

October 7, 2015

2:15 – 7:05 pm

1005 EECS

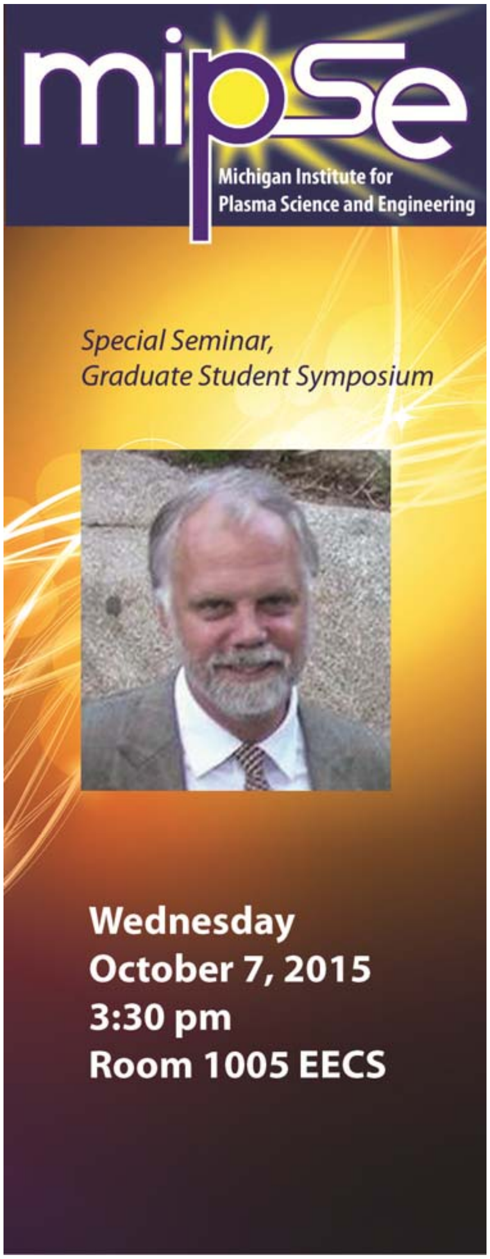
North Campus, University of Michigan

1301 Beal Avenue

Ann Arbor, MI 48109-2122

Schedule

2:15 – 3:00	**Registration, poster set-up**	EECS atrium
3:00 – 3:20	**Refreshments** (box lunch + coffee, tea)	1005 EECS
3:20 – 3:25	**Prof. Mark J. Kushner**, **Director of MIPSE** **Opening remarks**	1005 EECS
3:25 – 3:30	**IEEE NPSS South-East Michigan Chapter presentation**	1005 EECS
3:30 – 4:30	**Special MIPSE Seminar:** **Dr. Edmund Synakowski, U.S. Department of Energy** ***Transformative Passages in the Fusion and Plasma Sciences***	1005 EECS
4:30 – 5:15	**Poster session I**	EECS atrium
5:15 – 6:00	**Poster session II**	EECS atrium
6:00 – 6:45	**Poster session III**	EECS atrium
6:45 – 7:00	**Light refreshments**	EECS atrium
7:00 – 7:05	***Best Presentation Award*** **ceremony**	EECS atrium



Dr. Edmund J. Synakowski

U.S. Department of Energy

Leading Challenges and the Role of Transformation in the Fusion and Plasma Sciences

The fusion energy and plasma sciences have undergone remarkable transformational events in its history. Many of these events have shaped and reshaped our understanding of what the field's standards for excellence and progress ought to be. Indeed, many scientific developments have enlarged the consciousness of the field regarding what is even possible. Examples in magnetic fusion go all the way back to declassification, when there emerged a common understanding on both sides of the Cold War of the nature of the science of plasmas that emboldened scientists globally to reach for theoretical frameworks that spanned specific experimental configurations. While much of scientific progress is incremental, this talk takes a walk through the history of fusion and plasma science that is decidedly selective, with the choice made to focus on transformational developments that have led to rapid expansions in thinking of what it means to conduct this research. It is with this as backdrop that we can draw inspiration as we view the tasks in hand of establishing the scientific bases for fusion and the plasma sciences, and for mastering control of both the burning plasma and low temperature plasma regimes.

About the Speaker: Dr. Synakowski is the Assoc. Director of Science for Fusion Energy Sciences (FES) at the US Department of Energy. With an annual budget of >$400M, FES includes research at national labs, universities and industry. Prior to joining FES in 2009, Dr. Synakowski was the Fusion Energy Program Leader and Deputy Division Leader At-Large of the Physics Division at Lawrence Livermore National Lab. He has served on the Council of the US Burning Plasma Org., the Exec. Comm. of the APS Division of Plasma Physics, and Chair of the US Transport Task Force (2000-02). Dr. Synakowski was at Princeton Plasma Physics Laboratory from 1988 - 2005 where he was Head of Research and Deputy Program Director of the National Spherical Torus Experiment. His research and leadership on the Tokamak Fusion Test Reactor in the 1990's was in cross-magnetic-field transport, where he led detailed comparisons between measurements and turbulent transport theory, and made the only measurements to date of creation and transport of helium ash in a lab fusion plasma. He shared the APS Award for Excellence in Plasma Physics in 2001 and the Princeton U. Kaul Foundation Prize for Excellence in Plasma Physics Research & Technology Development in 2000. A Fellow of the APS and Institute of Physics, he has authored over 160 refereed publications. He received his Ph.D. at the Univ. Texas at Austin in 1988, performing research on the Texas Experimental Tokamak, and his BA from the Johns Hopkins Univ., where he was awarded the Kerr Memorial Medal for Excellence in Physics.

Poster Session I

1-01 **Xiao Feng,** Michigan State University
A Positivity-Preserving Single-Stage Single-Step High-Order Constrained Transport Method for Magnetohydrodynamic Equations

1-02 **Lois Smith,** University of Michigan
Wave Activity Connected to Plasmaspheric 1-10 eV Post-Midnight Ion Loss seen by Van Allen Probes

1-03 **Joshua Davis,** University of Michigan
Measurements of Laser Generated Soft X-ray Emission from Irradiated Gold Foils

1-04 **Shuo Huang,** University of Michigan
Dry Etching of Si_3N_4 Using Remote Plasma Sources Sustained in NF_3 Mixtures

1-05 **Jinpu Lin,** University of Michigan
Field Distribution in a Vacuum-nano Diode

1-06 **Greg Meece,** Michigan State University
Self Regulating AGN Feedback in Cool-Core Galaxy Clusters

1-07 **Neil Arthur,** University of Michigan
Increasing Extracted Beam Current Density in Ion Thrusters through Plasma Potential Modification

1-08 **Patrick Tracy,** University of Michigan
Relative Heating of Heavy Ions Observed at 1 AU with ACE/SWICS

1-09 **Alexander Rasmus,** University of Michigan
Interaction of a Plasma Jet with a Magnetized Planar Obstacle

1-10 **Janis Lai,** University of Michigan
Active Interrogation of Plasma-liquid Boundary Using 2D Plasma-in-liquid Apparatus

1-11 **Scott Rice,** Michigan State University
Simulation of Multipactor Initiation in FRIB Halfwave Cavities

1-12 **Frans Ebersohn,** University of Michigan
Simulation of Magnetic Nozzle Thruster Plasma Expansion

1-13 **Willow Wan,** University of Michigan
Observations of Vortex Merger and Growth Reduction in a Dual-mode, Supersonic Kelvin-Helmholtz Instability Experiment

1-14 **Peng Tian and Chenhui Qu,** University of Michigan
Properties of Bipolar and Unipolar DC-Pulsed Microplasma Arrays at Intermediate Pressures

1-15 **Rachel Young,** University of Michigan
Using the OMEGA Laser to Study Accretion Shocks on Forming Stars

Poster Session II

2-01 **Wei Guo,** Michigan State University
Asymptotic Preserving Maxwell Solver Resulting in the Darwin Limit of Electrodynamics

2-02 **Gang Kai Poh,** University of Michigan
MESSENGER Observation on Reconnection and Structure of Mercury's Magnetotail Lobes and Plasma Sheet

2-03 **Keegan Behm,** University of Michigan
Measurements of the Betatron Spectrum Around the K-edge of Thin Foils

2-04 **Chad Huard,** University of Michigan
Stochastic Defect Detection for Monte-Carlo Feature Profile Model

2-05 **C. F. Dong,** University of Michigan
Harmonic Generation in the Beam Current in a Traveling Wave Tube

2-06 **Derek Neben,** Michigan State University
Bremsstrahlung Measurement on the Superconducting Source for Ions (SuSI)

2-07 **Timothy Collard,** University of Michigan
Ion Energetics of the Modes of the CubeSat Ambipolar Thruster

2-08 **Jeffrey Fein,** University of Michigan
Experiments on the Scaling of Growth and Saturation of Multi-beam Two-plasmon Decay with Plasma Conditions

2-09 **Amanda Lietz,** University of Michigan
DBD on Liquid Covered Tissue: Modeling Long-Timescale Chemistry

2-10 **Adrian Lopez,** University of Michigan
Effects of Secondary Electron Emissions from a Plasma Immersed Graphite Substrate

2-11 **Stephen Zajac,** Michigan State University
Microwave Plasma Assisted Chemical Vapor Deposition of Boron Doped Diamond for Vertical Schottky Barrier Diode Fabrication

2-12 **Horatiu Dragnea,** University of Michigan
Development of a 2D Axial-radial Fluid Electron Model

2-13 **Adam Steiner,** University of Michigan
Characterization of a MA-Class Linear Transformer Driver for Foil Ablation and Z-Pinch Experiments

2-14 **Thomas Batson and Anthony Raymond,** University of Michigan
High Energy Electron Acceleration from Underdense Plasmas with the OMEGA EP Laser

2-15 **Patrick Wong,** University of Michigan
Spatial Amplification in a Disk-on-Rod Traveling-Wave Amplifier

Poster Session III

3-01 **Rajib Mandal,** Michigan State University
Wrinkling Pattern Formation in Stretchable Luminescent Films of Silicon Nano-crystals

3-02 **Manan Kocher,** University of Michigan
Anomalous Behavior of Carbon, Oxygen Charge States in a Population of Interplanetary Coronal Mass Ejections

3-03 **Yao Kovach,** University of Michigan
The Effect of Anode Material and Secondary Gas Injection on Self-organized Patterns in Atmospheric Pressure Glows

3-04 **Steven Exelby,** University of Michigan
Harmonic Generation on the Multifrequency Recirculating Planar Magnetron Experiment

3-05 **Ayan Bhattacharya,** Michigan State University
Charge Transport Properties of Plasma Assisted CVD Grown Single Crystal Diamond Irradiated with Swift-Heavy Ion Beam

3-06 **Scott Hall,** University of Michigan
30-kW, Constant-Current-Density Performance of a 100-kW-class Nested Hall Thruster

3-07 **Patrick Belancourt,** University of Michigan
Equation-of-State Measurements of Resorcinol Formaldehyde Foam Using Imaging X-Ray Thomson Spectrometer

3-08 **Selman Mujovic,** University of Michigan
The Time Evolution of Streamer Discharges in Single and Multiple Bubbles in Water

3-09 **Guy Parsey,** Michigan State University
Laser/Plasma-Pumped Rare Gas Laser: Global Model Study

3-10 **Archis Joglekar,** University of Michigan
Nernst Effect in Magnetized Hohlraums

3-11 **Omar Leon and Grant Miars,** University of Michigan
Model Validation for Plasma Contactor Mediation of Electron Beam Charged Spacecraft

3-12 **Robert VanDervort,** University of Michigan
A Diffusive Code, xRage, Is Compared to Experimental Data from Omega

3-13 **David Simon,** University of Michigan
Negative Mass Effects in Conventional, Planar, and Inverted Magnetrons

3-14 **David Yager-Elorriaga,** University of Michigan
Ultrathin Liner-Plasma Implosion Experiments on a sub-MA Current Generator

3-15 **Jungmoo Hah,** University of Michigan
A High Repetition Rate Laser-heavy Water Based Neutron Source

Abstracts
Poster Session I

A Positivity-Preserving Single-Stage Single-Step High-Order Constrained Transport Method for Magnetohydrodynamic Equations*

Xiao Feng [a], Andrew Christlieb [a], David Seal [b], and Qi Tang [c]

(a) Michigan State University (fengxia2@msu.edu, christlieb@math.msu.edu)
(b) United States Naval Academy (seal@usna.edu)
(c) Rensselaer Polytechnic Institute (tangq3@rpi.edu)

In this work we develop a high-order numerical scheme for magnetohydrodynamic equations that is single-stage, single-step, and therefore amenable to Adaptive-Mesh-Refinement (AMR). Our scheme is an extension of Picard-Integral-Formulation WENO (PIF-WENO) methods [1]. Here, we use a Taylor discretization of the time-averaged flux, and leverage the Cauchy-Kovaleskaya procedure to convert temporal derivatives into spatial derivatives. A further challenge particular to magnetohydrodynamic equations is the necessity to maintain divergence-free magnetic fields, where failure to do so has been shown to cause numerical instabilities [2-3]. To overcome this difficulty, we use an unstaggered constrained transport method, where we introduce a magnetic potential, evolve it in time, and correct the magnetic field from the curl of this potential [4-5]. We use tools from Hamilton-Jacobi solvers to evolve the magnetic potential in order to obtain non-oscillatory magnetic fields [5-6]. Finally, we include a flux limiter that produces positive density and pressure [7]. Our one, two and three dimensional numerical experiments verify that our scheme is third order in time and fourth order in space, and is able to resolve complex features of several classical test problems including shock-tube Riemann problems, Orzsag-Tang vortex formulations, and cloud shock interactions.

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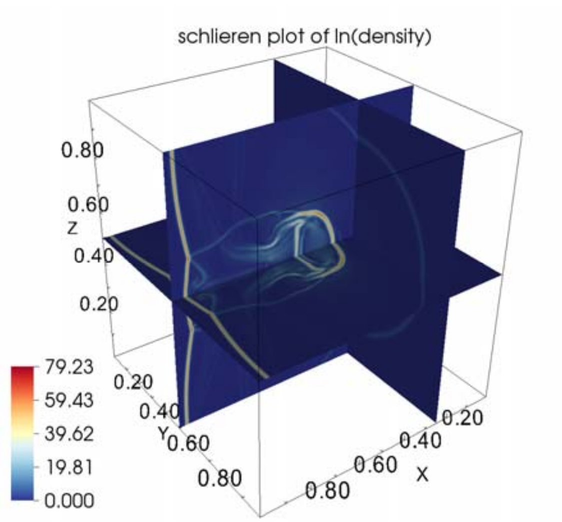


Figure 1 - 3D cloud-shock interaction problem

Wave Activity Connected to Plasmaspheric 1-10 eV Post-Midnight Ion Loss seen by Van Allen Probes

Lois K. Sarno-Smith [a] , Michael W. Liemohn [a] , Ruth Skoug [b] , Aaron Breneman [c], Steven Morley [b], Brian A. Larsen [b], Geoff Reeves [b], John R. Wygant [c], Craig Kletzing [d], Mark B. Moldwin [a], Roxanne M. Katus [d], Shasha Zou [a]

(a) University of Michigan (loisks@umich.edu, liemohn@umich.edu)
(b) Los Alamos National Laboratory (rskoug@lanl.gov)
(c) University of Minnesota
(d) University of Iowa

After the discovery of the plasmaspheric post-midnight 1-10 eV ion loss between L = 2 and L =3, we have expanded upon these results and connected the observed ion loss with changes in wave activity. Using the Van Allen Probes Helium, Oxygen, Proton, and Electron (HOPE) and the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instruments, we observed that changes in different frequency bands measured by EMFISIS are linked with changes in HOPE H^+ thermal ion measurements. In particular, we examined changes in cyclotron heating and changes in Whistler wave activity at different MLTs, and we will present the results of this study.

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

J. S. Davis, P. A. Keiter, R. P. Drake, S. R. Klein

University of Michigan (davisjs@umich.edu)

Soft x-ray sources may provide a means of driving photoionization fronts in materials with a Z >2. To generate these soft x-rays at a traditional UV laser facility, a gold converter foil can be implemented that absorbs the UV photons and heats up to act as a quasi-continuum blackbody emitter with a characteristic temperature of ~100eV. However, it takes time for the heating wave to propagate through the foil, with thicker foils having a longer delay before measureable emission is produced. Prior work has studied the emission characteristics of foil x-ray sources but was limited to laser pulses of 1ns or less. Our interest is in long duration sources (>1ns) which requires the use of thicker Au foils. To better understand how the increased foil thickness affects emission, we have performed experiments at the Omega-60 laser facility studying the x-ray intensity and total emission time of 0.5, 1.0, and 2.0um thick gold foils driven by a 2kJ, 6ns laser pulse. This poster will discuss the results of these experiments and will include a discussion of how these results compare with theoretical predictions.

*Work funded by the U.S. DOE, through the NNSA-DS and SC-OFES Joint Program in HEDPLP, grant No. DE-NA0001840, and the NLUF Program, grant No. DE-NA0000850, and through LLE, University of Rochester by the NNSA/OICF under Agreement No. DE-FC52-08NA28302

Dry Etching of Si_3N_4 Using Remote Plasma Sources Sustained in NF_3 Mixtures*

Shuo Huang and Mark J. Kushner

Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48109 USA
(shuoh@umich.edu, mjkush@umich.edu)

Remote plasma sources (RPS) are used in microelectronics fabrication to produce fluxes of radicals for etching and passivation in the absence of damage by charging and energetic ions. RPS reactors use distance, grids or other discriminating barriers to reduce or eliminate charged particle fluxes from reaching the surface of the material being treated. Nitrogen trifluoride (NF_3) is often used in RPS due to the efficiency of producing F atoms by dissociative attachment. RPS sustained in NF_3 gas mixtures, such as $Ar/NF_3/O_2$, increases the variety of reactive species, for example, N_xO_y and FO. For certain applications it may be desirable to separately optimize, for example, F atom fluxes; and O atoms, or N_xO_y so as to optimize the etch rates of Si_3N_4 and other materials. This separate optimization could, in principle, be performed using pulsed power or pulsed gas sources.

In this paper, we report on a computational investigation of RPS sustained in different NF_3 containing gas mixtures at pressures of less than a few Torr using continuous and pulsed power for low-damage plasma etching applications. Global and 2-dimensional reactor scale models have been used. The electron impact cross sections for NF_3, NF_2 and NF were produced using ab initio computational techniques based on the molecular R-matrix method. A reaction mechanism was developed for plasmas sustained in $Ar/NF_3/O_2$ mixtures and a surface reaction mechanism was developed for the etching of Si_3N_4. The surface kinetics resulting in etching were investigated using a surface site balance model embedded in the reactor scale models..

The fluxes of F atoms and NO molecules to the wafer and the etch rate of the Si_3N_4 wafer are shown in Fig. 1. The wafer is 15 cm downstream from the RPS, with grids placed in between them. The non-uniform etch rate is mainly due to the non-uniform flux of NO to the surface. The Si surface sites were etched by F atoms through the formation of SiF_4 and thus the N surface sites were exposed. Afterwards, the N surface sites were etched by NO through two channels: (1) N(surface) + NO $\rightarrow$ N_2 + O(surface), O(surface) + NO $\rightarrow$ NO_2; (2) N(surface) + NO $\rightarrow$ N_2O. Therefore, the limiting factor for the etch rate is NO flux to the wafer as shown in Fig. 1. Dependence of plasma properties and uniformity for the etch rate on different power scenarios and gas mixtures will be discussed.

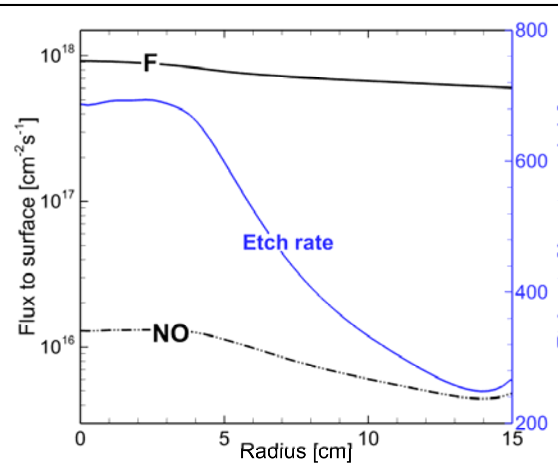


Figure 1 - Fluxes of F atoms and NO molecules to the surface of the Si_3N_4 wafer (left scale) and the etch rate of the wafer (right scale) by mixture of $Ar/NF_3/O_2$=90/5/5 sustained in an inductively coupled remote plasma source with input power of 300 W at 50 mTorr.

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

Field Distribution in a Vacuum-nano Diode*

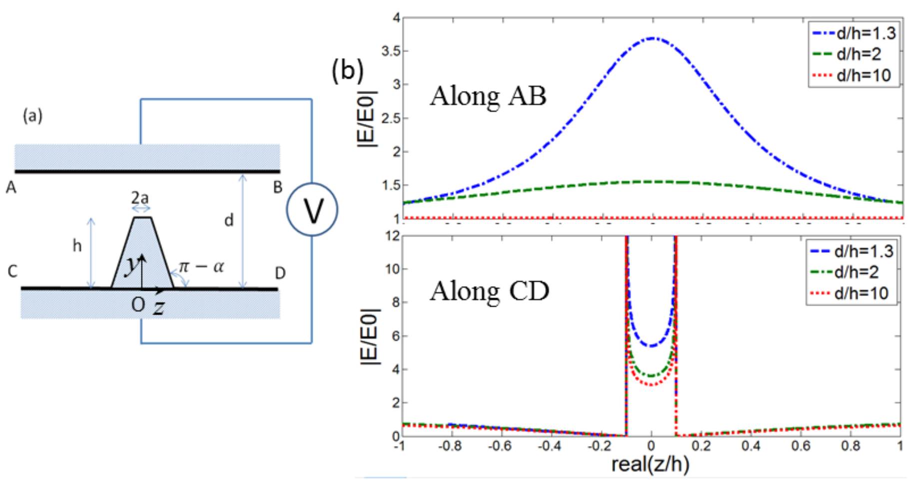
Jinpu Lin, and Peng Zhang

Department of Nuclear Engineering and Radiological Sciences
University of Michigan, Ann Arbor, MI 48109-2104 (umpeng@umich.edu)

There is growing interest in miniaturization of anode-cathode (AK) gap by using fine emission tips to realize a vacuum nano-diode [1,2]. The geometrically asymmetric vacuum nanodiode shows great potential for applications in energy harvesting and conversion in solar cells. Electron emission from flat graphene surface is also demonstrated by bringing a sharp anode tip sufficiently close to the graphene surface [3]. However, existing models on field emitters usually assume that the emission tip is far away from the anode, whose effect on tip field enhancement is thus ignored [4]. Here, we study the effects of *finite* AK gap on the electric field distribution on and around an emission tip.

Using Schwarz-Christoffel transformation, we calculated the local electric field inside the gap with a single trapezoid tip, shown in Fig. 1a. Examples of electric field profile along the two surfaces (AB and CD) are given in Fig. 1b, showing strong increase of field enhancements on both electrodes near the protrusion as the normalized AK gap (d/h) decreases. From these exact electric field profiles, we calculate the effective field enhancement factor for field emission by integrating the local current density along the electrode surfaces, where the flat electrode or the electrode with a protrusion can either be the cathode or anode, depending on the sign of bias. Scalings of the fields and current are studied as a function of geometric dimensions.

Figure 1 - (a) Cathode-anode gap with a trapezoide tip, (b) Normalized electric field profiles along the two surfaces AB and CD, with $\alpha = \pi/2$ and $a/h = 0.1$, for for various d/h = 1.3, 2, and 10. E_0 is the uniform electric field far away from the protrution, $|z/h| >> 0$.



*Work supported by Air Force Office of Scientific Research Grant No. FA9550-14-1-0309

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Self Regulating AGN Feedback in Cool-Core Galaxy Clusters

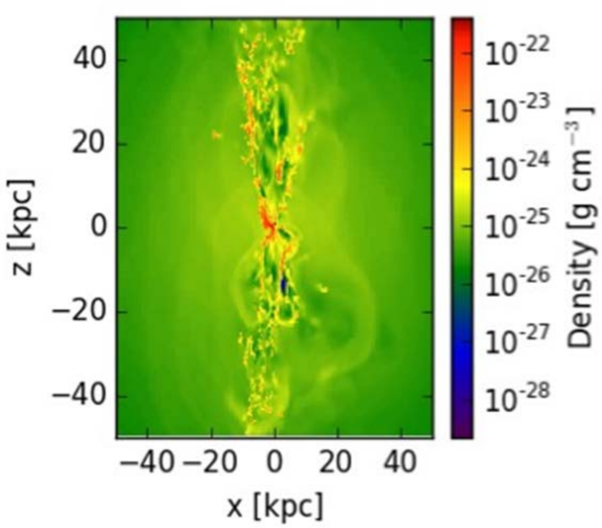
Gregory Meece, G. Mark Voit and Brian O'Shea
Michigan State University (meecegre@msu.edu, voit@pa.msu.edu, oshea@msu.edu)

Galaxy clusters are filled with hot plasma (the intra-cluster medium, or ICM) that emits X- rays via thermal Bremsstrahlung. In many clusters, the cooling time of the ICM near the cluster core is much shorter than the age of the cluster or any other relevant physical timescales. If the plasma were indeed cooling, the clusters would be expected to have high star formation rates and a constant flow of cooling gas towards the cluster core. Instead, real clusters show low rates of star formation and little cold gas accumulation. In recent years, cooling triggered feedback from active galactic nuclei (AGN) has been proposed as a self-regulating method for reheating the ICM and maintaining a rough thermal equilibrium in the cluster core.

In this work, we simulate feedback from AGN in idealized cool-core galaxy clusters. The cooling ICM plasma is thought to be thermally unstable, resulting in the condensation of cold gas out of the ICM whenever the ratio of cooling time to freefall time drops below ~10. Accretion of the precipitation by a super-massive black hole triggers AGN feedback that reheats the cluster, preventing further condensation. Thus, the interplay of cooling, precipitation, and AGN heating maintains the thermal state of the ICM.

By abstracting the details of accretion and jet production on scales below 100 pc, we are able to efficiently explore the link between AGN triggering and the thermal state of the ICM. We implement precipitation triggered AGN feedback where thermally unstable gas triggers AGN heating. This triggering mechanism is compared to other proposed triggers, including cold gas accretion, Bondi-Hoyle accretion, and fixed power jets. Additionally, we investigate the dependence on the feedback implementation. It is known that the ICM plasma is threaded with tangled magnetic fields. AGN have been suggested as a possible production mechanism for these fields, and we use our simulations to test our hypothesis. Finally, we investigate whether precipitation triggered AGN feedback can effectively balance cooling in the ICM and produce clusters with temperature, entropy, and metallicity profiles that agree with galaxy cluster observations.

Figure 1 - AGN Feedback in a simulated cluster. The jets, oriented along the z-axis, dredge up cold gas which falls back and condenses. Turbulence and shocks heat the surrounding ICM. (Meece 2015, in prep)



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Increasing Extracted Beam Current Density in Ion Thrusters through Plasma Potential Modification

Neil A. Arthur and John E. Foster

Nuclear Engineering, University of Michigan (arthurne@umich.edu, jefoster@umich.edu)

The extractable beam current of gridded ion thrusters is space charge limited according to the Child-Langmiur law. This classic law does not consider the ion injection velocity into the grid sheath. Ion drift velocity can be created by modifying the plasma potential in the thruster. This is accomplished by biasing the individual magnet rings. Experiments on a four ring, magnetic cusp ion thruster have shown that it is possible to modify the plasma potential in the bulk and establish ion drift towards the grid.

The increase in ion velocity and plasma potential have been confirmed using Mach probes. A retarding potential analyzer was used to show that the ion energy distribution function is shifted to higher energies when individual magnet rings are biased. The increased ion current to the grid plane was verified by measuring the current of the collector grid during simulated beam extraction. The next step is to operate with true beam extraction and verify that this method of varying plasma potential does indeed produce increased beam current. The same four ring thruster will be operated with true beam extraction in order to further investigate the preliminary data taken with simulated beam extraction.

Relative Heating of Heavy Ions Observed at 1 AU with ACE/SWICS

Patrick J. Tracy, Thomas H. Zurbuchen, Jim M. Raines, Justin C. Kasper, Paul Shearer, Jason Gilbert

Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan (ptracy@umich.edu)

Heavy ions (Z>4) observed near 1 AU, especially in fast solar wind, tend to have thermal speeds that are approximately equal, indicative of a mass proportional temperature. The fact that these heavy ions have similar thermal speeds implies that they have very different temperatures, and furthermore, that they are far from thermal equilibrium. By comparing the observed heavy ion temperatures amongst species with different mass and charge values we can critically evaluate heating theories for the solar wind.

Utilizing improved data processing techniques, results from the Solar Wind Ion Composition Spectrometer (SWICS) onboard the Advanced Composition Explorer (ACE) are used to analyze the thermal properties of the heavy ion population at 1 AU. We have shown in previous work that Coulomb Collisional relaxation has a significant effect on these heavy ion populations, and now we investigate how Coulomb Collisions effect the observed temperature ratios of different heavy ion species. We observe that the heavy ion to proton temperature ratio scales with the mass and charge values of species analyzed. These dependencies are compared to current heating theories to determine which best explains the observations. The results of this work are valuable for comparison with coronal spectroscopic observations of ion temperatures, existing solar wind observations at different distances from the Sun, and for predictions of the environment to be encountered by Solar Probe and Solar Orbiter.

Interaction of a Plasma Jet with a Magnetized Planar Obstacle

A. M. Rasmus [a], M. J.-E. Manuel [a], C. C. Kuranz [a], S. R. Klein [a], J. S. Davis [a], R. P. Drake [a], D. S. Montgomery [b], S. C. Hsu [b], C. S. Adams [b], and B. B. Pollock [c]

(a) University of Michigan (arasmus@umich.edu)
(b) Los Alamos National Laboratory, Los Alamos, New Mexico, USA
(c) Lawrence Livermore National Laboratory, Livermore, California, USA

The propagation of a high velocity plasma-jet into a transverse magnetic field has applications to pulsed power and fusion, as well as astrophysical processes, e.g. pulsed jets and the interaction of the solar wind with the magnetosphere. Experiments were performed at the Trident Laser Facility at Los Alamos National Laboratory in which an Al foil was irradiated (527nm, I □ 10^{14}W/cm^2), and the non-irradiated side release propagated into a uniform, 4.5T, magnetic field produced by an electromagnet. Targets were used in which the plasma flow collides with a planar obstacle. Interferometry and Faraday rotation were used to measure the path integrated electron density and magnetic field.

*Work funded under the auspices of the U.S. DOE under contract DE-NA0001840

Active Interrogation of Plasma-liquid Boundary Using 2D Plasma-in-liquid Apparatus*

Janis Lai and John E. Foster

University of Michigan (janislai@umich.edu, jefoster@umich.edu)

Plasma medicine and plasma-based water purification technologies rely on production and transport of plasma-derived (direct or indirect) reaction species into the bulk medium. This interaction takes place at the interface between the gas phase plasma and the liquid medium. The nature of radical production and subsequent radical transport from this region or boundary layer is not well-understood due to the difficulty of implementing diagnostics to interrogate this region. We present a 2-D plasma-in-liquid water apparatus that makes the interface region accessible to optical diagnostics. Using colorimetric chemical probes, acidification and oxidation fronts are tracked using high-speed imaging and spectroscopy. Additionally, observed, plasma-induced fluid dynamical effects are also discussed. Forces at the interface can play a key role in the transport of radicals into the bulk solution. Effects on bacterial viability are discussed.

* Work supported by DOE and NSF

Simulation of Multipactor Initiation in FRIB Halfwave Cavities*

Scott A. Rice and John Verboncoeur

Michigan State University (scott.a.rice@gmail.com, johnv@msu.edu)

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

The Facility for Rare Isotope Beams (FRIB) is a particle accelerator that is currently being constructed at Michigan State University. A portion of the beam line will employ coaxial half wave cavities to generate the fields to accelerate the charged beam. One of the cavity design considerations is the susceptibility to multipactor within these accelerating cavities; the presence of multipactor could hinder the cavities from realizing their intended field strength.

This research presents simulated results for multipactor initiation within the FRIB halfwave resonant cavities, for the case of both single- and multi-mode excitation. This work builds upon previous work [1][2] done to assess multipactor initiation in idealized coaxial cavities, but the present simulations use the actual FRIB cavity geometry. Comparisons to preliminary measured FRIB cavity data is also discussed.

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

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Simulation of Magnetic Nozzle Thruster Plasma Expansion*

Frans H. Ebersohn [a], J. P. Sheehan [a], Alec D. Gallimore [a] and John V. Shebalin [b]

(a) Aerospace Engineering, University of Michigan (ebersohn@umich.edu, sheehanj@umich.edu, alec.gallimore@umich.edu)

(b) Exploration Integration and Science Directorate, NASA Johnson Space Center (john.v.shebalin@nasa.gov)

Magnetic nozzles are strong guiding magnetic fields used to accelerate ions in plasma thrusters. A new quasi-one-dimensional (Q1D) particle-in-cell (PIC) method has been developed to study the fundamental physics of magnetic nozzles from a kinetic perspective.[1] This method captures two-dimensional effects by including the effects of the magnetic field forces and the plasma compression and expansion due to the magnetic field.

Simulations of a radio-frequency plasma device with parameters near the operating regime of helicon thrusters were performed.[2,3,4] The two-dimensional effects on the plasma were investigated by including the magnetic field force effects and compression/expansion effects both separately and together. The effect of varying the magnetic field topology was also investigated.

Ion-accelerating potential structures were formed when the effects of the magnetic field forces on the electrons were included. These magnetic field forces push the electrons out of the source region, resulting in the formation of a quasi-neutrality preserving electric field which accelerates the ions out with the electrons. The length of the potential structure was found to be a function of how rapidly the magnetic field diverges, with rapid potential drops seen for sharply diverging magnetic fields.

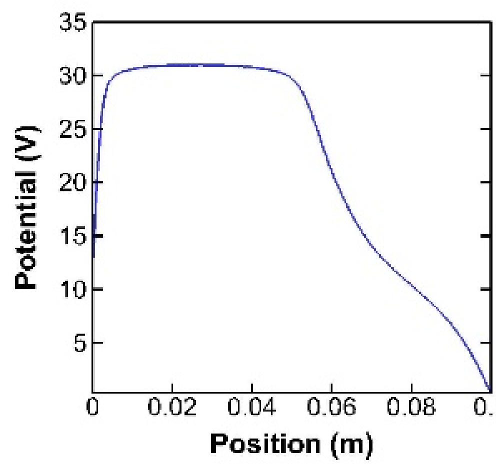

Figure 1 – The ion-accelerating potential structure which forms in a magnetic nozzle due to magnetic field forces on the electrons.

*Work supported by the NASA Space Technology Research Fellowship

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Observations of Vortex Merger and Growth Reduction in a Dual-mode, Supersonic Kelvin-Helmholtz Instability Experiment

W. C. Wan [a], G. Malamud [a, b], A. Shimony [b, c], M. R. Trantham [a], S. R. Klein [a], D. Shvarts [b, c], C.C. Kuranz [a], R. P.Drake [a]

(a) University of Michigan, USA (wwan@umich.edu)
(b) Nuclear Research Center, Israel
(c) Ben Gurion University of the Negev, Israel

The Kelvin-Helmholtz instability (KHI) is a basic hydrodynamic process that generates vortical structures and turbulence at an interface with shear flow. This instability is ubiquitous in natural and engineering systems including protoplanetary disks, stellar environments, and laboratory plasmas. In a supersonic shear flow, compressibility inhibits the linear growth rate of the KHI. Detailed measurements of behavior such as modulation amplitude growth and vortex merger evolving from well-defined initial conditions can validate and benchmark existing theories and hydrodynamic models. This experiment provides the first measurements of the vortex merger rate of well-characterized seed perturbations evolving under the influence of the KHI in a supersonic flow.

These data were obtained by utilizing a sustained laser pulse to drive a steady shockwave into low-density carbon foam, introducing shear along a precision-machined plastic interface. The evolution and merger of the modulations was measured with x-ray radiography and reproduced with 2D hydrodynamic simulations.

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Properties of Bipolar and Unipolar DC-Pulsed Microplasma Arrays at Intermediate Pressures

Peng Tian, Chenhui Qu and Mark J. Kushner

University of Michigan, Dept. Electrical Engr. & Comp. Sci., Ann Arbor, MI 48109-2122 USA
(tianpeng@umich.edu, chenqu@umich.edu, mjkush@umich.edu)

Microplasma arrays are being investigated to manipulate electromagnetic waves.[1] Such applications require control of plasma properties over large dynamic ranges across large areas, resulting in control of their absorptive, dielectric and metamaterial properties. In these applications, plasma often operates at intermediate pressure from tens to 100s of Torr, motivated by the tradeoff between obtaining fast response and large density of plasma, which scale with high pressure; and obtaining non-constrictive plasma, which optimizes at low pressure. Microcavities are then sized to hundreds of microns according to *pd* scaling. The dielectric inner surface of cavities inspires use of some form of bipolar excitation. Controlling cross-talk between microplasma units is also a challenge since normally they are not physically isolated in such applications.

In this project, the behavior of 1-D and 2-D microplasma arrays excited by pulsed dc-bipolar/unipolar waveforms is computationally investigated. Simulation results will be discussed aiming at maximizing the time averaged electron density and dynamic range during pulsing, and controlling cross-talk between microplasmas that are not physically isolated. Small arrays of hundreds of microns (3-6 microplasmas) are excited by short dc-bipolar/unipolar pulses (a few to tens of ns) in various rare gas mixtures at 10s-100s Torr.

The electron density profile for a typical case at the peak of a negative voltage pulse is shwon in Fig. 1. The electron density peaks up to 2×10^{14} cm^{-3} with a cathode fall region forming near the exposed cathode. Beam ionization by secondary electrons is the major source of electrons during both pulse-on and afterglow, while bulk source contributes approximately 30% of the ionization during the pulse. Cross talk between discharges is affected by the electric field, formed due to the fast transport of electrons during pulse-on period.

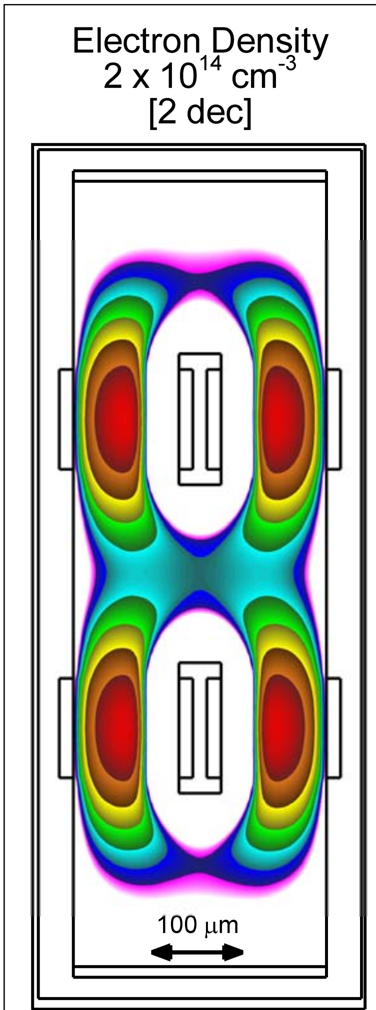

Figure 1 – Electron density profile during dc-negative pulse. (Ar, 60 Torr, 100 ns unipolar pulse, 300 V peak)

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Using the OMEGA Laser to Study Accretion Shocks on Forming Stars

R. P. Young [a], C. C. Kuranz [a], R. P. Drake [a], P. Hartigan [e], D. Froula [b], J. S. Ross [c], C. K. Li [d], G. Fiksel[b], P.-Y. Chang [b], A. Zylstra [d], H. W. Sio [d], and A. Liao [e]

(a) University of Michigan (rachelpierson@gmail.com)
(b) Laboratory for Laser Energetics
(c) Lawrence Livermore National Laboratory
(d) Massachusetts Institute of Technology
(e) Rice University

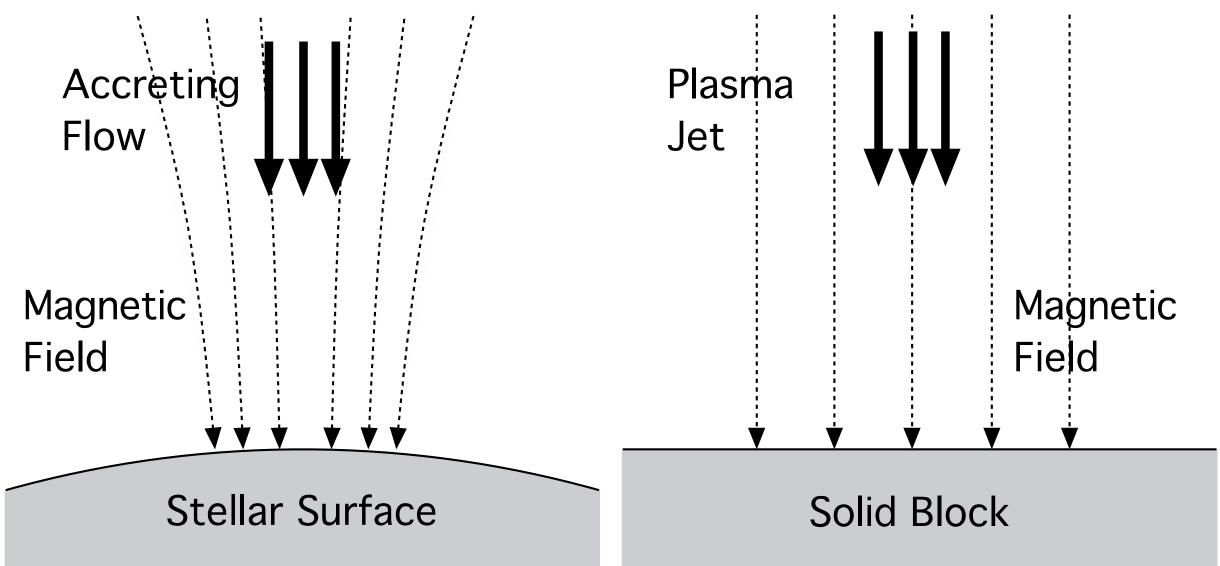
We present an on-going investigation into the "accretion shocks" that form when material from an accretion disk slams into the young, growing star at its center through a series of experiments using the OMEGA laser (Laboratory for Laser Energetics).

During star formation, material is "funneled" from the inner edge of the accretion disk to the star's along magnetic field lines, where it creates accretion shocks (left side of the figure).

There are open questions about the structure and evolution of accretion shocks and, in particular, about the role of the star's magnetic field. 2-D simulations of accretion shocks suggest that as the plasma beta increases, the hot, shocked accreting material "splashes out."

We have created a scaled experimental version (right side of figure). We use rear-irradiation of a thin CH cone to create a plasma jet (the "accreting flow") and drive it into a solid block (the "stellar surface") in the midst of a parallel magnetic field generated by OMEGA's MIFEDS system. Our primary diagnostics are proton radiography and visible light imaging.

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



Poster Session II

Asymptotic Preserving Maxwell Solver Resulting in the Darwin Limit of Electrodynamics

Yingda Cheng [a], Andrew J. Christlieb [a], Wei Guo [a] and Benjamin Ong [b]

(a) Department of Mathematics, Michigan State University (ycheng@math.msu.edu, andrewch@math.msu.edu, wguo@math.msu.edu)
(b) Department of Mathematical Sciences, Michigan Technological University (ongbw@mtu.edu)

In plasma simulations, where the speed of light divided by a characteristic length is at a much higher frequency than other relevant parameters in the underlying system, such as the plasma frequency, implicit methods begin to play an important role in generating efficient solutions in these multi-scale problems. Under conditions of scale separation, one can rescale Maxwell's equations in such a way as to give a magneto static limit known as the Darwin model of electromagnetics. In this work, we present a new approach to solve Maxwell's equations based on a Method of Lines Transpose MOL^T formulation, combined with a fast summation method with computational complexity $O(N \log N)$, where N is the number of grid points (particles). Under appropriate scaling, we show that the proposed schemes result in asymptotic preserving methods that can recover the Darwin limit of electrodynamics.

MESSENGER Observation on Reconnection and Structure of Mercury's Magnetotail Lobes and Plasma Sheet

Gangkai Poh [a], James A. Slavin [a], Xianzhe Jia [a], Jim M. Raines [a], Daniel J. Gershman [a,b], Brian J. Anderson [c]

(a) Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109, USA
(b) Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
(c) The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA

Magnetic reconnection is known to be the most important process for plasma transport and energy conversion in space plasma. MESSENGER observations taken at Mercury have shown that magnetic reconnection is the dominant driver of magnetospheric dynamics and that it is significantly more intense than at Earth. Hence, Mercury provides a perfect natural laboratory to study the structure and reconnection at Mercury's magnetotail as signatures of magnetic reconnections are expected to be more intense and prominent as compared to Earth and the outer planets. Using 4 years of MESSENGER's magnetic field and plasma data, we analyzed 356 plasma sheet crossings. We determined that the B-field magnitude in the magnetotail lobe and plasma sheet follows a power law relation as a function of downstream distance $|X_{MSM}|$. Statistical studies on the direction of B_z in the plasma sheet suggest that reconnection X-lines are most likely to occur at distance $|X_{MSM}| < -2.5R_M$. Using simple pressure balance, we have also estimate the plasma beta β in the plasma sheet as a function of $|X_{MSM}|$. Our results indicate that the beta is higher in the region of higher reconnection rate where X-lines are usually found. Finally, we compared our results at Mercury with previous studies on the terrestrial magnetotail. Our results are consistent with the canonical idea that Mercury's magnetotail is structurally similar to Earth's but with shorter timescale due to more intense reconnection at Mercury.

Measurements of the Betatron Spectrum around the K-edge of Thin Foils

Keegan Behm [a], Tony Zhao [a], Jonathan Wood [b], Jason Cole [b], Anatoly Maksimchuk [a], Victor Yanovsky[a], Stuart Mangles [b], Alexander Thomas [a], Karl Krushelnick [a]

(a) Center for Ultrafast Optical Science, University of Michigan
(b) Imperial College of London, London, UK

Simulations performed by colleagues at the Imperial College of London show temperature dependent absorption of thin metal foils near the K-edge. In order to experimentally measure the absorption of x-rays in these thin foils, it is necessary to have a diagnostic that can spectrally disperse x-rays. In the single photon regime, we have used a CCD camera to characterize the betatron spectrum from a LWFA. The main advantage of the CCD diagnostic is having the ability to measure the betatron spectra on a shot-by-shot basis as opposed to integrating shots. An algorithm to reconstruct the betatron spectra from a CCD image has been created to allow for higher flux shots to pass the single photon criteria. This algorithm has also let us measure various aspects of the spectra such as critical energy and total flux. An example of some single photon spectra calculated from the algorithm can be seein in Figure 1.

The drawback to using a CCD camera to reconstruct the betatron spectrum lies in the resolution of the CCD camera. Due to fairly poor resolution capabilities, the single photon reconstruction may not be sufficient to measure small changes in the K-edge. Therefore, curved Mica and HOPG crystals have been used to measure parts of the betatron spectrum at higher x-ray fluxes around the Kedge of different foils. The ability to measure absorption in the betatron spectrum due to the Kedge of thin foils will allow us to perform time resolved opacity measurements on a pump-probe experimental set up.

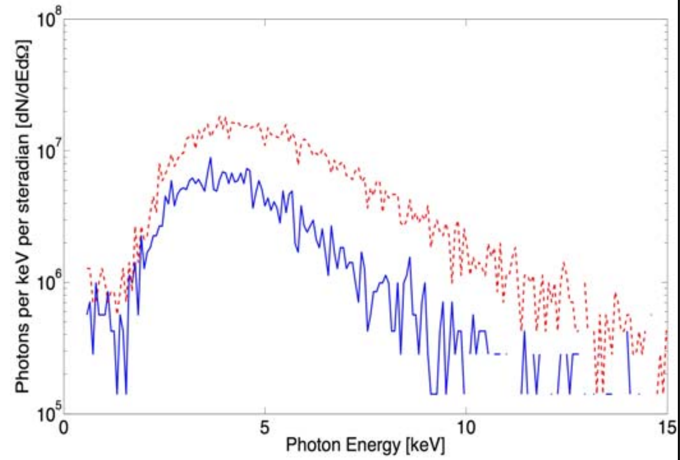


Figure 1 – A set of synchrotron spectra produced by betatron oscillations in a wakefield accelerator. The spectra were calculated by the single photon counting algorithm.

Stochastic Defect Detection for Monte-Carlo Feature Profile Model

Chad Huard and Mark Kushner

University of Michigan, Dept. of Electrical Engineering (chuard@umich.edu)

Reactive ion etching in plasma has become an indispensable tool in the semiconductor industry, and accurate modeling of this process is essential for current and future technology. As the critical dimension of integrated circuits decreases with progressive technology nodes, the tools we use to model semiconductor processing must also adapt to provide fidelity at these new length scales. The Monte-Carlo Feature Profile Model (MCFPM) is one such tool.[1] Designed to simulate the reactive ion etching process, the MCFPM is able to address technologically relevant length scales, but, due to its stochastic nature, it is prone to creating unphysical defects in the etch profile at the smallest resolvable scale. In this work we present an effective and computationally efficient method for detecting and resolving these defects.

The MCFPM works by launching gas phase pseudoparticles at an etch profile (represented by a structured grid), with species flux, energies and angular distributions derived from the Hybrid Plasma Equipment Model (HPEM).[2] These particles are tracked through space until they react with the solid profile, either etching the solid species, depositing on the solid surface or changing the chemical composition of the surface. Due to the stochastic nature of this process, often features can be etched in such a way that individual, or small clusters of, solid cells are left detached from the main profile. Without a separate mechanism to resolve the behavior of these clusters, they will remain hanging in space until they are eventually etched. This scenario, of a small solid cluster orphaned from the main profile, can affect the etch rate and profile in unphysical ways.

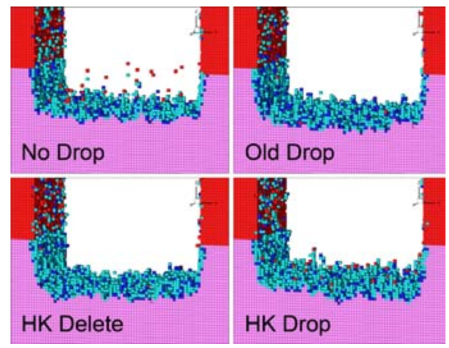


Figure 1 – Results of MCFPM showing etching of Si in Cl_2/Ar plasma using different drop routines investigated in this work

In order to resolve the issue of orphaned clusters of solid material we have implemented a Hoshen-Kopelman (HK) cluster labeling algorithm[3] to find and address each detached cluster. Once orphaned clusters are identified we are able to resolve them by either deleting them from the profile or dropping them vertically, as by gravity, onto the main profile eliminating the isolated cluster. As we can see in Figure 1, many of the orphaned cells are often photoresist. The decision to 'delete' or 'drop' these cells can have significant effect on cell-level detail and etch rate by creating micro-masking at the bottom of the etched feature. This HK technique, while remaining $O(n^3)$, is more computationally efficient and flexible than previous efforts to resolve this issue. Furthermore, the same technique is applicable in two or three dimensions without modification, providing consistency between 2d and 3d simulations of similar features.

*Work supported by LAM Research Corp.

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Harmonic Generation in the Beam Current in a Traveling Wave Tube*

Peng Zhang, C. F. Dong, D. Chernin, Y. Y. Lau, B. Hoff, D. H. Simon, P. Wong, G. Greening, and R. M. Gilgenbach

Department of Nuclear Engineering and Radiological Sciences
University of Michigan, Ann Arbor, MI 48109-2104 (yylau@umich.edu)

In a traveling wave tube (TWT), it is recognized that the linear theory of Pierce provides an adequate description of the electron-circuit interaction over approximately 85 percent of the tube length, even when the TWT is driven to saturation [1]. Because Pierce's theory is in the linear (small signal) regime, we are not aware of any analytic formulation that calculates the harmonic content in the AC current that would buildup over this 85 percent of tube length. This paper provides such a formulation.

We extend the klystron theory [2] of orbital bunching to a TWT. We assume that the electron orbits are governed by Pierce's classical 3-wave, linear theory. The crowding of these linear orbits may lead to charge overtaking and therefore harmonic generation on the beam current, as in a klystron. We analytically calculate the buildup of harmonic content as a function of tube length from the input. Figure 1 compares the analytic results with CHRISTINE code for a C-band TWT operating at $\omega_0 = 2\pi \times 4.5 GHz$, V_b = 2.776 kV, I_b = 0.17 A, and various Pierce parameters C, b, QC, and d. Excellent agreement is found. Also found is the surprisingly high level of harmonic contents in the electron beam current even when the TWT operates in the small signal regime. A dimensionless "bunching parameter" for a TWT, $X = \sqrt{2P_{in}/(P_b C)}$, is identified, which characterizes the harmonic content in the AC beam current, where P_{in} is the input power of the signal, P_b is the DC beam power, and C is Pierce's gain parameter.

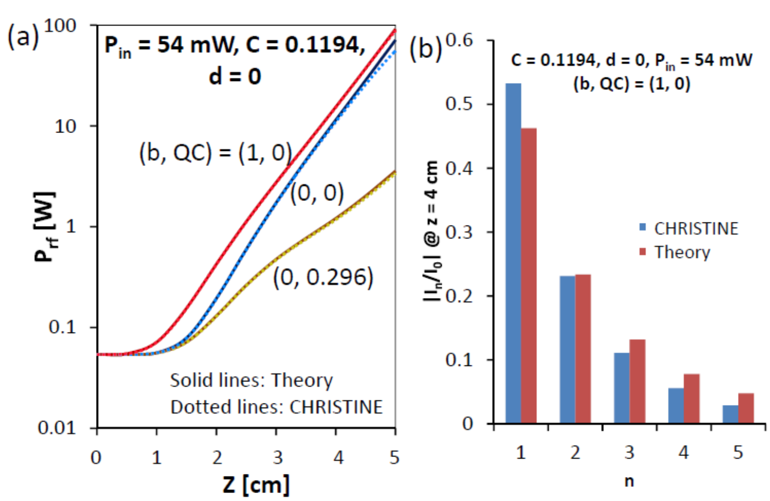

Figure 1 - (a) Evolution of RF power on the circuit wave for 54 mW drive with C = 0.1194, and d = 0. The three curves assume, from top to bottom, (b, QC) = (1,0), (0,0), and (0, 0.296). Excellent agreement between the (linear) analytic theory and (nonlinear) CHRISTINE results is found. (b) the n-th harmonic component in the beam current at z = 4cm for 54 mW drive, with C = 0.1194, d = 0, for the case (b,

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Bremsstrahlung Measurement on the Superconducting Source for Ions (SuSI)*

Derek Neben, Jesse Fogleman, Daniela Leitner, Guillaume Machicoane, Alfonse Pham, Andreas Stolz, and Larry Tobos

Michigan State University (neben@nscl.msu.edu)

Electron Cyclotron Resonance (ECR) ion sources are the choice of injector for many heavy ion accelerator facilities worldwide that are currently in operation, under construction, or proposed. Driven by demands of the scientific programs at those facilities, more particle current and at higher charge states are required from ECR ion sources. To meet these demands, fully superconducting sources with higher magnetic confinement fields operating at increased microwave frequencies are being developed. Technical design of these sources requires an understanding of the x-ray loading from the plasma into the cryostat. By measuring the x-ray spectrum from the plasma an estimate can be made for the expected heat load for the next generation of ECR ion sources. We aim to investigate the hot electron population (larger than 50 keV) residing in an ECR plasma over the next several years. In conjunction with ion confinement time measurements we will be able to better understand microwave heating at different frequencies and develop diagnostics to characterize ECR ion source plasma confinement.

This poster presents axial x-ray measurements on SuSI using a set-up that follows closely that of T. Ropponen *et. Al.* [1] to measure the hot electron population. Preliminary results from SuSI at 18 and 24 GHz heating frequencies as well as a description of our new data acquisition system will be presented.

*Work supported by Michigan State University and the National Science Foundation award number PHY-1415462

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Ion Energetics of the Modes of the CubeSat Ambipolar Thruster*

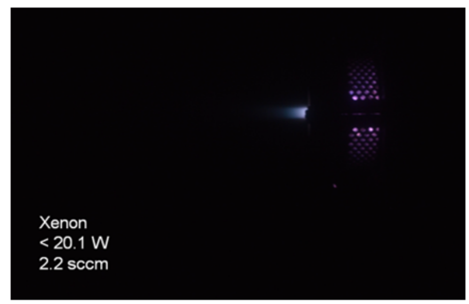
Timothy A. Collard, J. P. Sheehan and Alec D. Gallimore

Department of Aerospace Engineering, University of Michigan (collardt@umich.edu)

Over the past decade the reduced cost and accelerated mission development cycle of the CubeSat architecture has become an attractive option to commercial and scientific groups that are interested in a wide range of missions, from space weather monitoring to deep space exploration [1]. However, nanosatellites are limited to a narrow range of missions due to the lack of high performance propulsion systems. Current technology is limited to chemical and electric thrusters with ΔV capabilities of < 300 m/s [2]. While this is sufficient for station-keeping and orbit raising many mission-enabling maneuvers require ΔV > 1000 m/s, such as Earth escape and orbit inclination changes. The CubeSat Ambipolar Thruster (CAT) is an electrodeless, permanent magnet, helicon thruster being developed to increase the ΔV capabilities of nanosatellites to > 1000 m/s.

During testing CAT exhibited 2 - 3 distinct operational modes on xenon and argon by varying the power and the propellant mass flow rate [3]. A retarding potential analyzer (RPA) and an emissive probe were used to interrogate the plume in each of these modes. Energetic ion beams were present in some, but not all, of the modes observed. Figure 1 is an example of a mode with an energetic xenon ion beam. The various modes were demonstrated to be stable over a range of power and propellant flow rates, allowing for control over the ion beam energy and the thruster specific impulse.

It was observed that for the modes that exhibited an energetic ion beam a second, lower energy peak corresponding to the local plasma potential was present in the ion energy distribution at sufficiently high back pressures ($\sim 1\,x\,10^{-4}$ Torr, encountered at propellant flow rates > 5 sccm) and > 20 cm downstream. This was likely due to charge exchange collisions between the beam ions and the background neutrals. At conditions below this backpressure a significant ion population at the local plasma potential was not observed.



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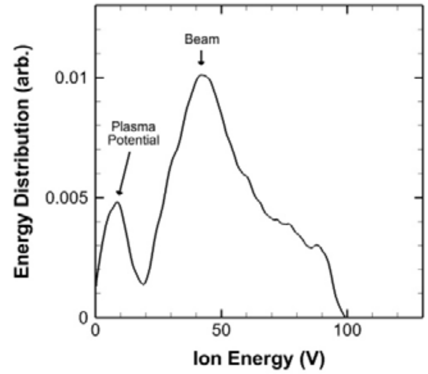

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Figure 1 - a) CAT operating on xenon with $\dot{m} = 2.2$ sccm, $P_{dep} < 20.1$ W, and $p = 3.56\,x\,10^{-4}$ Torr. b) The ion energy distribution.

*This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1256260 and NASA under Grant No. NNX14AD71G.

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Experiments on the Scaling of Growth and Saturation of Multi-beam Two-plasmon Decay with Plasma Conditions*

Jeff Fein [a], James Holloway,[a] Dana Edgell,[b] Dustin Froula,[b] Dan Haberberger,[b] Paul Keiter,[a] Jason Myatt,[b] Matt Trantham,[a] R. Paul Drake [a]

(a) University of Michigan, Ann Arbor, MI (jrfein@umich.edu)

(b) Laboratory for Laser Energetics, Rochester, NY (dfroula@umich.edu)

In inertial confinement fusion (ICF), multiple overlapping lasers interact with under-dense plasma to drive the two-plasmon decay (TPD) instability. The resulting plasma waves can produce hot electrons that preheat the ICF capsule fuel and reduce compression efficiency. Preliminary experiments have demonstrated that TPD can be controlled through varying electron density scale-length and temperature by increasing plasma Z [1]. Additionally, simulations have indicated that TPD may saturate by nonlinear processes that depend on plasma Z through the ion-acoustic wave damping rate [2]. We have performed experiments on OMEGA EP to thoroughly study the dependence of TPD on plasma conditions, through varying target material over a wide range of Z. Hot electron energy is observed to decrease as plasma Z increases, in a manner that is consistent with the shortening electron density scale-lengths that were measured. Finally, we present a scaling of total hot electron energy with the TPD linear gain parameter to identify whether the instability has nonlinearly saturated.

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DBD on Liquid Covered Tissue: Modeling Long-Timescale Chemistry*

Amanda M. Lietz [a] and Mark J. Kushner [b]

(a) Dept. of Nuclear Engr.& Radiol. Science, University of Michigan, Ann Arbor, MI 48109, USA
(b) Dept. of Electrical Engr. & Computer Science, University of Michigan, Ann Arbor, MI 48109,USA
(lietz@umich.edu, mjkush@umich.edu)

Dielectric barrier discharge (DBD) treatment of tissue has been shown to improve the healing of difficult-to-heal wounds [1] and is being investigated for cancer treatment [2]. Typically a wound or other biological sample is covered in a thin liquid layer of serum. As a result, the interactions between the plasma and the liquid are central to this type of medical treatment.

Though wound healing has been observed [1], the mechanism of the therapeutic effects is not well understood. One possible mechanism involves reactive species (ions and neutrals) solvating in the liquid, and eventually interacting with the tissue underneath. Reactive species of interest often include ozone, oxygen atoms, hydroxyl radicals, nitrous oxide, HNO_x and N_xO_y.

In this paper, we discuss results from a computational investigation of the plasma chemistry in the gas and the liquid layer as a function of the pulse repetition frequency and gas residence time. A 0-D plasma kinetics model, GlobalKin, couples the gas and liquid chemistry using Henry's Law for solvation of gases into water. GlobalKin is much less computationally demanding than spatially resolved models, which enables the investigation of a more complete chemistry and longer timescales. With this capability, carbon dioxide, sulfates and biomolecules can also be included in the analysis, in addition to the standard humid air chemistry.

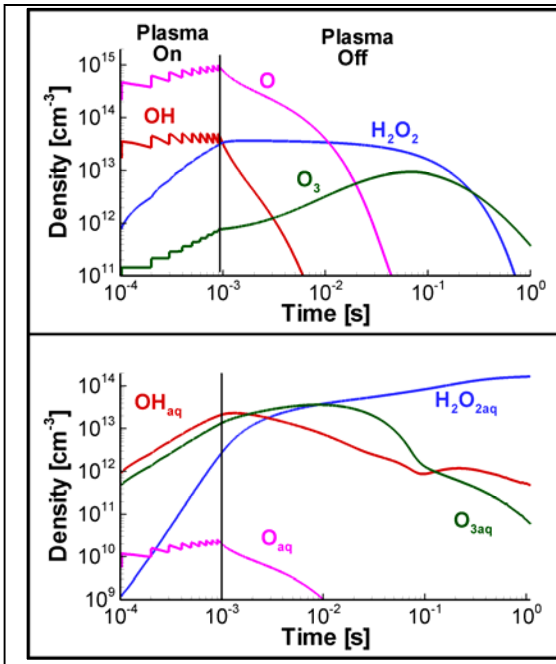

Figure 1 – The gas (top) and liquid (bottom) phase species of after 10 pulses of a DBD at 10 kHz.

An example of two of the simpler chemical mechanisms in this system is shown in Fig. 1. OH radicals are created in large amounts due to electron impact dissociation of water molecules evaporating from the liquid surface. The OH combines in both the gas and liquid phase to form H_2O_2. Oxygen atoms are formed by dissociative attachment of electrons to O_2. These oxygen atoms combine with ambient O_2 to form O_3, which solvates in the liquid and slowly decays. The production of these and many other reactive species will be explored in this study.

*Work supported by DOE Office of Fusion Energy Science (DE-SC0001319), National Science Foundation (CHE-1124724) and the NSF Graduate Research Fellowship Program

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Effects of Secondary Electron Emissions from a Plasma Immersed Graphite Substrate

Adrian Lopez and John E. Foster

University of Michigan (alopz@umich.edu, jefoster@umich.edu)

Secondary electron emissions (SEE) from surfaces immersed in plasma has the potential to affect not only the sheath potential distribution and overall sheath voltage, but also influence the near plasma properties. In order to better understand how SEE can bring about changes in the bulk plasma, electron energy distribution measurements are made outside the sheath using a Langmuir probe. Rather than numerically differentiating the I-V characteristic, an AC superimposed signal is used to obtain the electron energy distribution function (EEDF). This approach allows for better resolution of the distribution function, in particular, the distribution tail. In this manner, numerical noise and artificial structure that arises due to numerical differentiation can be avoided. EEDF changes will be correlated with observed changes in the sheath potential of a graphite substrate irradiated with a monoenergetic electron beam. The implications of these observations for Hall engine operation are discussed.

Microwave Plasma Assisted Chemical Vapor Deposition of Boron Doped Diamond for Vertical Schottky Barrier Diode Fabrication *

Stephen Zajac [a], Aaron Hardy [b] and Timothy A. Grotjohn [a,b]

(a) Department of Electrical and Computer Engineering, Michigan State University, 428 Shaw Lane, East Lansing, Michigan, 48824-1226, USA

(b) Center for Coatings and Diamond Technologies, Fraunhofer USA, Inc., 1449 Engineering Research Court, East Lansing, Michigan, 48824-1226, USA

Diamond is the ideal high power semiconductor material because of its thermal conductivity and breakdown electric field strength, enabling high current & high voltage devices [1-2]. This work will focus on high quality boron doped diamond growth, Schottky diode fabrication, and high power measurements up to 1000 V and 18 A.

An optimized process is developed for both heavily boron doped and lightly boron doped diamond. The diamond substrates are grown in a 2.45GHz microwave plasma assisted chemical vapor deposition (MPACVD) bell-jar type reactor. A 300 micron thick homoepitaxial layer was grown over multiple deposition runs totaling 54 hours of growth time. The depositions were done at 240 Torr using a hydrogen tank mixed with 1000 ppm diborane for the Boron source. The feedgas mixture of consisted of 96.25% hydrogen, 3.75% methane and .0025% diborane, resulting in a 1333 ppm B/C ratio in the gas phase. Microwave power was adjusted between 1500 and 1700W to maintain a substrate temperature in the range of 900 to 950 degrees C during deposition.

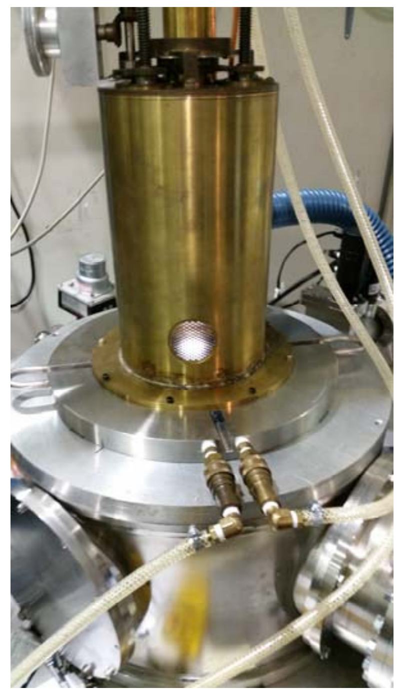

Figure 1 – Diamond deposition system used for growth of the lightly boron doped diamond layer of a vertical schottky barrier diode.

Large area Schottky diodes are fabricated using thin film metal sputtering, vacuum annealing, and plasma surface termination. Current, voltage, and capacitance measurements are taken over a wide range of temperatures. For the high voltage device, a reverse bias voltage of 1000 V with a leakage current of 1 mA is measured. For the high current device, a voltage drop of 4.5 V was measured for a forward current of 18 A. At this operating point, the current density is 900 A/cm2, and the power density is 4 kW/cm2. This measurement was repeated with pulses up to 1 second long with no damage to the device. Further, the sample had no forced cooling of any kind, with the only heatsink being two 5 mm x 10 mm x 1 mm copper plates.

*Work supported by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000455.

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Development of a 2D Axial-radial Fluid Electron Model*

Horatiu C. Dragnea [a], Kentaro Hara [b] and Iain D. Boyd [a]

(a) University of Michigan (horatiud@umich.edu, iainboyd@umich.edu)
(b) Princeton Plasma Physics Laboratory (khara@pppl.gov)

A Hall thruster is an annular spacecraft propulsion device that produces thrust by using electric and magnetic fields to accelerate ionized particles. Recent Hall thruster developments, such as magnetic shielding and nested channels, have prompted the need to improve simulation capabilities.

State-of-the-art hybrid methods such as HPHall [1] employ a quasi-1D fluid electron model, which decouples the electron transport along and across the magnetic field lines. However, this approach cannot be used for complex magnetic field topologies, or extended computational domains.

In this study, we present a fully 2D fluid electron model that directly captures the multidimensional electron transport in complex magnetic field configurations. More specifically, the plasma potential is calculated by solving a 2nd order partial differential equation obtained from the generalized Ohm's law for electrons in conjunction with the charge conservation equation, and assuming a quasineutral plasma. A 9-point Cartesian stencil is used to capture the effects introduced by the cross-terms and a thruster channel test case is constructed assuming dielectric channel walls as well as an anode and cathode. We present test cases under several magnetic field configurations in comparison with previous modeling results [2], and a quasi-1D model.

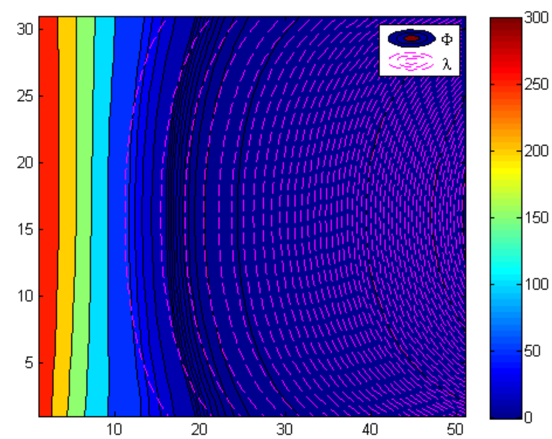

Figure 1 – Plasma potential contour plot for a Hall thruster-like coomputational domain. The magnetic field streamfunction is superimposed in purple.

*Work supported by a NASA Space Technology Research Fellowship

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Characterization of a MA-Class Linear Transformer Driver for Foil Ablation and Z-Pinch Experiments*

Adam Steiner, David Yager-Elorriaga, Sonal Patel, Nicholas Jordan, Ronald Gilgenbach, and Y.Y. Lau

University of Michigan, Plasma, Pulsed Power and Microwave Laboratory, Department of Nuclear Engineering and Radiological Sciences (amsteine@umich.edu)

The MAIZE linear transformer driver (LTD) facility at the University of Michigan is a 1-MA, 100 kV pulsed power device that has been used to drive foil-ablation experiments and wire array Z-pinches. The LTD machine consists of 80, 100 kV-rated capacitors and 40 multi-gap spark gap switches arranged in a circular geometry with the load at the center. Studies have been performed on MAIZE to analyze the Magneto-Rayleigh-Taylor instability, the effects of axial magnetic field shear, and the electrothermal instability. These studies have encompassed a wide variety of load geometries and electrical parameters. Because the LTD has 0.1-ohm driver-side impedance, its current and voltage output have been observed to depend strongly on load characteristics.

A full model of the LTD circuit has been generated, including the capacitor bank section, the inductive iron core path, and the non-uniform radial transmission line that delivers energy to the load. This model can be used to predict drive parameters, such as peak current and risetime, for any specified load resistance and inductance. Several important load geometries are analyzed, and maximum attainable current is shown to vary dramatically from the ideal current pulse generated by directly terminating the generator section into a 0.1-ohm matched load. Output from the model has been compared with experimentally observed voltage and current traces from resistive loads and foil ablation plasma experiments. Probing current and voltage at any point on the transmission line allows for time-dependent calculations of load resistance and inductance, enabling additional measurements such as effective current carrying radius. The effects of multiple switch firing times on peak current and risetime are also presented.

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High Energy Electron Acceleration from Underdense Plasmas with the OMEGA EP Laser*

T. Batson [a], A. Raymond [a], K. Krushelnick [a], L. Willingale [a], P. Nilson, [b] D. Froula [b], D. Haberberger [b], A. Davies [b], W. Theobald [b], J. Williams [c], H. Chen [c], A. Arefiev [d]

(a) Center for Ultrafast Optical Science, University of Michigan (tgbatso@umich.edu)

(b) Laboratory for Laser Energetics, University of Rochester (pnil@lle.rochester.edu)
(c) LLNL, (chen33@llnl.gov)
(d) University of Texas, Austin. (alexey@austin.utexas.edu)

Experiments performed using the OMEGA EP laser system studied channeling through an underdense CH plasma, as well as the energy spectra, pointing, and divergence of a direct laser accelerated (DLA) electron beam. An intense, ps scale laser pulse propagating through an under-dense plasma results in the expulsion of electrons from along the laser axis to form a channel [1]. Electrons can then be injected from the channel walls into the laser path, which results in the DLA of these electrons and the occurrence of a high energy electron beam [2]. The 4 omega optical probe diagnostic was used to characterize the density of the plasma plume and channel density, while proton radiography was used to observe the electromagnetic fields of the channel formation. 2D particle-in-cell simulations are used to investigate the effects of the plasma den-sity and laser parameters on the channel behavior and electron spectra.

*Work supported by the National Laser Users' Facility (NLUF), DOE

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Spatial Amplification in a Disk-on-Rod Traveling-Wave Amplifier*

P. Y. Wong [a], B. Hoff [b], D. H. Simon [a], D. Chernin [c], P. Zhang [a], Y.Y. Lau [a], R. M. Gilgenbach [a]

(a) Department of Nuclear Engineering and Radiological Sciences, University of Michigan (pywong@umich.edu)

(b) Air Force Research Laboratory, Kirtland AFB, NM

(c) LEIDOS, Reston, VA

High output power and wide bandwidth are the sought-after characteristics of traveling-wave tubes (TWTs). The disk-on-rod TWT is one such promising candidate (Fig. 1(a)). It employs a large-diameter, annular relativistic electron beam, which has a higher limiting current than the traditional pencil beam. The disk-on-rod slow-wave structure provides the wide bandwidth.

We studied a test case of this novel device, which at the same time provided a simultaneous comparison between the classical TWT theory of Pierce and three (3) widely used Particle-in-Cell codes: ICEPIC, MAGIC, and CHRISTINE. We analytically calculated the spatial amplification rate, β_i, by casting the exact dispersion relation of the device (which we derived) into Pierce's form and extracting the Pierce gain parameter C and the space-charge parameter QC. Figure 1(b) shows the comparison for a 124 kV beam operating at 2.832 GHz. The analytic theory, ICEPIC, MAGIC, and CHRISTINE all agree reasonably well. By comparing the red and black curves, one can see the effects of space charge on the device. The absolute instability [1] in the disk-on-rod TWT will be addressed.

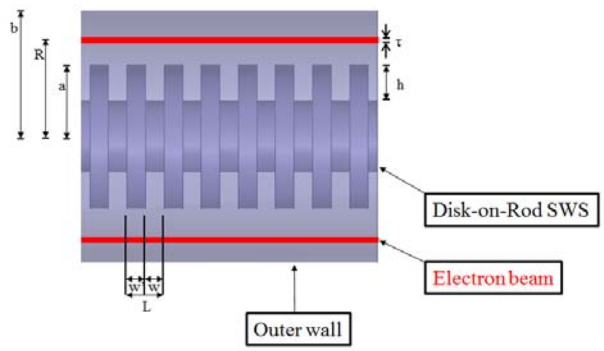

Figure 1(a) – Schematic diagram of the Disk-on-Rod TWT.

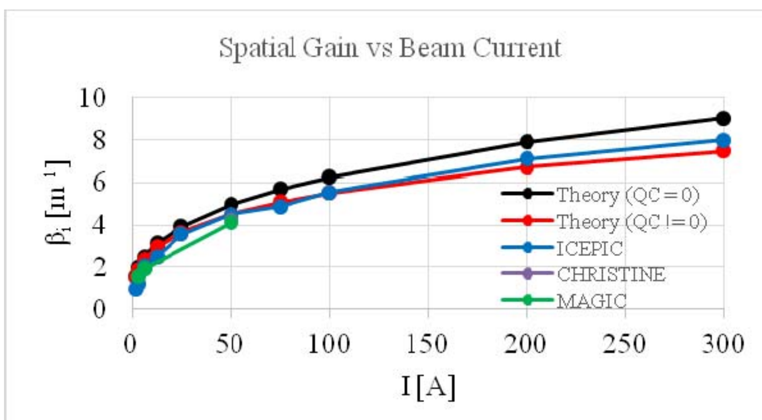

Figure 1(b) – Spatial amplification rate as a function of beam current for the Disk-on-Rod TWT, calculated from theory, ICEPIC, CHRISTINE, and MAGIC.

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Wrinkling Pattern Formation in Stretchable Luminescent Films of Silicon Nanocrystals

Rajib Mandal, Naomi Carlisle, Michael Bigelow and Rebecca J. Anthony
Department of Mechanical Engineering, Michigan State University, East Lansing, MI 48824
(ranthony@msu.edu)

Nanocrystalline silicon is widely known as an efficient and tunable optical emitter and is attracting great interest for applications such as light-emitting devices. To date, however, luminescent silicon nanocrystals have been used exclusively in traditional rigid devices. There is a need to investigate whether these nanocrystals can be used in flexible and stretchable devices.

Here we present a study on how the optical and structural/morphological properties of plasma-synthesized silicon nanocrystals (Si NCs) change when they are deposited on stretchable substrates made from polydimethylsiloxane (PDMS). The silicon nanocrystal synthesis was performed in a nonthermal, low-pressure gas phase plasma reactor. Silicon nanocrystals were deposited directly out of the plasma into thin-film layers using inertial impaction through a slit-shaped orifice. The PDMS substrates were either relaxed or pre-stretched to several different percentages of their original length ("stretching ratio") prior to deposition.
The morphologies of films deposited on both PDMS substrates and on rigid silicon wafer substrates were studied using SEM and are found out to be significantly different due to the difference in elastic properties of the PDMS as compared to silicon. From the photoluminescence (PL) measurement, the PL peak is adjusted by 80 nm between unstretched PDMS and PDMS stretched 40% beyond its original length. The main reason is believed to be due to different oxidation rates for different stretching ratio films.

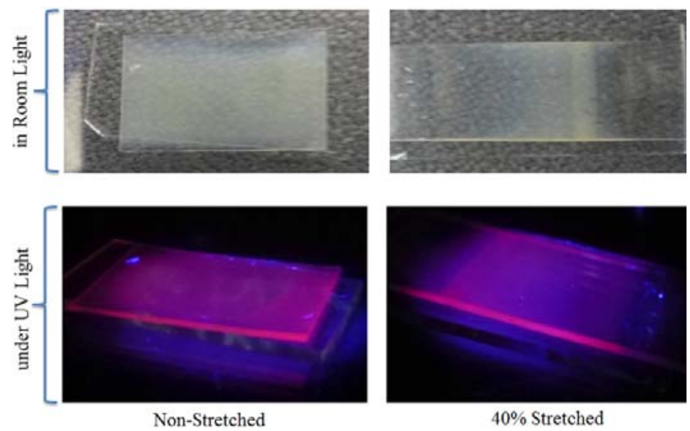

Figure 1 – Luminescence properties of stretched PDMS films.

Mechanical instabilities, specifically wrinkling, can create some unique surface patterns in soft materials that could be used for a wide range of applications relating surface topography and its dynamic tuning. In this work, we have focused on the buckling of a bilayer system to generate wrinkling instability, where a thin hard film of SiNC's coated on top of an expanded soft substrate (e.g. PDMS) endured a compressive force. The compressive force was provided by applying a mechanical strain.

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Anomalous Behavior of Carbon, Oxygen Charge States in a Population of Interplanetary Coronal Mass Ejections

Manan Kocher, Susan T. Lepri, Enrico Landi, Liang Zhao

Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor (mkocher@umich.edu, slepri@umich.edu, elandi@umich.edu, lzh@umich.edu)

A recent analysis of solar wind charge state composition measurements from the ACE/SWICS instrument showed that the expected correlation between the frozen-in values of the O7/06 and C6/C5 ratios was violated in ~5% of the slow solar wind in the 1998-2011 period (Zhao et al. 2015). In this work we determine that such anomalous behavior is also found in over 40% of Interplanetary Coronal Mass Ejections (ICMEs), as identified by Richardson and Cane (2010). An analysis of the plasma composition during these events reveals significant depletions in densities of fully stripped ions of Carbon, Oxygen, and Nitrogen. We argue that these events are indicators of ICME plasma acceleration via magnetic reconnection near the freeze-in region of Carbon and Oxygen above the solar corona.

The Effect of Anode Material and Secondary Gas Injection on Self-organized Patterns in Atmospheric Pressure Glows

Yao E. Kovach and John E. Foster

University of Michigan (yaok@umich.edu, jefoster@umich.edu)

Plasma self-organization on anode surfaces in DC glow discharges remains poorly understood. This effort aims to elucidate the nature of self-organization through the study of resulting patterns on both liquid and metal electrode surfaces. Self-organization pattern formation and behavior were studied as a function of inter-electrode spacing, electrode material type, gas composition and gas flow rate using emission spectroscopy and fast camera imaging. The response of the patterns to variation in these parameters is reported. These results are used as a basis for speculating upon the underlying physical processes that gives rise to the self-organization.

Harmonic Generation on the Multifrequency Recirculating Planar Magnetron Experiment

S. C. Exelby, G. B. Greening, N. M. Jordan, D. Simon,
P. Zhang, Y.Y. Lau and R. M. Gilgenbach

Plasma, Pulsed Power and Microwave Laboratory, Nuclear Engineering and Radiological Sciences Department
University of Michigan (scexlb@umich.edu)

The Multifrequency Recirculating Planar Magnetron (MFRPM) is a high power microwave source adapted from the Recirculating Planar Magnetron [1,2], currently under investigation at the University of Michigan. The device features 2 dissimilar slow wave structures allowing for the generation of (L-band) 1- and (S-band) 2-GHz high power microwave pulses simultaneously. These distinct frequencies offer the potential for variable coupling for defense applications, in particular for vehicle stoppers and counter-IED. Experiments have been performed on the RPM, driven by the Michigan Electron Long Beam Accelerator with a Ceramic insulator (MELBA-C) using a -300kV, 1-10 kA, 0.3-1.0 μs pulse applied to the cathode. Using the Mode Control Cathode and a coax-to-waveguide extraction system, the MFRPM has demonstrated simultaneous production of 20 MW at 1 GHz and 10 MW at 2 GHz. Interestingly, the L-band oscillator produced both 2- and 4-GHz oscillations when the S-band oscillator turns on. These harmonic frequencies continue after the S-band oscillator turns off. Because these frequencies are detected in WR-650, the waveguide is overmoded and accurate power measurements were impossible with this setup. Ongoing work will attempt to isolate these harmonics to measure the power accurately and confirm these observations.

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Charge Transport Properties of Plasma Assisted CVD Grown Single Crystal Diamond Irradiated with Swift-Heavy Ion Beam

A. Bhattacharya [a], A. Stolz [b] and T. A. Grotjohn [a]

(a) Department of Electrical & Computer Engineering, Michigan State University
(bhatta37@msu.edu, grotjohn@egr.msu.edu)
(b) National Superconducting Cyclotron Laboratory, Michigan State University
(stolz@nscl.msu.edu)

Single crystal diamonds are inherently radiation tolerant due to its material properties, and therefore a natural choice for radiation detector for high energy particle beams. Single crystal diamonds grown at Michigan State University (MSU) by microwave plasma assisted chemical vapor deposition (MPACVD) are used to develop detectors for swift heavy ion beam. Diamond plates, attached into detector mounts were irradiated with swift heavy ion beams in the range of 100-150 MeV/u at National Superconducting Cyclotron Laboratory (NSCL) at MSU. In addition to lab grown diamonds, commercially available electronic grade samples from different vendors were also used for detection at same radiation environment.

The charge transport properties of the samples (irradiated and non-irradiated) were looked into details by transient-current technique (TCT). ^{232}U α-particles of 5.4 MeV energy, were collimated through 1-mm aperture on the heavily and lightly irradiated segments of the diamond samples. Current pulse signals were recorded in the range of 0.1 V/μm - 1.1 V/μm applied field. The transient signals of both carriers (electron & holes) from irradiated and non-irradiated samples were compared. Due to beam induced damage, a significant drop of charge collection and carrier life time has been observed in the heavily irradiated segment of the detector.

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30-kW, Constant-Current-Density Performance of a 100-kW-class Nested Hall Thruster*

Scott J. Hall, Sarah E. Cusson and Alec D. Gallimore

Department of Aerospace Engineering, University of Michigan (sjhall@umich.edu)

There is strong interest in the electric propulsion community in scaling existing Hall thruster technology to power levels relevant for high-mass missions such as piloted missions to Mars. Concentrically nesting the discharge channels of a Hall thruster has been demonstrated to be a viable means to do this while maintaining reasonable device footprints [1]. This concept has been scaled up to the 3-channel, 100-kW class X3 [2,3] developed at the University of Michigan in collaboration with NASA and with the United States Air Force.

The X3 features an exceptionally large throttling range for a Hall thruster, being designed to operate from 2 to 200 kW discharge power. Its three channels can be operated separately or in any combination, providing seven operational configurations.

Recently, the X3 was operated up to 30 kW discharge power as part of a low-power performance characterization [4]. Each configuration of channels was operated at constant current density (about 75% of the nominal current density of the thruster) and 300 V anode potential. Thrust was measured using a new inverted pendulum thrust stand, and from that quantity, anode efficiency and anode specific impulse were calculated.

Over discharge powers ranging from 4 kW to 30 kW, the thrust ranged from about 270 mN up to 1.5 N, the anode efficiency ranged from 60% down to 22%, and the specific impulse ranged from around 2100 seconds down to 1200 seconds. Reasons for these large ranges will be discussed. At 30 kW total discharge power with all 3 channels operating together, the X3 produced 1.5 N of thrust and 1840 seconds anode specific impulse, operating at 45% anode efficiency.

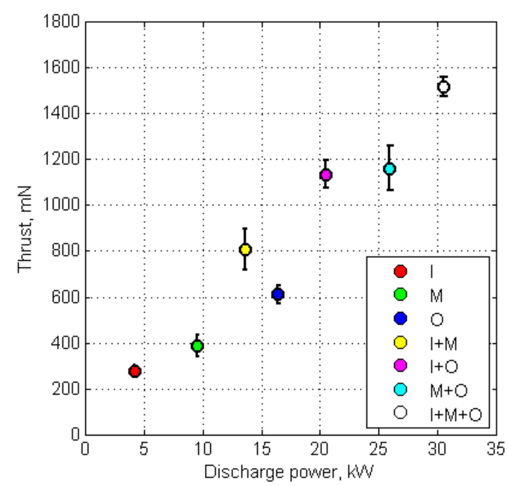

Figure 1 – Thrust versus discharge power across 300 V/100 A operating conditions for the X3, where I indicates inner channel; M, middle channel; and O, outer channel.

*Work supported by a NASA Space Technology Research Fellowship under grant NNX14AL67H. Additional funding provided by the Michigan/Air Force Center for Excellence in Electric Propulsion under grant FA550-09-1-0695

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Equation-of-State Measurements of Resorcinol Formaldehyde Foam Using Imaging X-Ray Thomson Spectrometer*

P. X. Belancourt [a], W. Theobald [b], P. A. Keiter [a], T. J. B. Collins [b], M. J. Bonino [b], P. Kozlowski [c] and R. P. Drake [a]

(a) University of Michigan (pxb@umich.edu)
(b) Laboratory for Laser Energetics, University of Rochester
(c) University of Oxford

Understanding the equation of state of materials under shocked conditions is important for laboratory astrophysics and high-energy-density physics experiments. This talk will focus on experiments dedicated to developing a platform for measuring the equation of state of shocked foams on OMEGA EP. The foam used in the development of this platform is resorcinol formaldehyde foam with an initial density of 0.35 g/cc. One OMEGA EP beam drives a shock into the foam, while the remaining three beams irradiate a nickel foil to create the x-ray backlighter. The primary diagnostic for this platform, the imaging x-ray Thomson spectrometer (IXTS), spectrally resolves the scattered x-ray beam while imaging in one spatial dimension. The IXTS is ideally suited to measure plasma conditions upstream, downstream and at the shock front in the foam. Preliminary results from these experiments will be shown.

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The Time Evolution of Streamer Discharges in Single and Multiple Bubbles in Water*

Selman Mujovic [a], Joseph Groele [b] and John Foster [c]

(a) University of Michigan Nuclear Engineering & Radiological Sciences (mujovics@umich.edu)
(b) University of Michigan Mechanical Engineering (jrgroele@umich.edu)
(c) University of Michigan Nuclear Engineering & Radiological Sciences (jefoster@umich.edu)

The interaction of plasma with liquid water lies at the heart of a variety of technological applications ranging from water treatment to wound healing. Plasma ignition and propagation in water, however, remains poorly understood. It has been theorized that plasma steamer propagation takes place in microbubbles[1]. In this work, discharge development in single[2] and multiple bubble acoustic systems is investigated using emission spectroscopy and high speed imaging, as shown in Figures 1 and 2. Optical filters also allow for time resolved measurements of specific species and the theorized phenomenon of multiple bubble streamer hopping is characterized as well. Better understanding of these breakdown processes will guide the design and construction of an effective plasma water purifier.

*Work supported by National Science Foundation (CBET: 1336375)

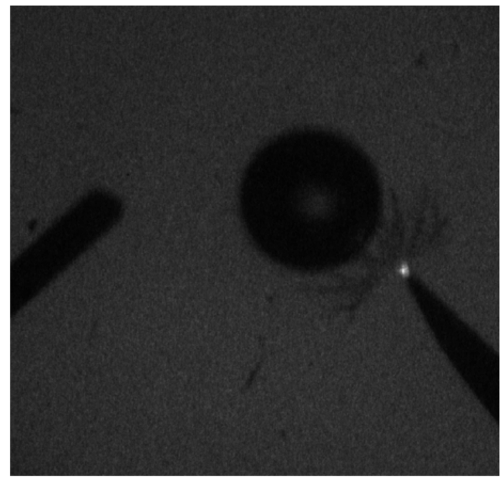

Figure 1 - Streamer discharges propagating through liquid water prior to bubble breakdown.

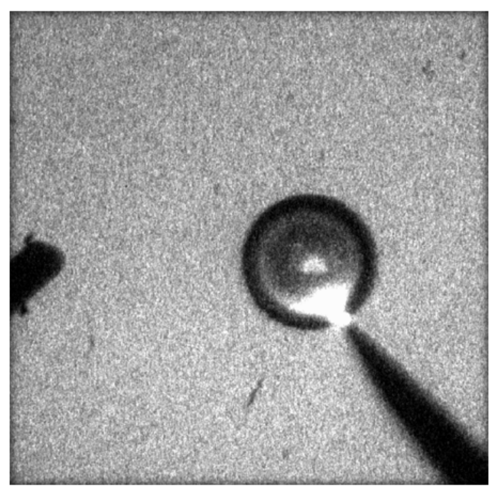

Figure 2 - Streamer discharges in an air bubble.

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Laser/Plasma-Pumped Rare Gas Laser: Global Model Study

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

(a) Michigan State University (parseygu,johnv,andrewch@msu.edu)
(b) Max-Planck Institute (yguclu@msu.edu)

Previous studies by Han and Heaven have extended from diode-pumped alkali vapor lasers (DPAL) to show that rare gas metastable states, $np^5\,(n+1)s[3/2]_2$, can operate as the base of a three-level laser with excitation of the (n+1)s → (n+1)p transitions.[1] Though both rare gas lasers (RGL) and DPALs are excited with incoherent optical pumping and share similar spectral characteristics, RGLs do not suffer from the highly reactive behavior of alkali metals. As opposed to vaporization-heating for DPALS, the metastable species are produced under pulsed electric discharge and are relatively inert with respect to buffer gases and system construction. In the case of an optically pumped system, laser pulses are delayed 2-25μs after the electric discharge to allow for relaxation of (n+1)s excitations. Since metastable populations are maintained via electric discharge, we hypothesized that a tuned electron energy distribution function (EEDF) could be utilized to improve RGL efficiency and potentially drive the gain mechanism without the need for intense optical pumping. Herein, we used the assumption that the EEDF is maintained by one or more electric discharges along with the introduction of electron sources.

In order to understand the effects of a plethora of tuning parameters, we used the kinetic global modeling framework (KGMf) and three different gas systems (pure argon and helium buffered argon and krypton) to rapidly map the possible parameter space. With electron impact reaction rates defined as convolutions of cross sections with the EEDF, we validated the two-way averaged intracavity intensity laser model, introduced by Demyanov et al.[2] for studying DPAL systems. In addition, our results obtained through the KGMf identified gain and energy efficiency baselines for each gaseous system being optically pumped. Parameter scanning and result-search methods were utilized to identify optimized EEDFs and system parameters for metastable production, generation of a lasing population inversion, and increasing RGL operation efficiencies. Finally, we determined if a RGL can efficiently operate without optical pumping.

*Work supported in part by the AFOSR and an MSU Strategic Partnership Grant

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Nernst Effect in Magnetized Hohlraums

Archis Joglekar [a], A. G. R. Thomas [a], C. P. Ridgers [c] and R. J. Kingham [d]

(a) University of Michigan (archisj@umich.edu)
(b) University of York
(c) Imperial College

2D Vlasov-Fokker-Planck-Maxwell modelling of electron plasma in a Omega-scale hohlraum is performed to explain the dynamic and complex interplay between thermal transport and externally imposed O(10) T magnetic fields that occurs. Externally imposed magnetic fields are blown away due to strong, non-local heat flows unless the magnetic field strength is > 60 T. These fields compress in the walls to strengths > 1 MG and also pile-up on the hohlraum axis over time-scales faster than that predicted by common MHD processes such as diffusion or frozen-in-flow. [1]

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Model Validation for Plasma Contactor Mediation of Electron Beam Charged Spacecraft*

Omar Leon [a] and Grant Miars [b]

(a) University of Michigan, Applied Physics Program (omarleon@umich.edu)
(b) University of Michigan, Department of Electrical Engineering (gmiars@umich.edu)

A high power electron beam can be fired from a spacecraft in the magnetosphere to trace the Earth's magnetic field lines. However, the density of the ambient plasma in this region is too sparse to maintain spacecraft neutrality while the electron beam is operating. PIC simulations suggest that the spacecraft can be neutralized by using a hollow cathode to produce a dense, ion emitting plasma which balances the beam's electron emission. [1,2] Here we present the results from a series of experiments which were performed at the Large Vacuum Test Facility (LVTF). These experiments were geared towards validating the PIC simulations and improving our understanding of the plasma-spacecraft interactions in this environment.

*Work supported by Los Alamos National Laboratory

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A Diffusive Code, xRage, Is Compared to Experimental Data from Omega*

R.VanDervort [a], L.Elgin [a], E. Farag [c], K. Mussack [b], J. Baumgaertel [b], P. Keiter [a], S. Klein [a], C. Orban [c], and R. P. Drake [a]

(a) University of Michigan (dervort@umich.edu)
(b) Los Alamos National Laboratory
(c) The Ohio State University

A sound speed discrepancy between solar models and data collected through helioseismology exists. The sound speed discrepancy is the most pronounced at the base of the convective zone (CZ) for otherwise consistent solar models. One potential solution is that the opacity models for important elements such as carbon, nitrogen and oxygen are incomplete. At these high energy-density conditions few relevant opacity measurements exist to compare to the models. Only relatively recently have user facilities been able to reach the temperature and densities that resemble the convective zone base. It is our long term goal to determine the opacities of carbon, nitrogen and oxygen at the relevant conditions. Preliminary testing has occurred at the Omega Laser Facility in Rochester, New York. Presented are the results of the shots taken on April 22, 2015. A half hohlraum was used to drive a supersonic radiation front through a dominantly carbon, CRF, foam. We measured the self-emission of the foam, which allows one to determine the position of the radiation front. We will also present results of simulations of the experiment using xRage code.

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Negative Mass Effects in Conventional, Planar, and Inverted Magnetrons*

D. H. Simon, Y.Y. Lau, G. Greening and R. M. Gilgenbach

Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI, 48109-2104 (dhsimon@umich.edu)

Simulations of the recirculating planar magnetron (RPM) [1] show that bunching occurred in the recirculating bends if the device was in an inverted configuration. A rotating electron in an inverted magnetron configuration possesses a "negative mass" effect, so that a thin electron layer suffers from the negative mass instability [2]. For this thin layer, the negative mass instability is the dominant instability, and the diocotron instability is secondary which becomes dominant in the planar limit, in which the negative mass effect is absent. Unanswered is the negative mass effect in a rotating Brillouin flow, which intrinsically has a large velocity spread. Since the Brillouin flow is the prevalent state in a crossed-field geometry, we systematically study its stability in conventional, planar, and inverted magnetron configurations [3]. To investigate the intrinsic negative mass effects in Brillouin flows, we consider electrostatic modes in a nonrelativistic, smooth bore magnetron.

Figure 1 shows the results of the eigenvalue problem. The AK gap was fixed at 1m and the hub width was fixed to 50% of the AK gap. The bunch frequency at the hub, defined as $m^*\omega_0$ (m is the azimuthal mode number, and ω_0 is the electron angular frequency evaluated at the top of the Brillouin hub) is also held to be a constant. In the case of planar magnetron, this constant is equal to k^*v, where k is the wave number and v is the electron velocity at the top of the Brillouin hub. In Fig. 1, the conventional magnetron corresponds to $r_c/r_a < 1$, the planar magnetron to $r_c/r_a = 1$, and the inverted magnetron to $r_c/r_a > 1$, where r_c and r_a are, respectively, the cathode and anode radius. This graph clearly shows that the growth rate is highest for the inverted magnetron, implying that inverted magnetron starts up the fastest [1,3]. For a planar magnetron, there is no negative mass effect, and the growth rate in the planar Brillouin flow is due only to the velocity shear which results in a diocotron-like instability. Figure 1 suggests that the negative (positive) mass effect intrinsic to the inverted (conventional) magnetron configuration tends to destabilize (stabilize) this diocotron instability.

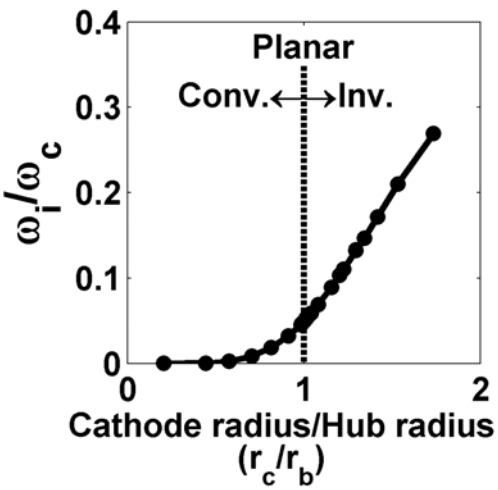

Figure 1 – Normalized growth rate as a function of r_c/r_b holding the AK gap, hub height, and bunch frequency constant [3].

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Ultrathin Liner-Plasma Implosion Experiments on a sub-MA Current Generator*

D. A. Yager-Elorriaga [a], A.M. Steiner [a], S. G. Patel [a], N. M. Jordan [a], M. R. Weis [b], P. Zhang [a], Y. Y. Lau [a] and R. M. Gilgenbach [a]

(a) University of Michigan (dyager@umich.edu)
(b) Sandia National Laboratories

In order to implode a cylindrical liner with a sub mega-ampere current generator, a small liner radius and low linear mass (mass per length) are required. For liners of reasonable radii, this requirement means the liner thickness must be extremely thin. A simple 0-D implosion model shows liners with millimeter-scale diameters require sub-micron thicknesses in order to implode. We first present a technique for fabricating ultrathin liners to study liner-plasma implosion physics on sub-MA current generators, and then use the technique to study the implosion dynamics and plasma instability growth.

The liners were fabricated from ultrathin aluminum foils and had a thickness of 400 nm, 1 cm height, and 6.55 mm diameter, and were imploded by discharging a current of 600 kA with 200 ns risetime using a 1-MA Linear Transformer Driver. The resulting plasmas were imaged with a four-frame laser shadowgraphy/interferometry system at 532 nm and show four stages: expansion, implosion, stagnation, and re-expansion. During these stages the plasma is susceptible to a variety of instabilities including the magneto Rayleigh-Taylor, sausage and kink instabilities [1]. We present measurements of instability growth rates along with preliminary studies of the stabilizing effects of an axial magnetic field. By comparing the measured acceleration to the acceleration predicted by the current pulse, we see that a significant amount of the driving magnetic field has diffused inside of the liner, reducing the observed acceleration. Finally, we present a modified load-hardware design for laser probing along the z-axis to study the interior of the liner.

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A High Repetition Rate Laser-Heavy Water Based Neutron Source

Jungmoo Hah, Zhaohan He, John Nees, Karl Krushelnick, and Alec Thomas

Center for Ultrafast Optical Science (jmhah@umich.edu)

Neutrons have numerous applications in diverse areas, such as medicine, security, and material science. For example, sources of MeV neutrons may be used for active interrogation for nuclear security applications. Recently, alternative ways to generate neutron flux have been studied. Among them, ultrashort laser pulse interactions with dense plasma have attracted significant attention as compact, pulse sources of neutrons. To generate neutrons using a laser through fusion reactions, thin solid density targets have been used in a pitcher-catcher arrangement, using deuterated plastic for example. However, the use of solid targets is limited for high-repetition rate operation due to the need to refresh the target for every laser shot. Here, we use a free flowing heavy water target with a high repetition rate (500 Hz) laser without a catcher. From the interaction between a 10 micron scale diameter heavy water stream with the Lambda-cubed laser system at the Univ. of Michigan (12mJ, 800nm, 35fs), deuterons collide with each other resulting in D-D fusion reactions generating 2.45 MeV neutrons. Under best conditions a time average of ~10^5 n/s of neutrons are generated.

*Work supported by the AFOSR

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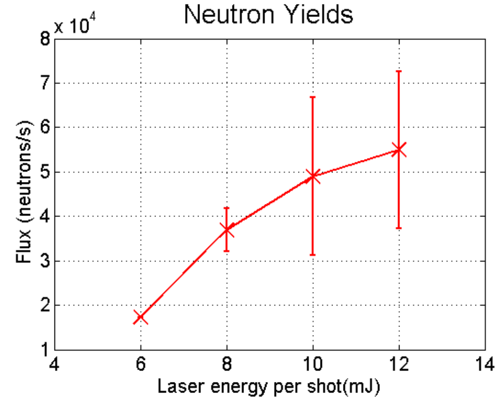

Figure 1 – Mesaused total neutron yields using neutron bubble detector. Laser energy is varied from 6 to 12mJ.

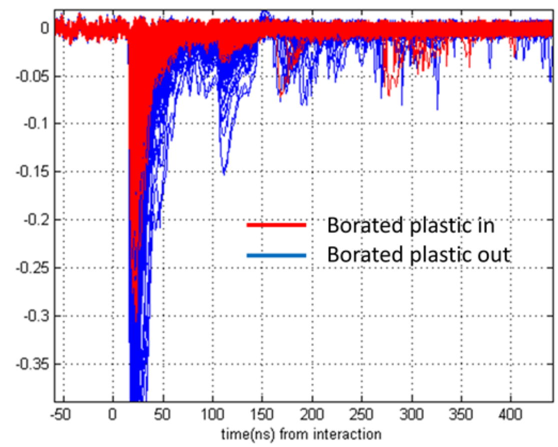

Figure 2 – Delayed and Scattered neutron (2.45MeV) signals due to Borated plastic cage.