Michigan Institute for Plasma Science and Engineering (MIPSE)

University of Michigan & Michigan State University

2nd ANNUAL GRADUATE STUDENT SYMPOSIUM

September 21, 2011

3:00 – 7:00 pm

1005 EECS

North Campus, University of Michigan

1301 Beal Avenue

Ann Arbor, MI 48109

University of Michigan
Ann Arbor, MI

MIPSE 2nd Graduate Student Symposium

Schedule

3:00 – 3:15	Prof. Mark J. Kushner, Director of MIPSE ***Opening Remarks***
3:15 – 4:00	**Poster Session I**
4:00 – 5:00	**Special MIPSE Seminar:** **Dr. Kimberly S. Budil,** Lawrence Livermore National Laboratory ***High Energy Density Plasma Physics:*** ***An Evolving Role on the National Scene***
5:00 – 5:45	**Poster Session II**
5:45 – 6:30	**Poster Session III**
6: 45 – 7:00	***Best Presentation Award* Ceremony**

Refreshments will be provided.

Poster Session I

1-01 **Rachel Young,** University of Michigan
Collisions between Red Giant Stars and Active Galactic Nuclei Accretion Disks

1-02 **Benjamin Yee,** University of Michigan
Intra-Pulse Rotational Spectroscopy for Pulsed-Nanosecond Discharges

1-03 **Michael Logue,** University of Michigan
Ion Energy Distributions in Pulsed Inductively-Coupled Plasmas Having a Pulsed Boundary Electrode

1-04 **Dzung Tran,** Michigan State University
Microwave Plasma-Assisted Etching for Smoothing Polycrystalline Diamond Films

1-05 **Yiting Zhang,** University of Michigan
Development of Ion Energy Angular Distributions through the Pre-sheath and Sheath in Partial Pulsed Dual-Frequency Capacitively Coupled Plasmas

1-06 **Carlos Di Stefano,** University of Michigan
Spike Morphology in Supernova-Relevant Hydrodynamics Experiments

1-07 **Will Schumaker,** University of Michigan
Ultrafast Electron Radiography of Magnetic Fields in High-Intensity Laser-Solid Interactions

1-08 **Paul Cummings,** University of Michigan
Computational Methods for Simulating the Generation of Synchrotron-Like Radiation in Laser Wakefield Acceleration Experiments

1-09 **Peiyao Liu,** Michigan State University
Atmospheric Pressure Microwave-Powered Microplasma Source

1-10 **Bradley Sommers,** University of Michigan
Nonlinear Oscillations of Levitated Gas Bubbles and Their Impact on Plasma Formation in Water

1-11 **David Liaw,** University of Michigan
Simulation of Self-Neutralization Techniques for Charged Particle Thrusters on Nanospacecraft

1-12 **Yajun Gu,** Michigan State University
Microwave Plasma Assisted CVD Reactor Design For High Deposition Rate Diamond Synthesis

1-13 **Christine Krauland,** University of Michigan
Reverse Radiative Shock Experiments on the OMEGA-60 Laser

Poster Session II

2-01 **Andrew Baczewski,** Michigan State University
Accelerated Cartesian Expansions (ACE): A Linear Scaling Method for the Rapid Evaluation of Pairwise Interactions

2-02 **Michael Vargas,** University of Michigan
Focusing Betatron Radiation Produced by Laser Wakefield Accelerated Electrons with a Spherically Curved Crystal

2-03 **Wei Tian,** University of Michigan
Plasma Discharge in Water Based on Pre-existing Bubbles and Electric Field Rarefaction

2-04 **Jing Lu,** Michigan State University
Microwave Plasma Assisted Synthesis of Single Crystal Diamond at High Pressures and High Power Densities

2-05 **Ian Rittersdorf,** University of Michigan
Effects of Random Circuit Fabrication Errors on Small Signal Gain and Output Phase in a Traveling Wave Tube

2-06 **Franklin Dollar,** University of Michigan
Novel Heavy Particle Acceleration from High Intensity, Short Pulse Lasers

2-07 **Paul Giuliano,** University of Michigan
Effects of Detailed Heavy Species Interactions in DSMC-PIC Simulation of a Simplified Plasma Test Cell

2-08 **Adam Steiner,** University of Michigan
Experimental Investigation of the Evolution of the Magneto-Rayleigh Taylor Instability on Thin Foils

2-09 **Naveen Nair,** Michigan State University
An Adaptive Locally Smooth Surface Parameterization for Integral Equations

2-10 **Eliseo Gamboa,** University of Michigan
Imaging X-Ray Thomson Scattering Spectroscopy for Characterizing Extreme Matter States

2-11 **Iverson Bell,** University of Michigan
Investigating the Potential of Electrodynamic Tethers to Enhance Capability of Ultra-small Spacecraft

2-12 **Sarah Nowak Gucker,** University of Michigan
Power and Decomposition Studies on an Underwater Dielectric Barrier Discharge Plasma

2-13 **Jun-Chieh (Jerry) Wang,** University of Michigan
Electron Current Extraction and Interaction of RF mDBD Arrays

Poster Session III

3-01 **Panpan Zhang,** Michigan State University
Two-dimensional PIC-MCC Simulations of the Electron Multiplication in a Gas Electron Multiplier

3-02 **Calvin Zulick,** University of Michigan
Bremsstrahlung Temperature Scaling in Ultra-Intense Laser-Plasma Interactions

3-03 **Nick Patterson,** University of Michigan
Investigation of Mixed Cell Treatment via the Support Operator Method

3-04 **Zhaohan He,** University of Michigan
Electron Generation from a High Repetition Lambda Cubed Laser Wakefield

3-05 **Peng Zhang,** University of Michigan
Analysis of Bulk and Thin Film Contact Resistance with Dissimilar Materials

3-06 **Shannon Demlow,** Michigan State University
Properties of Boron Doped Diamond Grown by Plasma Enhanced Chemical Vapor Deposition

3-07 **Sreenivas Varadan,** University of Michigan
Compressible Turbulence and Interfacial Instabilities

3-08 **Channing Huntington,** University of Michigan
Same-Shot X-Ray Thomson Scattering and Streaked Imaging of Xenon Radiative Shock Experiments

3-09 **Collin Meierbachtol,** Michigan State University
Self-Consistent Simulation of Microwave PACVD Reactors for Diamond Growth

3-10 **Laura Spencer**, University of Michigan
Analysis of Computational Work in Comparison with Experimental Results for an Atmospheric Pressure Microwave Plasma

3-11 **Sang-Heon Song,** University of Michigan
Control Etch Rate of SiO_2 in $Ar/CF_4/O_2$ Capacitively Coupled Plasmas Using Pulsed Power with Constant Power and Constant Voltage of the Substrate

3-12 **Aimee Hubble,** University of Michigan
Addressing Issues in Probing the Magnetic Cusp Region

3-13 **Kentaro Hara,** University of Michigan
1D hybrid-Vlasov Simulation for Hall Thrusters

HIGH ENERGY DENSITY PLASMA PHYSICS: AN EVOLVING ROLE ON THE NATIONAL SCENE

Dr. Kimberly S. Budil

Lawrence Livermore National Laboratory

Wednesday, 21 September 2011 - 4:00 pm, Room 1005 EECS Building

Abstract

The long-term commitment of the Department of Energy and now the National Nuclear Security Administration to the pursuit of research on inertial confinement fusion concepts and the investigation of the properties of matter in extreme environments has led to the coalescence of the discipline of high energy density plasma physics. A series of increasingly capable experimental facilities has been at the center of this, focused primarily on high-energy lasers and pulsed power technology. Along with dramatic advances in experimental capability significant progress has been made in computational techniques to address the very complex and scientifically rich set of questions posed by the most extreme states of matter. This talk will discuss the evolution of the DOE/NNSA research program in this area, highlight current research endeavors and project some future directions for this research area.

About the Speaker: **Dr. Kim Budil is the N Program Manager in the Global Security Principal Directorate at Lawrence Livermore National Laboratory. Prior to this assignment she was a Senior Advisor to the Under Secretary for Science at the Department of Energy. In this role she provided technical assistance on matters related to the National Nuclear Security Administration including its missions, the scientific and technical capabilities of the NNSA labs, and the relationship between the NNSA and the broader DOE. At LLNL, Dr. Budil's research includes high energy density physics, performing experiments on the Nova and Omega lasers investigating hydrodynamic instabilities, equations-of-state, and radiation transport, and computational studies of materials properties. She was the Associate B Program Leader for Science, Technology and Experiments in the Weapons and Complex Integration (WCI) Directorate at LLNL. In this role she managed the research programs supporting WCI including the Dynamic Material Properties Campaign and the Advanced Simulation and Computing Physics and Engineering Models Program.**

Poster Session I

1-01

Collisions between Red Giant Stars and Active Galactic Nuclei Accretion Disks

R. P. Young, E. S. Myra and R. P. Drake

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We simulate collisions between red giant stars and accretions disks surrounding active galactic nuclei. According to prevailing theory, an active galactic nucleus is a super-massive black hole (greater than 10^6 solar masses) surrounded by an accretion disk. We investigate one potential way for the accretion disk to grow: a collision with a red giant star that results in the accretion disk gaining matter at the expense of the star's outer envelope, first proposed by Armitage [1]. Using our radiative hydrodynamic code, CRASH, we simulate a star colliding with an accretion disk. Consistent with Armitage, we find that the column density of the disk is the dominant factor in the mass loss of the star. However, unlike Armitage, we find that the velocity of the star relative to the disk has little impact on mass loss.

This research was performed by the Center for Radiative Shock Hydrodynamics, funded by NNSA/ASC Predictive Science Academic Alliances Program grant DEFC52-08NA28616, and was also supported by the Center for Laser Experimental Astrophysics research, funded by NNSA/DS Stewardship Sciences Academic Alliances DOE Research grant DE-FG52-07NA28058 and National Laser User Facility grant DE-FG52-04NA00064, and by other grants and contracts.

References

[1] P.J. Armitage, W.H. Zurek, and M.B. Davies, *Astrophysical Journal* **470**, 237 (1996).

Intra-Pulse Rotational Spectroscopy for Pulsed-Nanosecond Discharges

B.T. Yee[a], S.J. Schneider[b], J.E. Foster[a] and I.M. Blankson[b]

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(b) NASA Glenn Research Center

Pulsed-nanosecond discharges provide challenging environments for diagnostics. Physical probes may significantly influence the discharge properties and are often subject to electric fields on the order of 10 kV/cm. As a result, optical diagnostics and I-V measurements have become the preferred way to examine such discharges. However, in many cases, the equipment used to make these measurements lack the bandwidth to resolve intra-pulse characteristics. Therefore little information is available on the intra-pulse evolution of such discharges.

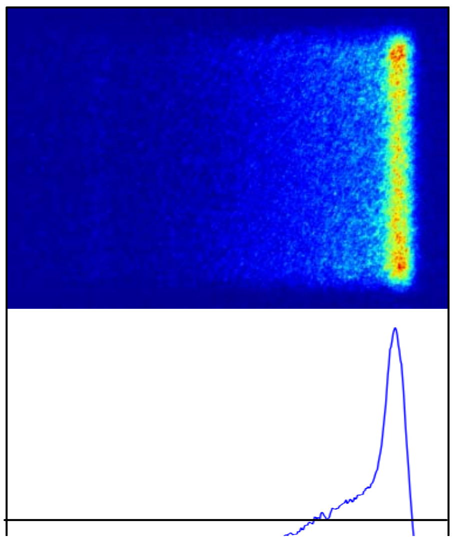

Fig. 1: An ICCD image (upper) and spectrum (lower) of the second positive system in nitrogen following post-processing. The 0-0 transition is shown with a peak at 337.1 nm.

Here, we present measurements of the rotational temperature at 500 ps intervals in a pulse-nanosecond discharge for a variety of conditions. The device has been previously described by Schneider et al.[1] Several modifications were made to accommodate longer run times including the use of a high temperature ceramic for holding the electrodes. The electrodes were circular copper plates with diameters of 2.5 cm held at a distance of 2.5 cm. The peak-to-peak magnitude of the voltage pulse was varied between 9 and 15 kV with repetition rates of 20 and 30 kHz. The chamber pressure was held at approximately 20 Torr of ambient air.

Measurements were made with a Spex 500M monochromator fitted with a grating with 2400 g/mm blazed for 300 nm. The monochromator was fitted with a LaVision PicoStar HR, an intensified CCD capable of gates below 300 ps. The band examined is the 0-0 transition of the second positive system of nitrogen. A computer program was written to simulate expected spectra and determine the best match with the experiment. The methods used have already been described by Herzberg and others[2][3]. The current and voltage signals are used to approximate the energy transfer to the discharge and an estimate of the ionization cost per ion is made.

References

[1] S.J. Schneider, H. Kamhawi and I.M. Blankson, 47^{th} Aerosp. Scis. Mtg., Orlando, FL, 2009-1050.
[2] G. Herzberg, Molecular Spectra and Molecular Structure, Vol. I., 1989.
[3] A. Chelouah, E. Marode, G. Hartmann and S. Achat, J. Phys. D: Appl. Phys. **27**, 940 (1994)

1-03

Ion Energy Distributions in Pulsed Inductively-Coupled Plasmas Having a Pulsed Boundary Electrode*

Michael D. Logue[a], Mark J. Kushner[a], Hyungjoo Shi[b], Weiye Zhu[b], Lin Xu[b], Vincent M. Donnelly[b] and Demetre J. Economou[b]

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In many applications requiring energetic ion bombardment, such as plasma etching, it is the time averaged ion energy and angular distribution (IEAD) to surfaces that is most important. In these situations, pulsed plasmas can be used to piece together IEADs from different times during the power pulse to craft the desired IEAD. A recent development in obtaining control of IEADs in inductively coupled plasmas (ICPs) is the use of a boundary electrode in which a continuous or pulsed dc bias is applied to the plasma. The resulting shift in the plasma potential modifies the IEADs to surfaces without significant changes in the bulk plasma properties. When this pulsing of the boundary electrode is combined with pulsing of the ICP power, additional control can be obtained. In this paper we discuss results from a computational investigation of IEADs to a grounded substrate in low pressure (a few to 100 mTorr) ICPs sustained in argon and Ar/H_2 mixtures. The investigation was conducted using the Hybrid Plasma Equipment Model (HPEM) with which electron energy distributions and the IEAD as a function of position and time are obtained using Monte Carlo simulations. Both the sustaining ICP power and boundary voltage are applied in continuous and pulsed formats. Results from the model for Ar plasmas densities, electron temperatures, electron distributions and IEADs will be compared to experimental data obtained using a Langmuir probe and a gridded retarding field ion energy analyzer. Preliminary results of the model reflect trends seen in the experimental data, though measured and modeled values differ somewhat.

*Work supported by SRC and U.S. Department of Energy Office of Fusion Energy Science.

1-04

Microwave Plasma-Assisted Etching for Smoothing Polycrystalline Diamond Films

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Polycrystalline diamond films are promising for several applications for which a smooth surface is important, such as optical windows, X-ray masks, SAW filters and other electronic devices. Mechanical lapping and polishing techniques are fairly well established, however the diamond lapping removal rate is very low. Consequently there is interest in the development of more efficient smoothing methods. Examples include thermal-chemical polishing [1], laser polishing [2] and planarizing layers combined with oxygen ion-beam etching [3]. This paper describes development of methods to smooth polycrystalline diamond films using microwave plasma-assisted etching combined with mechanical polishing and combined with sacrificial planarizing layers.

A 2.45 GHz, microwave plasma-assisted etching reactor is utilized for high etch rate processes on diamond substrates as previously described [4]. The first surface smoothing method combines plasma etching with mechanical lapping/polishing. The whiskers, produced on the diamond surface after plasma etching due to the micro-masking effect are relatively easy to remove by the mechanical lapping/polishing. Using this method in which etching, followed by lapping/polishing was repeated several times, the surface roughness R_a was improved from 3802 nm to 53 nm. This method shortens the time required for smoothing, but still required both mechanical lapping and polishing. The second method combines plasma etching and planarizing layers such that the etch is designed to remove the planarizing layer and diamond at comparable rates. Planarizing layers tested include photoresist, Si_3N_4, and SiO_2 with the latter showing best results. A plasma-enhanced chemical vapor deposition (PECVD) layer of oxide is deposited to a thickness comparable to the R_Z of the diamond surface. Then the oxide layer is polished and planarized using chemical-mechanical-polishing. This step is followed by plasma-assisted etching sufficiently long to remove the remaining oxide. The result is a significantly smoother diamond surface created without the need for a time consuming lapping step. Sequential applications of the procedure produce optically smooth surfaces. Important experimental parameters include etch-gas composition and mechanical polishing speed and down force.

References

[1] M. Yoshikawa, Diamond Optics III, SPIE, 1325, 210 (1990).
[2] A.M. Ozkan, A.P. Malshe, W.D. Brown, Diamond and Relat. Mater., 6, 1789 (1997).
[3] D. F. Grogan, T. Zhao, B.G. Bovard, and H. A. Macleod, Applied Optics, 31, 1483 (1992).
[4] D. T. Tran, T. A. Grotjohn, D. K. Reinhard, J. Asmussen, Diamond and Relat. Mater., 17, 717 (2008).

1-05

Development of Ion Energy Angular Distributions through the Pre-sheath and Sheath in Partial Pulsed Dual-Frequency Capacitively Coupled Plasmas

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Ion properties in the sheath and pre-sheath, and the ion energy and angular distribution function (IEAD) to the surface, are of critical interest to plasma etching processes in the microelectronics industry. With single frequency capacitively coupled plasmas (CCPs), the narrowing in angle and spread in energy of ions as they cross the sheath are well definable functions of frequency sheath width and mean free path. Multiple frequency biases having widely different values are now being used to obtain flexible control of the ion flux and IEADs. The Ratio between the RF bias τrf and the average ion transit time τion will highly affect the characteristics of the sheath. Under these conditions, the development of the IEAD is significantly more complex than in single frequency systems.

In this paper, we report on a computational investigation of the development of IEADs in low pressure plasmas having multifrequency substrate biases as the ions transition from the bulk plasma, through the presheath and sheath, and are incident on the substrate. Under the intermediate frequency (τrf / τion ≈ 1), the IEAD at the substrate are bimodal and in the high frequecy regime (τrf / τion >> 1), the high frequency sheath has a neglilgible effect on the final energy of ions and the IEAD respond to the time averaged bias potential.[1] Pulsing one of the frequency or both of them will change the IEAD shape and improve the etch rate and uniformity in industry.

These simulations are performed with an ion Monte Carlo Simulation embedded within the Hybrid Plasma Equipment Model (HPEM). IEADs are tracked as a function of height above the substrate and phase within the rf cycle. Computed results are compared to laser-induced fluorescence experiments of ion velocities performed in an inductively coupled plasma having 8 different phases during the whole cycle. Gas pressures are a few to 10s of mTorr, in Ar and Ar/O2 gas mixtures.

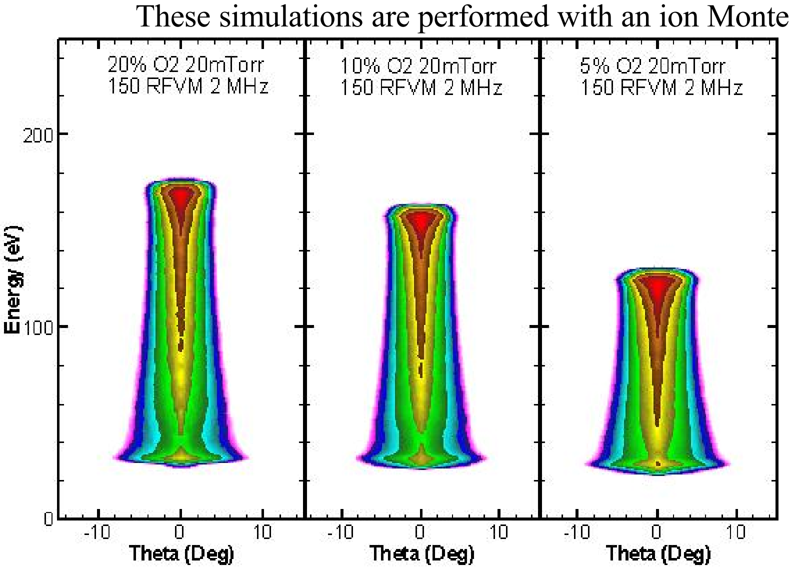

Fig. 1: IEAD under different oxygen presentage mixed with argon gas, operated at 20 mTorr 2MHz RF bias

1-06

Spike Morphology in Supernova-Relevant Hydrodynamics Experiments

C. Di Stefano [a], C.C. Kuranz [a], R.P. Drake[a], M.J. Grosskopf [a], C.M. Krauland [a],

D. C. Marion [a], S.R. Klein [a], B. Fryxell [a], A. Budde [a], and T. Plewa[b]

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This presentation describes experiments performed on the Omega and Omega EP lasers exploring the 3D Rayleigh-Taylor instability at a blast-wave-driven interface. These experiments are well-scaled to the He-H interface during the explosion phase of SN1987A. Laser energy is used to create a planar blast wave in a plastic disk, which then crosses the interface between the disk and a lower-density foam, inducing the RT instability. The plastic disk has an intentional pattern machined at this interface. This seed perturbation is three-dimensional with a basic structure of two orthogonal sine waves with a wavelength of 71 μm and amplitude of 2.5 μm. Interface structure has been detected under these conditions using dual, orthogonal radiography, and some of the resulting data will be shown. Current experiments are further examining the features of the unstable interface using proton radiography.

This work is funded by the NNSA-DS and SC-OFES Joint Program in HEDLP, by the NLUF in NNSA-DS and by the PSAAP in NNSA-ASC. The corresponding grant numbers are DE- FG52-09NA29548, DE-FG52-09NA29034, and DE-FC52-08NA28616.

1-07

Ultrafast Electron Radiography of Magnetic Fields in High-Intensity Laser-Solid Interactions

Will Schumaker[a], C. McGuffey[a,b], N. Nakanii[c], A. G. R. Thomas[a], V. Chvykov[a], F. J. Dollar[a], G. Kalintchenko[a], V. Yanovsky[a], C. Zulick[a], A. Maksimchuk[a], K. Tanaka[c], K. Krushelnick[a]

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(b) University of California, San Diego (Current Institution)
(c) Graduate School of Engineering, Osaka University

Using sub-30 fs electron bunches generated with laser wakefield acceleration (LWFA) as a probe, the femtosecond temporal evolution of a 4 x 10^{19} W/cm^2 short laser pulse with solid targets has been studied experimentally. Magnetic fields of ~100 megagauss were observed travelling outward from the interaction point of the laser with a 10 μm aluminum foil at nearly the speed of light under ideal laser conditions. With degraded contrast, a pre-plasma forms on the front surface, containing the front surface magnetic field to the hole-boring region. This proof-of-principle experiment demonstrates the utility of LWFA electrons as a diagnostic technique for magnetic fields with femtosecond timescale and/or in sufficiently dense plasma. These results are supported by OSIRIS particle-in-cell simulations.

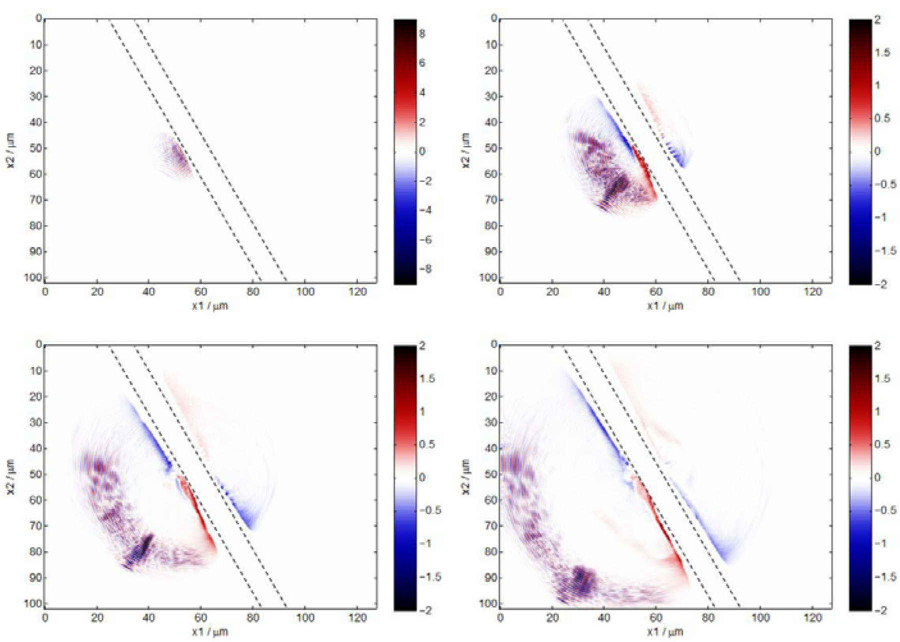

Fig. 1: OSIRIS PIC simulation slices of the normalized magnetic field ($|e|\,B_z/m_e\,\omega_0$) component in Z direction taken at (a) $\omega_0 t$=354, (b) $\omega_0 t$=472, (c) $\omega_0 t$=589 and (d) $\omega_0 t$ =708 for an ideal contrast interaction. The initial target position is indicated by the dashed lines.

1-08

Computational Methods for Simulating the Generation of Synchrotron-Like Radiation in Laser Wakefield Acceleration Experiments

Paul Cummings and Alec G. R. Thomas

NERS Department & CUOS (cummingp@umich.edu, agrt@umich.edu)

A promising application of laser wakefield technology is as a tunable source of x-ray and gamma radiation via synchrotron radiation. Such a source could serve as a valuable tool for detecting materials characterization[1], radiation-based cancer therapy[2], and nanoscale imaging of advanced materials[3]. Consequently, the generation of synchrotron radiation in LWFA experiments is investigated computationally using the particle-in-cell simulation code OSIRIS 2.0. A novel computational algorithm for explicitly simulating synchrotron radiation, involving the generation of particle-like ``macrophotons," is derived. A skeleton particle tracking code is developed to validate this model, and the results of this validation are presented and discussed. Results from simulations of Thomson scattering using this code are presented and discussed. Potential applications for integrating this algorithm into OSIRIS 2.0 are presented and discussed. Specifically, the utilization of this algorithm, in conjunction with earlier work implementing the explicit simulation of optical aberrations, to study the experimentally-observed relationship between the comatic aberration and the synchrotron spectrum critical frequency[4], is discussed.

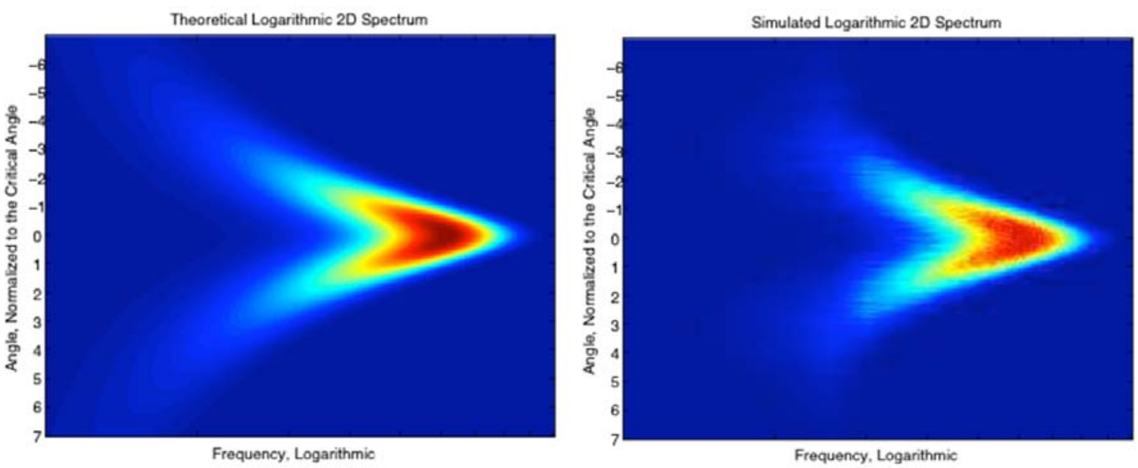

Fig. 1: The theoretical (left) and simulated (right) normalized two-dimensional synchrotron spectra generated by an electron traveling in a uniform magnetic field.

References

[1] W. Ludwig, A. King, M. Herbig, P. Reischig, J. Marrow, L. Babout, E. M. Lauridsen, H. Proudhon, and J. Y. Buffiere, JOM 62(12), 22 (2010).

[2] M. Sadeghi, M. Enferadi, and A. Shirazi, J. Cancer Res. Ther. 6, 239(2010).

[3] A. Sakdinawat and D. Attwood, Nature Photon. 4(12), 840 (2010).

[4] S. P. D. Mangles, G. Genoud, S. Kneip, M. Burza, K. Cassou, B. Cros, N. P. Dover, C. Kamperidis, Z. Najmudin, A. Persson et al., Appl. Phys. Lett. 95, 181106 (2009).

1-09

Atmospheric Pressure Microwave-Powered Microplasma Source

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Portable low-cost microplasma sources are of interest for their potential application in materials processing, as well as biomedical, chemical analysis and optical radiation source uses.[1-6] This is especially true for the atmospheric pressure plasmas. Further, by using higher frequency energy (rf and microwave) to power the microplasma discharge, the erosion of electrodes can be reduced.

In this investigation a microwave-powered microplasma system based on a double-stripline structure is developed for the generation of atmospheric pressures plasmas with various feedgases and feedgas mixtures. The microplasma system is constructed with the top and bottom copper striplines separated by a dielectric material, either teflon or ceramic. The stripline structure is powered at one end and the plasma is formed at the other end where the two metal striplines are brought together to a gap distance that is varied from 50-250 microns. The feedgas is flowed through a channel in the dielectric such that it exits with the feedgas flowing between the gap created by the two striplines. The flow rate is varied from 0.3-3 slpm. The gas flow channel in the dielectric is 0.25 mm high by 8 millimeters wide.

Argon and argon/oxygen microplasma discharges are formed in the gap between the two metal striplines. The microwave power used for the argon discharges varies from 2 to 60 Watts. The power density in the plasma discharge ranges from 500 to few 1000 W/cm^3. The plasma volume is obtained by photographic images of the discharge. The addition of oxygen to the argon feedgas increases the power density of the discharge. The gas temperature of the discharges is measured by adding a small amount of nitrogen gas to the feedgas and doing optical emission spectroscopy of the nitrogen rotational temperature. This paper will report on both experimental measurements, as well as initial simulation results, of the microwave field behavior of the double-stripline structure.

References

[1] J. Kim, and K. Terashima, Appl. Phys. Lett. 86 (2005) 191504
[2] J. Kim, M. Katsurai, D. Kim and H. Ohsaki, Appl. Phys. 93 (2008) 191594
[3] K. Ogata and K. Terashima, J. Appl. Phys., 106(2009) 023301
[4] J. Gregorio, L. L. Alves, O. Leroy, and C. Boisse-Laporte, Eur. Phys. J. D., 50(2010) 627
[5] S. Schermer, N. H. Bings, A. M. Bilgic, R. Stonies, E. Voges. J. A. C. Broekaert, Spectrochimica Acta Part B 58 (2003) 1585-1596
[6] U. Engel, A. M. Bilgic, O. Haase, E. Voges, and J. A. C. Broekaert, Anal. Chem. 72(2000) 193

1-10

Nonlinear Oscillations of Levitated Gas Bubbles and Their Impact on Plasma Formation in Water

Bradley S. Sommers, John E. Foster

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In this work, we investigate the effects of a time varying electric field on air bubbles submerged in water. The applied field induces electrical stress, which acts on the bubble's surface and results from the dielectric structure of the gas-liquid interface and the free charge deposited there by the water's conductivity. [1] This driving pressure can cause the bubble to undergo severe distortions to its shape, leading potentially to a local enhancement of the electric field at areas of sharp curvature and a decrease in its internal pressure during sudden expansion. These two effects can combine to drastically increase the reduced field (E/N) near the dielectric boundary and consequently ease the conditions for streamer initiation inside the bubble. This type of enhancement could have a broad impact on the viability of liquid plasma technologies, which tend to suffer from high voltage requirements.

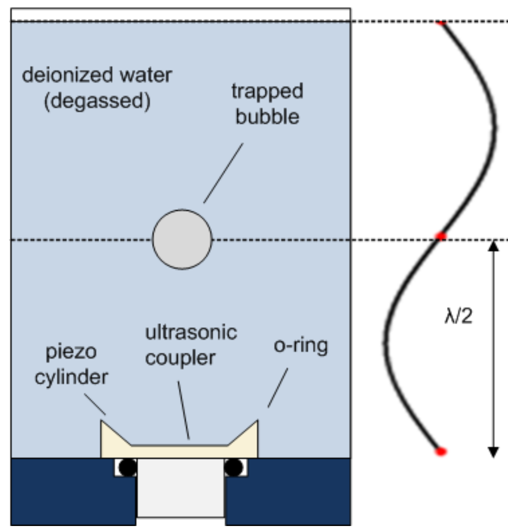

Fig. 1: A gas bubble is levitated at the node of an ultrasonic standing wave.

Air bubbles are isolated for study by levitating them in an underwater ultrasonic acoustic field, as shown in Fig. 1. This allows for the study of shape and volume distortions through a controlled and repeatable procedure. Bubbles with 0.5-3.0 mm diameter are trapped in the node of a 26.5 kHz underwater acoustic field while either alternating or pulsed voltage signals of 5-20 kV are applied across their diameter. Bubble response is captured using a high speed camera (10,000 frames per second), along with a high sensitivity hydrophone. The response is documented over a wide range of factors, including bubble size, field frequency, and field strength. A typical response is shown in figure 2. The observed deformations of the bubble shape are subsequently used to predict changes to the reduced field (E/N) within the bubble.

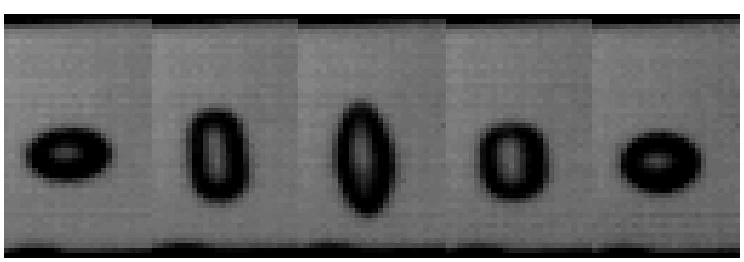

Fig. 2: The vertically directed field streches and compresses the bubble during different phases of its oscillation.

References

[1] Garton, Krasucki. Proc. Roy. Soc. Lon., Vol. **280**, No. 1381, July 1964.

1-11

Simulation of Self-Neutralization Techniques for Charged Particle Thrusters on Nanospacecraft

David C. Liaw, Thomas M. Liu, and Brian E. Gilchrist

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There is an emerging class of nanospacecraft thrusters under development that use colloids or nanoparticles that can be charged either positively or negatively to provide thrust. An issue to be examined is how the ability to charge equal number of particles to both polarities is beneficial to the system in terms of being able to provide self-neutralization of the thruster[1]. An important consideration here is that, unlike traditional ion thruster technology, which emit a single particle polarity and is separately neutralized by highly mobile electrons, this neutralization scheme will be predicated on equal charge, equal mass, massive, cold particles to provide neutralization. Thus, different issues need to be examined, such as strong electric fields near the spacecraft.

We explore two approaches for charged particle thruster neutralization: spatially and temporally separated, oppositely charged populations of nanoparticles. Both approaches would result in equal amounts of oppositely charged particles being emitted, resulting in a net neutral spacecraft.

Our investigation is accomplished through particle-in-cell simulation using XOOPIC™, OOPIC PRO™, and analytical modeling. Through simulations, we are able to observe the behavior of spatially separated, equal mass particles with opposite charge. We observe that even when equal numbers of oppositely charged particles are emitted simultaneously from spatially separated regions, there is still a local charge buildup on the spacecraft wall due to an image charge effect. This results in an electric field between the emitted beam and the nearby spacecraft surface, which can decrease particle beam velocity by a few percent. As expected, oppositely charged nanoparticle beams tend to converge. Thus collisions of equal mass particles where charge can be separated from the particle center-of-mass must be considered.

For particle emissions that are non-neutral (temporally separated), analytical modeling enables us to estimate how quickly a 30 cm diameter nanospacecraft would charge up. For example, emitting 10 mA of current would result in the spacecraft potential reaching 5% of the equivalent beam energy in under 10 μs requiring oscillation of the charging and accelerating scheme at approximately 100 kHz.

References

[1] Liu, Thomas M. "The Design Space of a Micro/Nano-Particle Electrostatic Propulsion System." Dissertation. University of Michigan, 2010.

1-12

Microwave Plasma Assisted CVD Reactor Design for High Deposition Rate Diamond Synthesis

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There is a need to continue to improve existing microwave plasma assisted reactor designs that enable high quality and high deposition rate single crystal diamond (SCD) synthesis. It is widely recognized that both the quality and growth rates of microwave plasma assisted CVD (MPACVD) synthesized diamond are improved by using high power density microwave discharges operating at pressures above 160 Torr [1]. Thus we are developing microwave plasma reactor designs and associated process methods that are both robust and are optimized for high pressure and high power density operation [2], and thereby take advantage of the improved deposition physics and chemistry that exist at high pressures. These reactors can operate in the 160-320 Torr pressure regime. Here we describe the design methodologies, and present the specific design details of a new 2.45 GHz MPACVD reactor design that enables optimized reactor performance and high growth rate diamond synthesis in the high pressure regime.

The design principles that we employed in the reactor design process are: (1) single phi symmetric TM_0 mode excitation, (2) internal cavity impedance matching, (3) variable substrate position, (4) four tuning variables L_p, L_s, L_1, and L_2 that enable the nonlinear optimization of discharge positioning, discharge size adjustment and growth rate enhancement as the input variables such as power, pressure, gas chemistry etc. are changed, (5) scalability of the reactor design versus excitation frequency. The reactor design also incorporates dimensions that allow the coupling/transfer of large amounts of microwave power into the discharge at high pressure. In this design the plasma discharge is pulled away from the reactor walls by employing the larger quartz dome and reactor diameters. Another important feature is the excitation of a single hybrid TM_{02} /TEM_{001} mode to create the microwave discharge above and in direct contact with the substrate. The final reactor design is experimentally evaluated by observing the reactor performance over the multivariable experimental variable space, and performing polycrystalline and single crystal diamond synthesis using CH_4/H_2 input chemistries over the 160-320 pressure regime. The reactor has been operated for over 2000 hours and has synthesized both thick polycrystalline and single crystal diamond plates. It has exhibited high reliability and requires minimal maintenance. High power density discharges are produced with absorbed power densities of 100-1000 W/cm^3 and optical quality, type IIa SCDs are synthesized with growth rates over 80 microns/hour. The diamond synthesis rate is 1.2-2.5 times greater than the earlier designs. [2]

References

1. F. Silva, K. Hassouni , X. Bonnin X, and A. Gicquel, J. Phys.: Condens. Matter 21, 364202 (2009).
2. K. Hemawan, T. Grotjohn, D. Reinhard and J. Asmussen, D.R.M., 19, 1446, (2010).

1-13

Reverse Radiative Shock Experiments on the OMEGA-60 Laser

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In many Cataclysmic Binary systems, mass onto an accretion disk produces a 'hot spot' where the infalling flow obliquely strikes the rotating accretion disk. It has been argued [1] that the shocked region may be optically thin, thick, or intermediate, which has the potential to significantly alter its structure and emissions. We report two experimental attempts to produce this type of radiative reverse shock in a colliding plasma stream. In the laboratory this requires producing a sufficiently fast flow (>100 km/s) within a material whose opacity is large enough to produce energetically significant emission from experimentally achievable layers. The experiments have been performed at the Omega-60 laser facility. We will discuss the astrophysical context, our experimental design, and the available data.

This work is funded by the Predictive Sciences Academic Alliances Program in NNSA-ASC via grant DEFC52- 08NA28616, by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-FG52-09NA29548, and by the National Laser User Facility Program, grant number DE-NA0000850.

References

[1] P. Armitage and M. Livio, ApJ, **493**, 898 (1998).

Poster Session II
2-01

Accelerated Cartesian Expansions (ACE): A Linear Scaling Method for the Rapid Evaluation of Pairwise Interactions

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It is well-known that the computational cost of evaluating pairwise interactions between N bodies scales as $O(N^2)$. Consequently, fast methods for mitigating this quadratic cost, with an O(N log(N)) or O(N) framework, have significant implications for particle dynamics simulations, in which such interactions must be computed at each time step. Tree-based methods such as the Fast Multipole Method (FMM) [1], as well as interpolatory methods such as Particle-Particle Particle-Mesh (P3M) [2] are but two of the fast methods that are commonly used in particle dynamics, among a wide variety of applications. The method of Accelerated Cartesian Expansions (ACE), is an O(N) tree-based method, similar to FMM that offers a number of advantageous features, including exact tree-traversal, amenability to non-uniform systems, and a nearly kernel-independent framework [3]. This final feature is particularly advantageous for particle dynamics simulations in which the same tree can be used to effect multiple types of interactions simultaneously, i.e., a system in which particles experience long-range Coulombic, screened Coulombic (Yukawa), and short-range (Lennard-Jones) interactions. Recent extensions of the ACE algorithm have also made possible the O(N) evaluation of potentials and forces in systems with periodicity of arbitrary co-dimension [4], as might arise in simulations of bulk systems in which electrostatic forces in the absence of screening have an effectively infinite range.

In this work, we will present the ACE algorithm as an accelerator for energy and force calculations that arise in a particle-dynamics framework. Specifically, error convergence and linear scaling will be demonstrated for a number of exemplary systems, both finite and periodic. Results will also be presented concerning progress towards the integration of the ACE algorithm into the popular molecular dynamics code, LAMMPS [5]. To this end, the construction of a complimentary parallelization strategy, as well as its utility in evaluating multiple potentials will be discussed in detail. Future applications of this work will see the integrated LAMMPS-ACE software used in the modeling of the PVD deposition of diamond thin films.

References

[1] L. Greengard and V. Rokhlin, J. Comp. Phys. **73**(2), 325-348 (1987).
[2] R.W. Hockney, S.P. Goel, J.W. Eastwood, Chem. Phys. Lett., **21**(3), 589-591 (1973).
[3] B. Shanker and H. Huang, J. Comp. Phys. **226**(1), 732-753 (2007).
[4] A.D. Baczewski and B. Shanker, arXiv:1107.3069 (2011) (*under review with J. Comp. Phys.)*
[5] S. Plimpton, J. Comp. Phys. **117**(1), 1-19 (1995).

2-02

Focusing Betatron Radiation Produced by Laser Wakefield Accelerated Electrons with a Spherically Curved Crystal

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Laser Wakefield Acceleration[1] in the bubble regime can be used to accelerate electrons to GeV energies while simultaneously wiggling them to produce a synchotron like x-ray radiation.[2-4] Using HERCULES, a 100TW TiSapphire laser, 30fs pulses are focused onto a 5mm He gas jet to accelerate electrons in the bubble regime. The betatron x-rays produced by the transverse motion of the accelerated electrons are focused onto a detector by a spherically curved quartz crystal. This result shows the feasibility of dynamic studies of crystal diffraction, with femtosecond level accuracy, using pump probe techniques.[5]

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References

[1] Tajima, T. & Dawson, J. M. Phys. Rev. Lett. 43, 267–270 (1979)
[2] Schlenvoigt, H.-P. *et al*. Nature Phys. 4, 130–133 (2008)
[4] A. Rousse *et al.*, Phys. Rev. Lett. **93**, 135005 (2004)
[4] Jaroszynski, D. A. *et al*. Phil. Trans. R. Soc. A 364, 689 (2006)
[5] Chapman, H. *et al*. Nature Phys. 2, 839–843 (2006)

2-03

Plasma Discharge in Water Based on Pre-existing Bubbles and Electric Field Rarefaction

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Non-thermal plasma discharges in water have received a lot of attention these years. They are efficient to produce highly chemically reactive radicals, such as O, H and OH, which are essential for applications in pollution removal, sterilization and medical treatment. In order to maximize efficiency and minimize byproducts, the physical mechanisms of plasma discharges in water have to be understood. One possible mechanism is that pre-existing bubbles and gas channel creation assist the discharge in view of its analogy to vapor phase discharge. The discharge initiation is determined by local low-density areas, especially within bubbles; in contrast, the discharge development depends on the processes in the bulk water, where the gas channel creation is dominating.

In this work, this mechanism has been confirmed by the two-dimensional simulations of the plasma discharge initiation and propagation in water. Instead of a pin-to-plate geometry, the parallel electrodes are used here in order to eliminate the electric field enhancement by the geometric factor. A bubble contacting with the powered electrode initiates the discharge. After that, a phase-like transition due to highly intense electric fields creates a gas channel, in which the discharge develops. The field electron emission from the gas-liquid interface is also considered. These simulations were preformed using nonPDPSIM, which solves Possion's equation and transport equation for charged species and electron temperature. The water is treated as a condensed phase plasma with an appropriate charged particle reaction mechanism.

Computed results are shown in the figure. The discharge initially occurs within the bubble because electrons are able to gain enough energy for ionization there. The potential lines are expelled out of the conductive bubble, which becomes an extension of the powered electrode and makes the electric field concentrated at its top. The enhanced electric field is so strong that a phase-like transition occurs there. The densities, compositions and other phase-related properties are changed respectively. As the phase-like transition creates a gas area upwards, the plasma discharge extends itself to the created area. The potential lines are expelled again, inducing more phase-like transitions. The loop continues until the discharge reaches the grounded electrode. In this mechanism, the field electron emission from the gas-liquid interface also contributes to the breakdown.

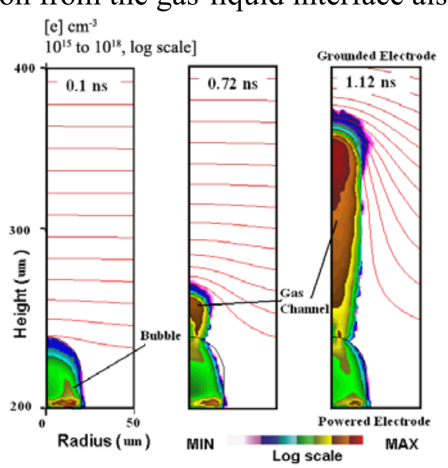

Figure. The electron density (flood) and electric potential (lines) development with time. The electrons are created initially within the bubble and then extend to the gas channel created by the electric field. The potential lines are compressed as the discharge develops.

2-04

Microwave Plasma Assisted Synthesis of Single Crystal Diamond at High Pressures and High Power Densities

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Current microwave plasma assisted chemical vapor deposition (MPACVD) diamond synthesis theory suggests that CVD synthesized diamond quality and growth rates can be improved by using high power density microwave discharges operating at pressures above 160 Torr [1]. Thus we are experimentally exploring single crystal diamond (SCD) synthesis under high pressure and high power density conditions that take advantage of the improved deposition chemistry and physics that may exist in the high pressure (180-300 Torr) regime. Here in this poster paper the experimental results for SCD synthesis are presented using a recently improved 2.45 GHz microwave plasma assisted CVD reactor design [2].

The SCD synthesis was carried out using H_2/CH_4 input gas chemistries over the 180-300 Torr regime. SCD growth rates versus pressure, input gas chemistry (with and without N_2 addition), and substrate temperature are presented, and output SCD quality was evaluated by Micro-Raman, IR-UV transmission spectrometry and SIMS analysis. SCD growth rates increase as pressure, methane concentration and discharge power density increase. Linear growth rates of 70-80 micron/hr are achieved without N_2 addition. SCD growth rates additionally increase with small amounts of N_2 additions (10-200 ppm) to the feed gas. Under similar growth conditions, i.e. temperature, methane concentration, etc., growth rates increase faster vs. N_2 addition at higher pressures than at lower pressures. A SCD growth window was observed between 950 - 1300 °C, the details of which have not been published by other investigators up to now. Micro-Raman spectroscopy, IR-UV transmission spectrometry and SIMS measurements showed that the synthesized SCD was of excellent quality (type IIa, gem quality or better) within the growth window of 1030 – 1250 °C with high growth rates of 40-45 micron/hr. Fig. 1 shows an example of a microwave plasma assisted synthesized SCD plate, which is a near colorless, type IIa, 1.1 carat MPACVD diamond plate. This plate was cut off of an approximately 7x7 mm^2 HPHT diamond seed and then was mechanically polished.

Fig. 1: An example of large size CVD synthesized SCD plate.

References
[1] D. G. Goodwin, J. Appl. Phys. 74, 6888 (1993).
[2] K. W. Hemawan, et al., Diamond and Related Materials, 19, 1446-1452 (2010).

2-05

Effects of Random Circuit Fabrication Errors on Small Signal Gain and Output Phase in a Traveling Wave Tube

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Traveling-wave tubes (TWTs) are widely used as amplifiers in broadband radar, communications, and electronic warfare [1]. Random fabrication errors in the manufacture of slow wave circuits may have detrimental effects on the performance of traveling-wave tubes of all types. Such errors will pose an increasingly serious problem as TWTs are designed and built to operate in the sub-millimeter wavelength regime, which employ miniature, difficult-to-manufacture slow-wave circuits. As a result of performance degradation from random errors, the manufacturing yield, and therefore the cost of manufacturing, is seriously affected. In this paper we present analytical and numerical results on the expected degradation of the small signal gain, and the expected output phase variations, of a TWT when small random, axially varying perturbations are present in the circuit phase velocity. A new scaling law for the ensemble-averaged gain and phase variations is derived from the governing differential equation with randomly varying coefficients that models the beam-wave interaction in a TWT in the presence of small errors [1]. Analytical results compare favorably with results from numerical integrations of the differential equation over a 500 run sample size, for a broad range of design parameters (Fig. 1). This work was supported by AFOSR, L-3, Northrop Grumman, and MIPSE.

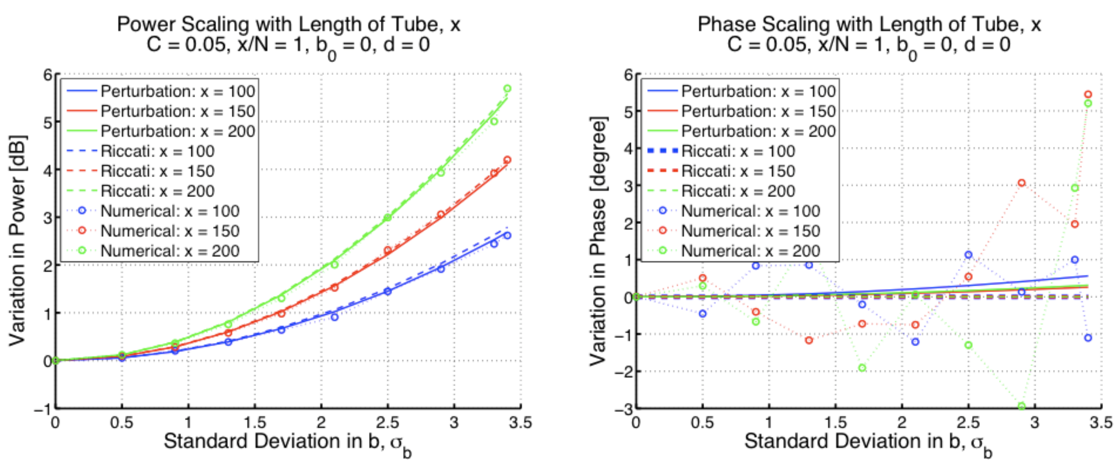

Fig. 1: Variation in output power (left) and phase (right) as a function of the standard deviation of random errors for TWTs of varying lengths (x) as predicted by two different analytical formulations (Perturbation, Riccati) as well as a numerical calculation of the governing equation.

References

[1] P. Pengvanich, D. Chernin, Y. Y. Lau, J. W. Luginsland, and R. M. Gilgenbach, *IEEE Trans. Electron Devices* **55**, 916 (2008); and references therein.

2-06

Novel Heavy Particle Acceleration from High Intensity, Short Pulse Lasers

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Compact particle accelerators have a wide variety of applications including ion therapy, fast ignition inertial confinement fusion, and nuclear physics. In the past decade, new classes of high power laser systems have opened the door to laser based particle acceleration. Laser intensities of up to 10^21 Wcm^-2 are used to set up electric fields in excess of teravolts per meter, which can then be used to accelerate ions in high density plasmas to energies over MeV. These beams have several attractive properties such as low emittance and small source sizes.

At the Center for Ultrafast Optical Science, much work has been done investigating the mechanisms involved in heavy particle acceleration. Since pioneering work on the target normal sheath acceleration (TNSA) mechanism a decade ago [1], recently research at the HERCULES 300 TW laser system has been aimed at investigating new regimes of acceleration that as of yet have only been studied in simulations. These new regimes explore circumstances where the maximum energy and the energy spread of the beam can be controlled, making laser based acceleration competitive with conventional technology.

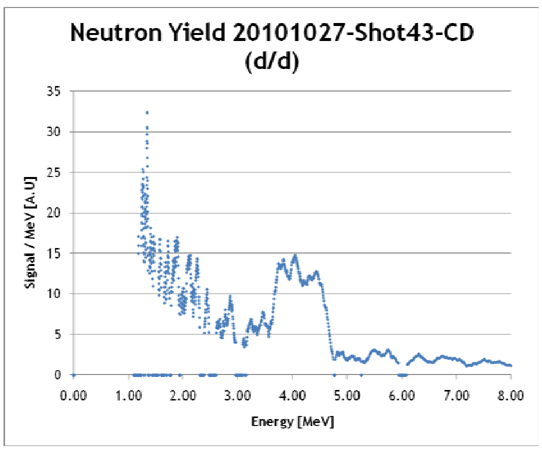

Fig. 1: Time-of-flight measurements of a d-d produced neutron beam generated from a laser produced deuteron beam.

In our recent work, monoenergetic light ion beams have been produced by careful control over the target density. Efficient acceleration of light ions has been shown with circular polarization at thin films, exploring a new regime of laser ion acceleration. In addition, high energy proton and deuteron beams have been used to generate a high flux of collimated neutrons, through a variety of nuclear reactions.

These novel interactions have been studied experimentally and have been supported using a wide array of numerical simulations, including hydrodynamic codes, Vlasov-Fokker-Planck simulations, and particle-in-cell simulations utilizing the Center for Advanced Computing's Nyx Cluster.

References

[1] A. Maksimchuk, et al, Phys. Rev. Lett. **84**, 4108 (2000).

2-07

Effects of Detailed Heavy Species Interactions in DSMC-PIC Simulation of a Simplified Plasma Test Cell

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This study concerns an electric propulsion modeling effort with a focus on stepping back from full-device Hall effect thruster (HET) modeling in order to validate tools which can simulate and predict the fundamental physical processes occurring in HET operation. There is a particular interest in the simulation of anomalous electron transport mechanisms through the use of kinetic methods such as direct simulation Monte Carlo (DSMC) and particle-in-cell (PIC) algorithms. Kinetic methods have the advantage of not limiting electron behavior to fluid assumptions, such as having a Maxwellian distribution, which have been proven to be grossly inaccurate due to such nonequilibrium phenomena as inelastic processes and sheath formation.

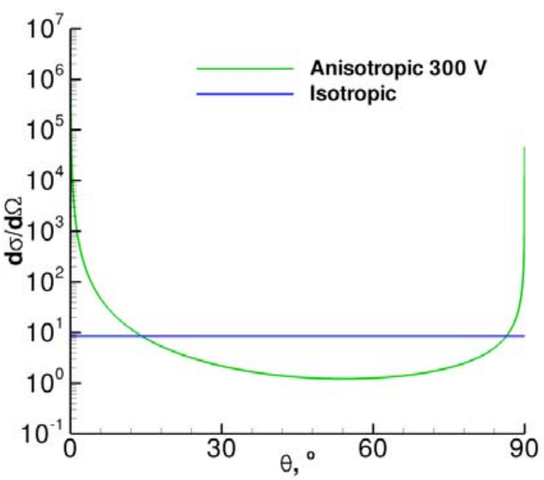

Fig. 1: An example of the difference between an isotropic and anisotropic differential cross-section curve for a heavy species interaction.

However, it is largely understood that anomalous electron transport is a collective effect arising in magnetized, low-temperature devices such as HETs, requiring high fidelity simulation of more than just electron physics. The inelastic processes and transport mechanisms of the heavy species involved in these devices must be understood so that an anomalous transport model can be built incrementally, introducing the complexities of multiple species, device geometry, and magnetic fields. The aim of this computational study is to mirror the developments of an experimental counterpart [1] in which a high-voltage xenon ion beam is accelerated into a controlled test cell for the purpose of observing the physics of momentum- and charge-exchange scattering effects. This study utilizes the kinetic simulation tool MONACO-PIC (MPIC) [2] to compare simulated ion-beam environments to experimental values via a juxtaposition of cross-section and post-collision scattering models utilized in momentum-exchange (MEX) and symmetric charge-exchange (CEX) interactions. Figure 1 displays an example of an isotropic differential cross-section model for post-collision scattering compared to an anisotropic model for xenon. This study will analyze the results of an upgrade from a simple, isotropic scattering model to a differential cross-section-based, anisotropic scattering model which more accurately reflects true physics [3].

References

[1] R. Wirz, L. Chu, M. Patino, H. Mao, and S. Araki. *Well-Characterized Plasma Experiments for Validation of Computational Models.* 32nd International Electric Propulsion Conference, Wiesbaden, Germany, 2011
[2] Y. Choi. *Modeling an Anode Later Hall Thruster and its Plume.* Thesis, University of Michigan, 2008
[3] T. D. Huismann and I. D. Boyd. *Improving Hall-thruster Plume Simulation through Investigation of the Near-field Environment.* 32nd International Electric Propulsion Conference, Wiesbaden, Germany, 2011

2-08

Experimental Investigation of the Evolution of the Magneto-Rayleigh Taylor Instability on Thin Foils

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The magneto-Rayleigh Taylor (MRT) instability is investigated on the 1-MA linear transformer driver (LTD) facility at the University of Michigan using dynamic 400 nm aluminum foil loads. The load geometry drives current through the foil with return plates on either side, causing an MRT unstable interface as the foil plasma accelerates towards the centerline of the system. Expanding foil plasmas are characterized using laser backlit shadowgraphy at various times up to and immediately after peak current of the ~100 ns risetime pulse. A quantitative image analysis algorithm originally developed by Zier [1] and extended for this work is used to map the plasma contours on each interface for spectral analysis.

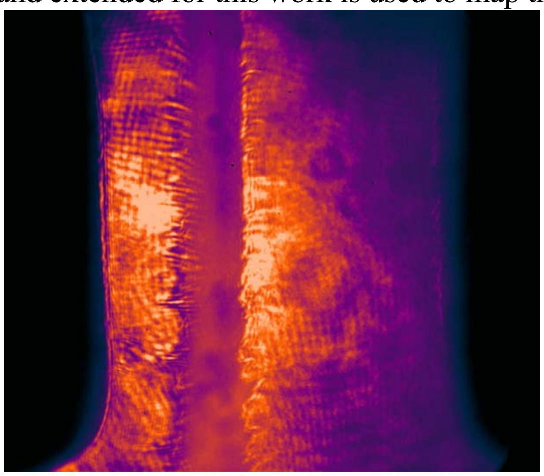

Fig. 1: Laser backlit image from shot 339, contrast enhanced and false color added. Current is 50 kA.

A sample shadowgraph image at 60 ns after start of current is shown in figure 1. The structure on the plasma interface is believed to be composed of a short-wavelength electrothermal instability that forms as the foil vaporizes and a longer wavelength MRT instability that forms in the plasma state. Fourier analysis is employed to examine the time evolution of the component wavelengths of the plasma interface structure. Results from comparing the wavelength spectra before and after complete foil vaporization will be presented.

References

[1] J. Zier, Ph.D. Thesis, University of Michigan, 2011; AAT 3458935

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2-09

An Adaptive Locally Smooth Surface Parameterization for Integral Equations

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Surface integral equation models are valuable in both the analysis of the interaction of plasma with various structures [1], and in plasma shape identification [2]. The ability to model complex surfaces is an important aspect in the accurate analysis of these interactions. This paper proposes a novel and highly flexible surface parameterization designed for use with surface integral equations.

Traditionally surface integral equations start from a simplicial tessellation of the surface of the object under study, called a mesh. The construction of such a surface mesh, for complex geometries, is a highly involved, labor intensive task. Even when such a mesh is constructed, it is highly inflexible and the smallest perturbations to the geometry require that the mesh be reconstructed. In this paper, we propose a resolution to this problem.

It is apparent that the most direct way to model a complex surface is using a "point cloud". Given a cloud of points, changes to the geometry can be locally effected simply by moving a collection of points. The construction of a surface representation from a point cloud is a highly over determined problem and most algorithms fail to construct a "mesh" that can be effectively coupled to an integral equation. Further, given a mesh, a very desirable property is that the mesh be adaptive in size and order. In other words, the mesh should be large and smooth in the smooth areas of the geometry and small and high order in the sharp areas. However, none of the existing meshing algorithms permit these features. This paper presents a resolution to this problem.

In this work, we propose an algorithm to construct a locally smooth surface parameterization starting from a point cloud. We will demonstrate that we can construct locally smooth surface approximations to extremely complex structures that cannot be meshed using standard meshing algorithms. Further, we will demonstrate the ability of the technique to allow for arbitrary merging and splitting of patches to adaptively adjust the "size" of the mesh to the local smoothness of the structure.

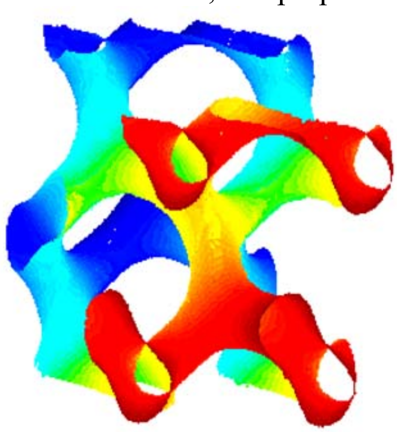

Fig. 1: Locally smooth surface parametrization of a gyroid

We will also provide results that describe the numerical solution of surface integral equations constructed on this novel surface parametrization using a novel basis function framework that we have developed elsewhere [3].

References

[1] P. Merkel, J. Comp. Phys. **66**, 83-89, (1986)

[2] K. Kurihara, Nucl. Fusion **33**, 399-412, (1993).

[3] N. Nair, and B. Shanker, IEEE Trans. Antennas and Prop. **59**, 2280-2293, 2011

2-10

Imaging X-Ray Thomson Scattering Spectroscopy for Characterizing Extreme Matter States

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Radiation heat waves, the process by which radiation may diffusively penetrate matter, are a pervasive feature of many astrophysical phenomena. They are central to the dynamics of stars, from the seeding of stellar nurseries, heat transport out of the cores of stars, to the sometimes-dramatic death in supernova. Understanding this method of radiation transport is of central importance not only to the fields of high-energy density physics and laboratory astrophysics, but also efforts to achieve controlled nuclear fusion.

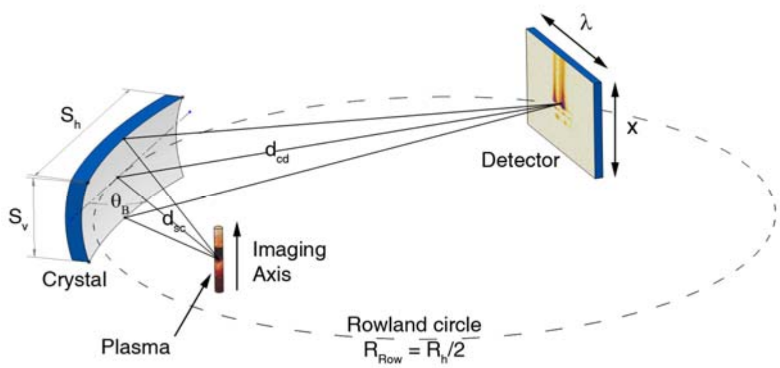

Diagram of the imaging x-ray spectrometer

In many laboratory astrophysics experiments, intense laser irradiation creates novel material conditions with large, one-dimensional gradients in the temperature, density, and ionization state. X-ray Thomson scattering (XRTS) is a powerful technique for measuring these plasma parameters. However, the scattered signal is typically measured with little or no spatial resolution, which limits the ability to diagnose these inhomogeneous plasmas.

We report on an experiment on the Omega laser to diagnose a radiation-driven heat wave driven in a low-density carbon foam[1]. The temperature profile of the heat wave is resolved spatially using a new imaging x-ray Thomson scattering diagnostic. Diffraction of scattered x-rays from a toroidally curved crystal creates high-resolution images that are spatially resolved along a one-dimensional profile in the target while simultaneously spectrally resolving the scattered radiation. The new spectrometer will allow us to extend the technique of XRTS to characterize the spatial structure of a heat wave in a way that has never before been possible.

References

[1] G. Gregori *et al.*, Phys. Rev. Lett. 101, 045003 (2008).

2-11

Investigating the Potential of Electrodynamic Tethers to Enhance Capability of Ultra-small Spacecraft

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The growing success of and interest in nanospacecraft (1–10 kg) over the past decade has generated interest in exploring the potential for even smaller spacecraft, both as stand-alone or as a distributed swarm.[1] Based on advances in integrated circuit and microelectromechanical systems (MEMS) technology, the feasibility of miniaturized spacecraft at the levels of fully monolithic semiconductor integrated circuits (10–100 mg) or hybrid integrated circuits (10–100□g) is being seriously investigated. Effectively, this can be thought of as a small "satellite-on-a-chip", or ChipSat. However, flat ChipSat wafers have an inherent high area-to-mass ratio. This results in a very short orbital life in low Earth orbit (LEO) due to atmospheric drag, ranging from a few days to a few hours. The use of a traditional thruster with propellant and directed flow to compensate for drag and possibly for maneuverability would increase the size, mass, and complexity of ChipSats.

In this paper, we investigate one particular approach that appears to scale to the small size needed and is propellantless. The approach uses a short, semi-rigid electrodynamic tether (EDT) for propulsion while keeping overall ChipSat mass low and thrust-to-atmospheric drag ratio greater than one. The EDT exploits the Lorentz force, using a current in the tether conductor to generate a force in the presence of the perpendicular components of the Earth's magnetic field. The tether circuit is closed by collecting electrons from the Earth's ionosphere at one end and emitting them back to the ionosphere at the other end.

We report on our trade studies to assess the feasibility of using the EDT for ChipSat propulsion.[2] We have analyzed the EDT anode's ability to draw current from the ionosphere and thus generate thrust and compared this to the tether mass and material, electron emitter and collector types, and needed power to determine EDT capability of overcoming atmospheric drag forces. The study lead to the development of a system concept and mission scenario using the simulation tool TeMPEST to estimate tether voltages and currents based on tether configuration and ambient conditions. TeMPEST uses current geomagnetic field models, ionospheric and atmospheric conditions, plasma contactor modeling, and precise orbital calculations. The results revealed that an insulated tether only a few meters long and tens of microns in diameter can provide milligram to gram-level ChipSats with complete drag cancellation and even the ability to change orbit.

We expand upon our previous trade study and explore the feasibility of using an advanced EDT system concept to enhance maneuverability for a range of femtosatellites. We also investigate current collection from the ambient ionosphere. The estimated current-voltage (I–V) characteristic at the anode is compared to that predicted by theory.[3-5]

References

[1] D. Barnhart, T. Vladimirova, and M. Sweeting. J Spacecraft Rockets **44** (2007) p1294.
[2] I. C. Bell. Spacecraft Charging and Technology Conference (2010).
[3] H.M. Mott-Smith and I. Langmuir. Phys. Rev. **28** (1926) p727.
[4] J. Rubinstein and J. Laframboise. Phys. Fluids **25** (1982) p1174.
[5] L. W. Parker and B.L. Murphy. J. Geophys. Res. **72** (1967) p1631.

2-12

Power and Decomposition Studies on an Underwater Dielectric Barrier Discharge Plasma

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The production of non-thermal plasma discharge in non-potable liquid water has shown the capacity to break down and remove contaminates, sterilizing the liquid [1, 2, 3]. The plasma-water interaction creates copious amounts of short-lived radicals, electrons, excited species, ultrasound and UV photons, which react with contaminants in the liquid. All together, these components are "advanced oxidation processes" (AOPs). They have the ability to destroy microbial, bacterial and viral particles and drive the decomposition of toxic organic compounds [4].

Key to the practical implementation of this novel water purification method is an understanding of the ideal physical parameters (i.e., power requirements, modes of operation), the chemical mechanics of plasma-induced decomposition, and toxicological surveys of the processed liquids. Presented here are results of several of these studies on an underwater DBD plasma jet.

References

[1] Andreozzi, R. et al., Advanced Oxidation Processes (AOP) for Water Purification and Recovery. *Catalysis Today* 53 p. 51-59 (1999).
[2] Foster, J. et al., Underwater Operation of a DBD Plasma Jet. *Plasma Sources Sci. Technol.* 19 (2010).
[3] Magureanu, M. et al., Decomposition of Methylene Blue in Water by Corona Discharges. *Plasma Chem and Plasma Proc*. 28 (6) p. 677-688 (2008).
[4] Burts, M. L. et al. Use of Atmospheric Non-thermal Plasma as a Disinfectant for Objects Contaminated with Methicillin-resistant *Staphylococcus Aureus*. *American Journal of Infection Control*. 37 (9), pp 729-733 (2009).

2-13

Electron Current Extraction and Interaction of RF mDBD Arrays

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Micro-dielectric barrier discharges (mDBD's) are developed for atmospheric pressure, non-thermal plasma sources. These micro-plasma devices (10-100 μm) are attractive as planar sources of radicals and charged species. The devices of interest, mDBD arrays, have apertures tens of microns in diameter with spacing of tens to hundreds of microns. The arrays are excited with radio-frequency (RF) waveform and the individually controlled apertures are used for charge extraction to treat or pattern surfaces. When using mDBDs to produce plumes of charged species, there are potential interactions between the mDBD devices. This is particularly the case when auxiliary electrodes are used to extract the charged species.

In this presentation, we will discuss properties of mDBD's arrays sustained in atmospheric pressure N_2 and air using results from a two-dimensional simulation. The devices consist of sandwich structures of dc and rf biased electrodes to shape the plume. The model, nonPDPSIM, solves Poisson's equation and transport equations simultaneously for charge and neutral species and the electron energy conservation equation for electron temperature. A Monte Carlo simulation is used for tracking sheath accelerated electrons. Rate coefficients and transport coefficients for bulk electrons are obtained from local solutions of Boltzmann's equation for the electron energy distribution. Radiation transport is addressed using a Green's function approach.

We find that the adjacency of the mDBDs and the dielectric properties (capacitance and conductivity) of the materials being treated are important to determine how independently the mDBDs operate. Charge extraction and the shape of the plume can also be optimized by choice of gas composition and pressure. Scaling laws will be presented for mDBD arrays as a function of geometry, gas mixture, frequency and phasing of the arrays.

Poster Session III

3-01

Two-dimensional PIC-MCC Simulations of the Electron Multiplication in a Gas Electron Multiplier

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The gas electron multiplier (GEM) consists of a thin polymer foil, metal-coated on each side, and perforated by a high density of holes.[1] With numerous advantages, it has being the subject of many studies in recent years. However, direct or indirect access to the GEM in experiment has many limitations due to the small size and short response time. Numerical simulation has been very useful for investigating the GEM. A unique two-dimensional PIC-MCC simulation, XOOPIC, is applied to simulate the electron multiplication progress in the GEM [2].

The PIC-MCC simulation models the kinetics of species by solving fundamental equations without making any assumption, which can make the simulation rather time consuming. Therefore, the electron multiplication in one single hole is simulated. The reduced GEM structure is presented in Figure 1. In the model, Kapton foil is represented by the dielectric whose thickness is 50 μm with a hole diameter of 70 μm and a pitch of 140 μm. The drift and induct distance are 600 and 200 μm at about 2 and 6 kV/cm, respectively. The voltage difference applied to the foil faces is in the range of 300-700 V in pure Xe at one atmosphere

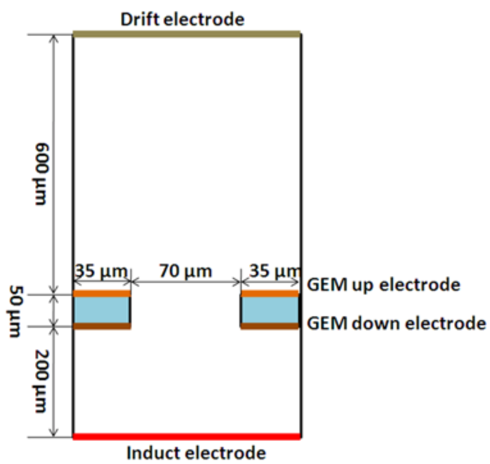

Fig. 1: Schematic view of a GEM cell simulated with XOOPIC.

Electrons emitted into the cell are gradually collected into the holes when drifting towards the induct electrode. Significant multiplication takes place and abundant electrons are produced there. Most avalanching electrons reaches the induct electrode and contribute to the effective gain, less a fraction being collected by the inside-wall of the hole and GEM electrode. In addition, the gain of the GEM increases exponentially with the voltage difference applied to the foil faces, in agreement with previous work. To understand the gain characteristics of a full size GEM, the next step is to study the dependence of the GEM gain on the geometry and the electric field intensity of the drift and induct regions.

References

[1] F. Sauli, Nucl. Instrum. Methods Phys. Res., Sect. A, **386,** 531(1997).
[2] C.K. Birdsall, IEEE T. Plasma Sci. **19**, 65(1991).

3-02

Bremsstrahlung Temperature Scaling in Ultra-Intense Laser-Plasma Interactions

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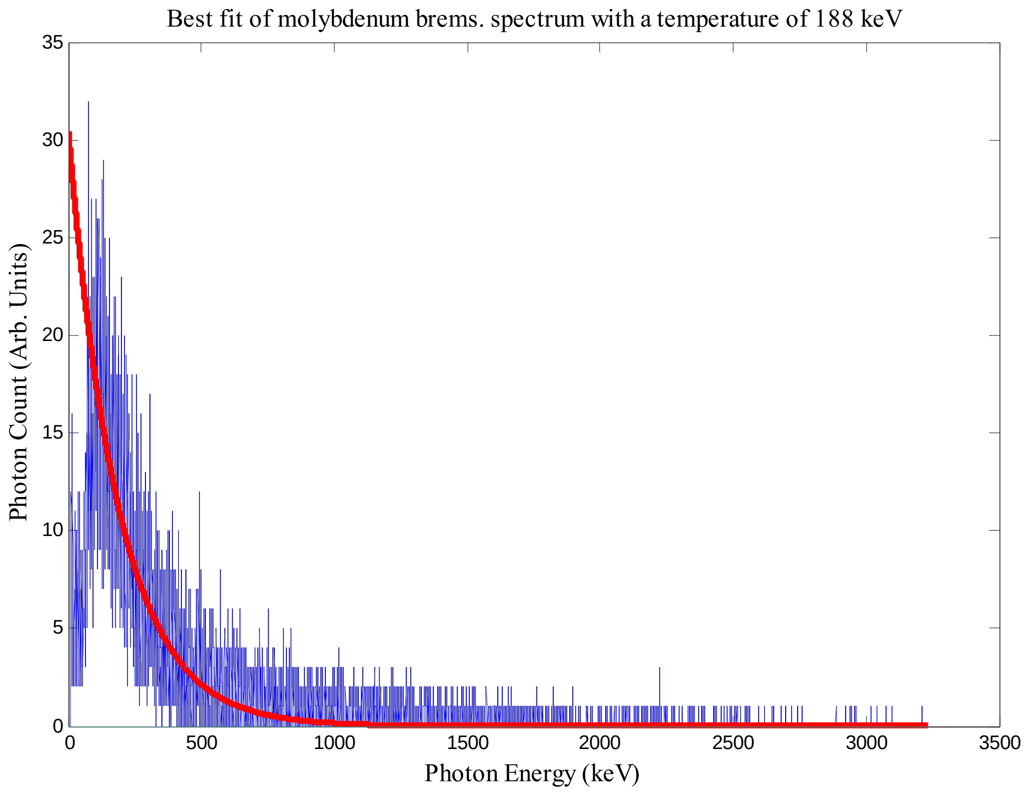
The absorption of laser energy during ultra-intense ($I < 10^{18}$ W/cm^2) laser-plasma interactions results in the production of a hot electron current, which can subsequently generate energetic protons, ions, and photons. The energetic photons are of particular interest in isomer excitation, positron production, and homeland security applications.



Experiments were performed on the high repetition rate (500 Hz) Lambda Cubed laser ($I \approx 5 \cdot 10^{18}$, duration 30 fs) allowing high resolution ($\lambda/\Delta\lambda$ = 300) spectroscopy of X-ray and γ-ray bremsstrahlung photons in the 20 keV to 3 MeV energy range. The effective bremsstrahlung temperature was measured over a range of laser energies, target materials, and detection angles. Additionally, simulations (MCNPX and GEANT4) were used to correlate experimental bremsstrahlung temperatures with hot electron temperatures, which were compared to existing electron temperature scaling laws.

This work was supported by the National Science Foundation (NSF) through the FOCUS Physics Frontier Center PHY-0114336, and by the Department of Homeland Security and NSF through grant EECS-0833499.

3-03

Investigation of Mixed Cell Treatment via the Support Operator Method

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A support operator method (SOM) discretization of the diffusion equation is used to examine treatment of mixed cells. The diffusion equation is used to simulate radiation transport in optically thick system. Multiple fluids or species can be simulated by assigning distinct diffusivities to different regions of the computational domain. A mixed cell occurs when the boundaries of the fluids do not align with the boundary of the mesh cells. The SOM discretizes the diffusion equation into a symmetric and positive-definite matrix system, which allows for more efficient solvers. The SOM is spatially second-order accurate for isotropic, anisotropic, continuous, or discontinuous diffusion coefficients. The use of anisotropic diffusion tensor is explored as a means of simulating the material interface in a mixed cell by rotating a diagonal diffusion tensor. The results are compared with more typical mixed cell treatments, such as global or local grid refinement, or setting the diffusivity equal to that of the fluid occupying the largest volume of the cell. This work is funded by the NNSA-ASC Predictive Sciences Academic Alliances Program via grant DEFC52- 08NA28616.

3-04

Electron Generation from a High Repetition Lambda Cubed Laser Wakefield

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High intensity ultrafast laser pulses can be used to drive nonlinear plasma waves known as wakefield through an underdense plasma, which is capable of producing high quality relativistic electron beams [1]. In this section, we present the preliminary results from the experiments performed to investigate electron generation using the lambda-cubed laser at the University of Michigan - a table-top high-power laser system operating at 500 Hz repetition rate. The high repetition rate will allow statistical studies of laser propagation and electron acceleration, which are not accessible with typical sub-0.1 Hz repetition rate systems

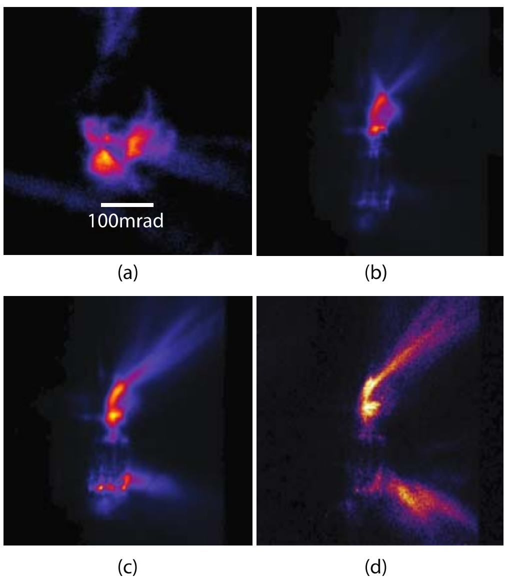

Fig. 1. Electron beam profile data from (a) capillary ID=75µm, 100 laser shots; (b) capillary ID=100µm, 100 laser shots; (c) same condition as (b) at a higher density; (d) a single laser pulse under the same condition as (c) image contrast is increased. The gas used in this data is He with 5% N_2 impurity

In the experiments, the 10mJ laser pulses are focused to an optimized spot size of about 2.4µm by an f/2 off-axis parabolic mirror after being reflected off a deformable mirror. The gas target nozzle design is important to create desired plasma density profile suitable for laser plasma interaction. To match the scale of our experiment, the plasma is generated by carefully aligning the laser focus near the tip of a fused silica capillary tube, where the strong laser pulse ionizes the gas molecules that continuously flow into the vacuum chamber. The inner diameter of the tubing has the sizes of 50µm, 75µm or 100µm. The gas jet experiences free expansion into vacuum. Interferometric characterization was performed independently using argon at much higher backing pressures. The capillary tube is manipulated on a motorized XYZ controller at micrometer accuracy. An imaging lens with a CCD camera and a PIN silicon X-ray diode are used to aid the alignment of the target for maximum signal yield. The generated electrons are recorded on Fuji image plates (IP) placed at 10cm after the target. Moderately collimated electron beams were observed using argon or helium mixed argon/nitrogen. The typical electron beam profile data is shown in Fig. 1, where the estimated charge is on the order of femtocoulomb per shot based on IP calibration [2]. We find that the electron beam profile is reproducible from shot to shot but can be varied as changes in gas density profile or laser focusing condition occur. Computational simulations were performed using 3D particle-in-cell code OSIRIS to investigate the physical processes that are yet unclear from experiments until further diagnostics are implemented to measure the electron spectra and plasma density profile.

References

[1] E. Esarey et al., Rev. Mod. Phys. 81, 1229 (2009).
[2] K. Tanaka et al., Rev. Sci. Instrum. 76(1), 013507 (2005).

3-05

Analysis of Bulk and Thin Film Contact Resistance with Dissimilar Materials

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Contact resistance is important to integrated circuits, thin film devices, carbon nanotube based cathodes, interconnects, field emitters, wire-array z-pinches, metal-insulator-vacuum junctions, and high power microwave sources, etc. In other applications, the electrical contacts are formed by thin film structures of a few microns thickness, such as in microelectromechanical system (MEMS) relays and microconnector systems. This paper summarizes the recent modeling efforts at the University of Michigan, addressing the effect of dissimilar materials and of finite dimensions on the contact resistance of both bulk contacts and thin film contacts. In paricular, we vastly extend Holm's a-spot theory of bulk contacts to higher dimensions, including dissimilar materials [1]. The Cartesian and cylindrical geometries are analyzed. Accurate analytical scaling laws are constructed for the contact resistance over a large range of aspect ratios and resistivity ratios. These were validated against known limiting cases and spot-checks with experiments and numerical simulations. New models of thin film contact resistance are developed [2], also including the effects of dissimilar materials.

Figure 1a shows the Cartesian (cylindrical) geometry of thin film contact, where the current flows inside the base thin film with width (thickness) h and electrical resistivity ρ_2, converging towards the center of the joint region, and feeds into the top channel with half-width (radius) a and electrical resistivity ρ_1. Scaling laws [2] for the contact resistance has been constructed for arbitrary values of a, h, b, ρ_1, and ρ_2, for both Cartesian and cylindrical current channels. Figure 1b shows the normalized contact resistance for the cylindrical geometry of Fig. 1a. All known limiting cases are recovered from this scaling law. The scaling laws are also spot checked against MAXWELL 3D simulation.

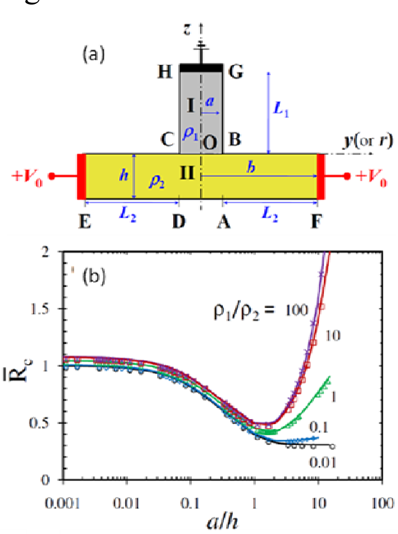

Fig. 1. (a) Thin film structures in either Cartesian or cylindrical geometries. (b) The normalized contact resistance for cylindrical thin film structures in (a), as a function of aspect ratio a/h, at various resistivity ratio $_1/\ _2$; symbols for the exact theory, solid lines for the constructed scaling laws [2].

References

[1] Y. Y. Lau and W. Tang, *J. Appl. Phys.* **105**, 124902 (2009); M. R. Gomez et al., *Appl. Phys. Lett.* **95**, 072103 (2009); P. Zhang et al., *J. Appl. Phys.* **108**, 044914 (2010).

[2] P. Zhang et al., *Appl. Phys. Lett.* **97**, 204103 (2010); *J. Appl. Phys.* **109**, 124910 (2011); Proc. 57th IEEE Holm Conf. on Electrical Contacts (2011).

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3-06

Properties of Boron Doped Diamond Grown by Plasma Enhanced Chemical Vapor Deposition

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Diamond has the potential to be an exceptional semiconductor material, due to superlative properties like high breakdown voltage and wide bandgap, which would make it particularly well suited to high-temperature and high-power devices. Boron doped *p*-type diamond would be particularly well suited to electronic device applications such as high power Schottky-barrier diodes. Realizing useful electronic devices requires the controlled deposition of high quality diamond with controlled dopant levels, and the fabrication of high quality Schottky and Ohmic contacts able to operate over a wide range of conditions.

Homoepitaxial doped diamond films are grown by microwave plasma chemical vapor deposition (MPCVD) on high pressure, high temperature (HPHT) substrates with gas chemistries containing hydrogen, methane, diborane and carbon dioxide. Low reactor pressures of 75-80 torr, higher pressures of 160 torr, and gas chemistries with 0-3.5% carbon dioxide in the reactor feedgas are investigated in order to determine the effect of these parameters on the incorporated boron concentration in grown films. In our work on characterization of boron-doped single crystal diamond (SCD), we have used temperature-dependent conductivity measurements to fit the activation energy, and investigated feedgas chemistries containing carbon dioxide for the control of doping to achieve boron incorporation levels less than 10^{17} cm^{-3} [1,2]. We use and compare infrared absorption techniques and SIMS measurements for the determination of incorporated boron, and have shown that infrared absorption spectroscopy is sensitive to surface defects on grown samples [1].

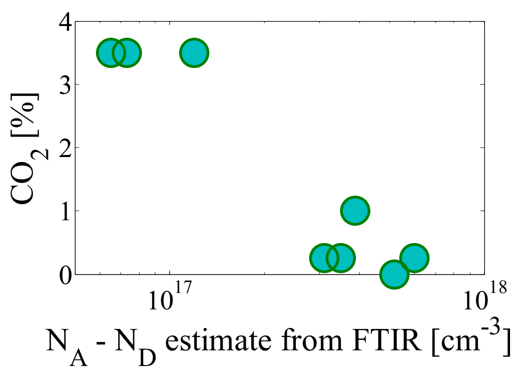

Fig. 1: The addition of CO_2 to the plasma gas chemistry reduces the electrically active boron concentration, as determined by Fourier Transformed Infrared (FTIR) spectroscopy.

Feedgas mixtures with 3.5% CO_2 showed a noticeable drop in electrically active boron concentration as shown in Fig. 1. Reactor pressure and concentrations of 1% or less CO_2 in the feedgas are not seen to have a significant effect on the boron concentration. Lower reactor pressures and the presence of CO_2 are shown to lower the growth rate.

References

[1] S.N. Demlow, M. Becker and T. Grotjohn, Diam. and Rel. Mater. *Submitted*

[2] S.N. Demlow, T.A. Grotjohn, T. Hogan, M. Becker and J. Asmussen, MRS Proceedings 1282 (2011) mrsf10-1282-a05-15

3-07

Compressible Turbulence and Interfacial Instabilities

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Type Ia supernovae are thought to be the standard candles of the Universe. Numerical simulations have shown that the fusion front in this phenomenon produces a series of expanding bubbles that exhibit Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities and transition to turbulence. These also occur in Inertial Confinement Fusion (ICF), where uneven compression of the target surface leads to premature mixing, thereby reducing the heating efficacy. Thus, an understanding of RT and RM is important in explaining carbon detonation in Type Ia supernovae as well as preventing premature mixing in ICF.

We investigate the RT instability that occurs between two fluids when the pressure and density gradients are oppositely directed. A special case of this, when the interface is impulsively accelerated by a shock, i.e., the RM instability, is also considered. To assess the implications of compressibility on the late time turbulent mixing, we have also studied Isotropic compressible turbulence [1].

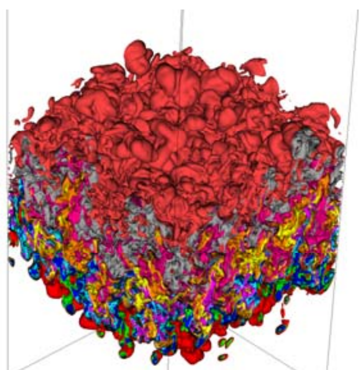

Fig. 1: Iso contours of Mass fraction of the heavier fluid (Xenon) at late time.

Our numerical methods for compressible turbulence with shocks are based on hybridizing the shock-capturing ability of Weighted Essentially Non Oscillatory schemes (WENO) with explicit central schemes that have excellent bandwidth resolution properties [2]. A sensor based on local smoothness is used to switch between the two sub-schemes. Our numerical tests indicate that the current scheme is well suited for the complexity of compressible turbulent flows. Our codes are implemented both in the finite volume and finite difference framework and are parallelized using MPI, with HDF5 parallel input/output capabilities.

Fig. 1 shows the mixing region in a three-dimensional simulation of a compressible RT instability between Xenon and Neon, which are initially in hydrostatic equilibrium at constant temperature. The mass fraction is initially diffuse and the interface is initialized with random perturbations with most of the energy in mode 14. This simulation reveals that, if given enough room, a shock can form at later times in the upper fluid due to acoustic waves generated initially by the mixing layer merging [3].

We have also investigated the effect of numerical dissipation on the simulation of the Richtmyer-Meshkov instability with a single mode perturbation of the interface between two fluids. The initial conditions are set up based on experiments and the results are validated.

The results from these simulations as well as a brief description of the numerical methods used will be presented.

References

[1] S. Lee, S.K. Lele and P. Moin, *Phys. Fluids* **3** (1991), pp. 657–664

[2] F. Ducros et al, *J. Comput. Phys.* **161** (2000), pp. 114–139.

[3] B.J Olson and A.W Cook, *Phys. Fluids*. **19**, 128108 (2007).

3-08

Same-Shot X-Ray Thomson Scattering and Streaked Imaging of Xenon Radiative Shock Experiments

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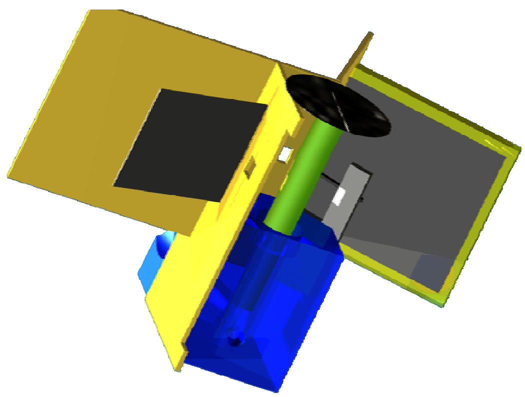
(b) L-399, Lawrence Livermore National Laboratory, Livermore CA

We review the experimental design and results from recent experiments at the Omega Laser facility. In this experiment ten Omega beams deliver a total of 3.8 kJ of laser energy to a 20 micron beryllium disk that caps a xenon-filled shock tube. The ablatively-accelerated Be acts as a piston, driving a fast shock into the gas. Strong radiative energy flux influences the density and temperature profiles in the system and leads to a radiatively-collapsed layer of dense Xe behind the shock front.

These experiments seek to measure the plasma parameters of the xenon radiative shock system with high accuracy, employing streaked x-ray radiography and x-ray Thomson scattering diagnostics on each shot. We detail how this diagnostic combination allows for precise interrogation of the different regions of the shock, including the radiation-heated upstream precursor, the radiatively collapsed cooling layer, and the downstream material. Spatially and temporally correlated data from the x-ray streak camera and gated spectrometer is shown, and plans for future iterations of radiative shock experiments are also discussed.



Fielding multiple simultaneous x-ray diagnostics requires an intricate target with attention paid to shielding and precise positioning of components.

This work is funded by the PSAAP in NNSA-ASC via grant DEFC52- 08NA28616, by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-FG52-09NA29548, and by the NLUF Program, grant number DE-NA0000850.

3-09

Self-Consistent Simulation of Microwave PACVD Reactors for Diamond Growth

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Microwave Plasma-Assisted Chemical Vapor Deposition (PACVD) reactors have been utilized for the growth of thin diamond films for many years. Recent experiments at higher pressures have reported faster diamond growth rates and higher quality samples.[1] This transition necessitates the development of numerical models that can accurately capture the underlying physics in this new pressure regime. Such a model will provide insight into the governing physics contained in the system, as well as aid in the development and design of new reactors. To begin this process, a flexible-geometry, multi-physics, self-consistent simulation for hydrogen plasmas in the microwave PACVD reactor is being developed.

In order to capture both the microwave characteristics and plasma formation during operation, there are two major components of this model: 1) a finite difference electromagnetic solver, and 2) a fluid-based plasma simulation. Since the incident microwave energy is primarily introduced at a single frequency, the electromagnetic model consists of a finite-difference frequency domain solver. This is coupled to the plasma solver through the absorbed power distribution.

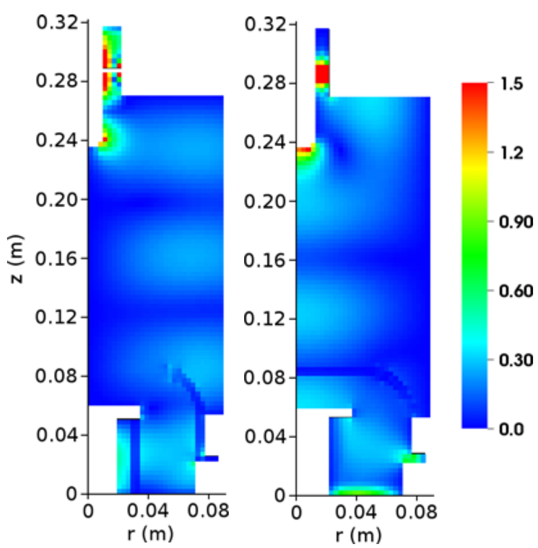

Fig. 1: Normailzed r- and z-components of electric field solution during plasma ignition.

Within the plasma model, nine different hydrogen-based species, along with three temperatures, are tracked while ensuring mass and energy conservation.[2] Two-body chemical reactions, diffusion coefficients, and energy exchange rates are also computed. An iterative technique is used to converge to a stable solution. The electrical conductivity is then calculated and passed to the electromagnetics model. This process is repeated until a stable solution across both models is achieved to the desired tolerance.

Numerical results for various known reactor geometries, as well as pressures and powers will be presented at the time of the conference.

References

[1] K. Hemawan, T.A. Grotjohn, D.K. Reinhard, and J. Asmussen, Diam. Rel. Mater. **19**, 1446-1452 (2010).
[2] K. Hassouni, T.A. Grotjohn, A. Gicquel, J. Appl. Phys. **86**, 134 (1999).

3-10

Analysis of Computational Work in Comparison with Experimental Results for an Atmospheric Pressure Microwave Plasma

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An atmospheric pressure microwave plasma source was developed to study the conversion of CO_2 to CO as a method for carbon emission control. The device consists of surface-wave launcher called the *Surfaguide*, which provides a maximum intensity electric field at the location of interaction between the microwaves and the discharge tube. This creates a quasi-thermal plasma with gas temperature reaching around 5000K. Such high gas temperature requires a cooling mechanism for the 1-cm diameter quartz discharge tube. Thus an oil-cooling jacket was designed to surround the discharge tube, operating with a recirculating chiller.

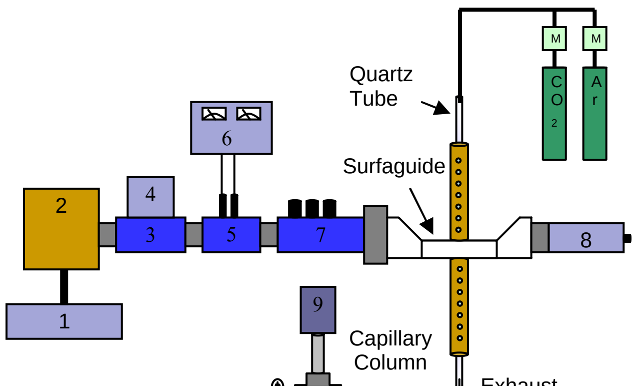

Fig. 1: Microwave plasma setup. 1) 2-kW power supply, 2) Magnetron head, 3) Three-port circulator, 4) Dummy load, 5) Directional coupler, 6) Power meters, 7) Three-stub tuner, 8) Sliding short circuit, 9) RGA, 10) Turbo pump.

Experimental data was obtained using a Residual Gas Analyzer (RGA) to determine the gas species present in the discharge. Quantatative analysis of the data determined the energy efficiency and the conversion efficiency of the plasma chemical reaction

$$CO_2 \rightarrow CO + 1/2O_2,\ \Delta H = 2.9\ eV.$$

The experimental results are compared to computational results from a zero-dimentional, global kinetic model called Global_kin. The model can take into account over 100 different reactions between electrons, neutrals, and ions to determine species densities in the simulated plasma for a given power level, pressure, and initial species mole fractions.

In addition to plasma energy efficiency analysis, efforts have been made to improve efficiency of the entire setup by eliminating the need for a discharge tube cooling system. Gas flow modeling simulations using Fluent were performed to aid in the design of a vortex flow gas input system. In this design, an outer layer of gas creates a vortext flow around the circumference of the inside of a 3.8-cm diameter tube. Axial gas flow is injected in the top and is ionized by the plasma. The vortex gas flow provides an insulating layer between the plasma and the quartz tube, which prevents melting and removes the need for a chiller.

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Control Etch Rate of SiO_2 in $Ar/CF_4/O_2$ Capacitively Coupled Plasmas Using Pulsed Power with Constant Power and Constant Voltage of the Substrate*

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Feature scale etch or deposition properties in plasma processing of microelectronic devices are determined by the energies and fluxes of radicals and ions to the wafer. These fluxes are ultimately controlled by controlling and customizing the electron energy distribution function $f(\varepsilon)$ which determines the dissociation patterns of feedstock gases. One way to customize $f(\varepsilon)$ in dual frequency capacitively coupled plasmas (CCPs) is using pulse power for either or both of the high frequency or low frequency. Pulsed power in CCPs is attractive for controlling $f(\varepsilon)$ and plasma properties as it provides a means for producing combinations of fluxes (e.g., magnitude, identity and energy) not otherwise attainable using continuous wave excitation. Also the ion energy distribution, $f_I(\varepsilon)$ has a crucial role in etching, which is determined by the relationship between applied power and sheath potential. The self bias on the substrate electrode has an effect on the ion energy in different ways, whether it is operated in constant power or constant voltage scheme. In these systems, not only do the choices of duty cycle and pulse repetition frequency (PRF) have an important role in determining the cycled average value of $f(\varepsilon)$ and $f_I(\varepsilon)$, but also the applied scheme on the substrate electrode has a crucial role in determining $f_I(\varepsilon)$, whether it has constant power or constant voltage scheme. To demonstrate the ability to control etch rate through control of $f(\varepsilon)$ and $f_I(\varepsilon)$ using pulsed plasmas, simulations were performed separately in two regions – on the equipment scale using the Hybrid Plasma Equipment Model (HPEM) and on the feature scale using the Monte Carlo Feature Profile Model (MCFPM). The fluxes of radicals and ions to the wafer from the HPEM are transferred to the MCFPM to calculate the etch properties. Plasma properties, $f(\varepsilon)$ and $f_I(\varepsilon)$, and ratios of fluxes to the wafer for an $Ar/CF_4/O_2$ gas mixture in a 2-frequency CCP will be discussed. The tuning of etch rates of SiO_2 resulting from these fluxes will then be summarized.

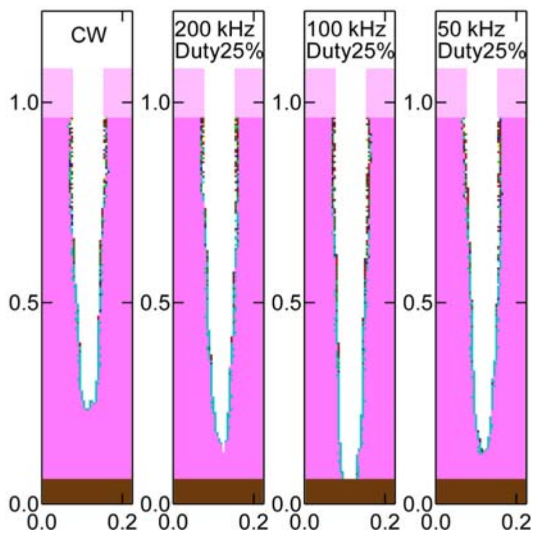

Fig. 1: The etch profile with different pulse repetition frequencies (PRFs) at a given etch time (300 sec). The etch rate and profile are controllable by PRF.

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3-12

Addressing Issues in Probing the Magnetic Cusp Region

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There are several inherent difficulties in making spatially resolved electrostatic probe measurements of plasma properties within a current collecting magnetic cusp. It is difficult to insert a physical probe into the region without shadowing current flow to the anode as a result of the physical obstruction of field lines by the probe body. Current flow to the probe collecting surface can also be shadowed by the probe body blocking flux lines that curve away from the probe surface as a consequence of the physical magnetic field distribution in the region. Shadowing can therefore significantly reduce collected current at the probe, the anode, or both. The problem is complicated by the presence of the plasma sheath and the large magnetic field at the anode surface. Since the sheath potential varies spatially, it is not possible to simply set the voltage on a collecting probe and measure electron density when the potential is changing as a function of probe position. Unless the probe is biased at the local plasma potential at each point, the probe sheath will interfere with the local plasma conditions.

A solution to these issues is proposed in the form of a joint emissive/collecting probe that will negate the shadowing issue as well. The probe will measure plasma potential and then interrogate the cusp region by actively biasing the probe in collection mode at the plasma potential. At the plasma potential, the maximum current flowing through that point is collected provided shadowing affects are accounted for.

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1D hybrid-Vlasov Simulation for Hall Thrusters

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The partially magnetized plasma in a Hall thruster is known to be in a nonequilibrium state due to the operation mechanism and its complexity. For example, high-energy electrons collide with the channel wall and reflect with lower energy so that the velocity distribution function (VDF) of electrons is not isotropic nor Maxwellian. The Vlasov equation, which discretizes the physical space and velocity space, describes time evolution of the VDF of a plasma component such as ions and electrons.

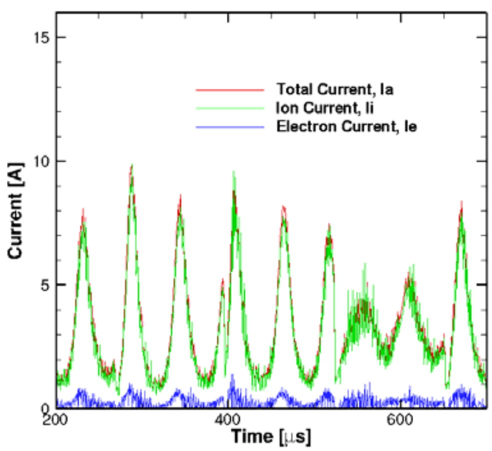

Fig. 1: Discharge current oscillation of the 1D hybrid-Vlasov simulation

We developed a 1D hybrid-Vlasov solver that employs a fully kinetic 1D1V Vlasov description for ions and a fluid model for electrons. The advantage of using a Vlasov solver instead of a particle model is that the VDF can be obtained in a more concise way and the numerical noise, due to the use of super-particles, is greatly reduced. A new bounded upwind scheme [1] for a fully kinetic Vlasov solver was developed in order to avoid unphysical numerical oscillations. In cells where the solution obtained using the 2nd-order corner-transport-upwind (CTU) scheme is outside the physical boundary such as positive VDF, the scheme is switched to the first-order upwind scheme. The rest of the cells retain the original 2nd-order solution. A fluid model [2] for electrons is based on a quasi-neutral assumption where electron number density is equal to ion number density. The momentum and energy equations are solved in order to obtain electrical field and electron temperature.

Figure 1 illustrates discharge current oscillations computed for the SPT-100, which is a typical Hall thruster. A high-frequency oscillation, which is often called the breathing mode, can be seen from the result. The 1D unsteady hybrid-Vlasov simulation showed excellent agreement with experimental results [3] including the breathing mode frequency of 20 kHz.

References
[1] M. Hermann et al., AIAA Journal **44** (12), 2879 (2006).
[2] J. P. Boeuf and L. Garrigues, J. Appl. Phys. **84** (7), 3541 (1998).
[3] I.G. Mikellides et al., AIAA-2001-3505 (2001).