Michigan Institute for Plasma Science and Engineering (MIPSE)

University of Michigan
Michigan State University
Michigan Technological University

7th ANNUAL
GRADUATE STUDENT SYMPOSIUM

October 5, 2016

2:15 – 7:20 pm

1005 EECS

North Campus, University of Michigan

1301 Beal Avenue

Ann Arbor, MI 48109-2122

Schedule

2:15 – 3:10	**Registration, poster set-up**	EECS atrium
3:10 – 3:30	**Refreshments** (box lunch + coffee, tea)	1005 EECS
3:30 – 3:40	**Prof. Mark J. Kushner**, **Director of MIPSE** **Opening remarks**	1005 EECS
3:40 – 4:40	**Special MIPSE Seminar:** **Prof. Luís Silva** Instituto Superior Técnico, Lisbon, Portugal ***In Silico Plasmas under Extreme Conditions:*** ***From Particle Accelerators to Pair Plasmas in Pulsars***	1005 EECS
4:45 – 5:30	**Poster session I**	EECS atrium
5:30 – 6:15	**Poster session II**	EECS atrium
6:15 – 7:00	**Poster session III**	EECS atrium
7:00 – 7:15	**Poster removal**	EECS atrium
7:15 – 7:20	***Best Presentation Award* ceremony**	EECS atrium

Prof. Luís O. Silva

Instituto Superior Técnico
Lisboa, Portugal

In Silico Plasmas under Extreme Conditions: from Particle Accelerators to Pair Plasmas in Pulsars

The advent of ultra-intense lasers and particle beams is opening new frontiers in physics by triggering the exploration of scenarios with unprecedented extreme conditions dominated by relativistic effects. In some conditions, even QED effects play an importance role, with the production of hard photons and electron-positron pairs. These scenarios are highly nonlinear and can only be fully captured via self-consistent ab initio massively parallel kinetic simulations. I will review some of the most important advances and the open challenges in the field, illustrating how large scale numerical simulations are helping to capture in silico these extreme laboratory and astrophysical environments.

About the Speaker: Luís O. Silva is Professor of Physics at Instituto Superior Técnico, Lisbon, Portugal, where he leads the Group for Lasers and Plasmas. He obtained his MSc 1992, PhD 1997 and Habilitation 2005 from IST. He was a post-doctoral researcher at UCLA from 1997 to 2001. Since 2013, he is also the President of the Scientific Council of IST. His research focuses in the interaction of intense beams of particles and lasers with plasmas, from fundamentals and towards applications for secondary sources for biology and medicine. He was awarded an Advanced Grant from the European Research Council in 2010 and 2015, one of the few scientists in Europe with two ERC Advanced grants. He was awarded the 2011 Scientific Prize of the Technical University of Lisbon, the distinction Young Scientist 2009 at the Summer Davos of the World Economic Forum, the IBM Scientific Prize 2003, the 2001 Abdus Salam ICTP Medal for Excellence in Nonlinear Plasma Physics by a Young Researcher, and the Gulbenkian Prize for Young Researchers in 1994. He was elected Fellow of the American Physical Society and to the Global Young Academy in 2009.

Poster Session I

1-01 **Scott Rice,** Michigan State University
Additional Survey of Multipactor Trajectory Migration via Higher-Order Mode Perturbations

1-02 **Timothy Collard,** University of Michigan
Initial Plume Characterization of the CubeSat Ambipolar Thruster

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

1-04 **Gautham Dharuman,** Michigan State University
Atomic Bound States and Scattering in Strongly Coupled Plasmas Using Effective Momentum-dependent Potentials

1-05 **Yao Kovach,** University of Michigan
Optical Emission Spectroscopy Investigation of an Atmospheric Pressure Plasma Glow that is Associated with Self-organization Pattern on Liquid Surface

1-06 **Steven Lanham,** University of Michigan
Inductive and Capacitive Power Distribution and Impact on Plasma Properties in Inductively Coupled Plasma Reactors

1-07 **Rajib Mandal,** Michigan State University
Gas-Phase Synthesis of Gallium Nitride (GaN) Nanocrystals using Non-Thermal Plasma

1-08 **Kurt Terhune,** Michigan Technological University
Ionic Liquid Ferrofluid Electrospray

1-09 **Amina Hussein,** University of Michigan
The Role of Hot Electrons in the Creation of Hollow Atoms by Relativistic Laser Plasma Interaction

1-10 **Grant Miars,** University of Michigan
Ion Emission Energetics from a Charged Hollow Cathode Plasma Contactor System

1-11 **Amanda Lietz,** University of Michigan
Electrode Configurations in Atmospheric Pressure Plasma Jets

1-12 **Astrid Raisanen,** University of Michigan
Boundary Conditions in a Two-dimensional, Axisymmetric, Direct Kinetic Hall Thruster Simulation

1-13 **Rachel Young,** University of Michigan
Using the OMEGA Laser to Study Accretion Shocks on Forming Stars

Poster Session II

2-01 **Amanda Charris,** Michigan State University
The Influence of the Substrate Holder Depth on the Surface Morphology and Crystal Shape of Single Crystal Diamonds Grown via MPACVD

2-02 **Abigail Azari,** University of Michigan
Investigation of the Evolution of Plasma Injection Events within Saturn's Magnetosphere

2-03 **Sarah Cusson,** University of Michigan
Investigation of Channel Interactions in a Nested Hall Thruster

2-04 **Alborz Izadi,** Michigan State University
Gas-phase Nanoparticle methods for Processing Silicon Nanorod Formation

2-05 **Kenneth Engeling,** University of Michigan
Time-Resolved Imaging of Micro-Plasmas as a Function of Dielectric Media

2-06 **Juliusz Kruszelnicki,** University of Michigan
Effects of Pulse-to-pulse Residual Species on Discharges in Repetitively Pulsed Discharges Through Packed Bed Reactors

2-07 **Omar Leon,** University of Michigan
Determining the Quasi-neutral Plasma Plume Region in the Presence of a Biased Cathode

2-08 **Kevin Ma,** University of Michigan
Numerical Modeling of LLNL's Au-Sphere Experiments on the OMEGA Laser

2-09 **Guy Parsey,** Michigan State University
Kinetic Global Modeling of Rare Gas Lasers

2-10 **Janis Lai,** University of Michigan
Schlieren High Speed Imaging of Fluid Flow in Liquid Induced by Plasma-driven Interfacial Forces

2-11 **Chenhui Qu,** University of Michigan
Customizing Arrays of Microplasmas for Controlling Properties of Electromagnetic Waves

2-12 **Robert Vandervort,** University of Michigan
Experimental Design to Understand the Interaction of Stellar Radiation with Molecular Clouds

2-13 **Paul Campbell,** University of Michigan
Relativistic Magnetic Reconnection in High-intensity Laser-plasma Interactions

Poster Session III

3-01 **Ethan Dale,** University of Michigan
Sheath Capacitance Effects in High-speed Langmuir Probes

3-02 **Gautham Dharuman,** Michigan State University
Generalized Mesh-based Ewald Decomposition for Molecular Dynamics Simulation of Correlated Plasmas with Screened Coulomb Interactions

3-03 **Foivos Antoulinakis,** University of Michigan
Effects of Temperature Dependence of Electrical and Thermal Conductivities on the Heating of a One Dimensional Conductor

3-04 **Keegan Behm,** University of Michigan
Production of 100 MeV Gamma Rays Through Inverse Compton Scattering on a Laser Wakefield Accelerator

3-05 **Janez Krek,** Michigan State University
KGMf – Model Class and Boltzmann Equation Solver

3-06 **Yao Kovach,** University of Michigan
An Investigation of the Role of Near-anode Plasma Conditions on Anode Spot Self-organization in Atmospheric Pressure DC Glows

3-07 **Joseph Levesque,** University of Michigan
Exploring Astrophysically Relevant Bow Shocks Using MIFEDS and the OMEGA Laser

3-08 **Thomas Batson,** University of Michigan
High Energy Electron Acceleration from Underdense Plasmas with the OMEGA EP Laser

3-09 **Ahmet Mazacioglu,** University of Michigan
Advanced Ignition Technologies for Heavy-Duty Natural-Gas Engines

3-10 **Selman Mujovic,** University of Michigan
High Throughput Plasma Water Reactor

3-11 **Shuo Huang,** University of Michigan
Etching of High Aspect Ratio Contacts in SiO_2 by Pulsed Capacitively Coupled Plasmas Sustained in $Ar/C_4F_8/O_2$ Mixtures

3-12 **Willow Wan,** University of Michigan
Vortex Merger in a Supersonic, Dual-mode Kelvin-Helmholtz Instability Experiment

Abstracts
Poster Session I

Additional Survey of Multipactor Trajectory Migration via Higher-Order Mode Perturbations*

Scott A. Rice and John Verboncoeur

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

Multipactor [1][2] is a resonant phenomenon in which an electromagnetic field causes a free electron to impact a surface, resulting in the surface emitting one or more secondary electrons. If the surface geometry and electromagnetic fields are appropriately arranged, the secondary electrons can then be accelerated and again impact a surface in the bounding geometry. If the net number of secondary electrons participating in multipactor is non-decreasing, then the process can repeat indefinitely. This phenomenon is of considerable practical interest in the design and operation of radio frequency (RF) resonant structures, windows, and supporting structures.

The ability to control the specific impact points of multipacting electrons within a structure may be of interest to RF system operators. This capability could be employed for such tasks as cleaning a given location in a structure to reduce further susceptibility to multipactor, or for directing multipacting electrons to a specific location in the geometry which is more or less susceptible to sustaining multipactor, depending on the desired objective.

In work presented earlier this year [3], we provided initial results of how multipactor impact points change when a 3rd harmonic perturbative higher-order mode is present, in addition to the fundamental mode which is primarily driving the multipactor. In this poster, we present additional simulated data for 2nd and 4th harmonic perturbative higher-order modes. Simulated results are shown for a parallel-plate geometry, and the results are expected to be generalizable to coaxial and more complicated geometries.

* This work supported by an MSU Foundation Strategic Partnership Grant on Accelerator Technology

References

[1] Vaughan, “Multipactor”, IEEE Transactions on Electron Devices, Vol. 35, No. 7, July 1988, pp. 1172-1180
[2] Padamsee et. al, RF Superconductivity for Accelerators, Chapter 10: Multipacting, pp. 182-197
[3] Rice and Verboncoeur, "Migration of Multipactor Trajectories Via Higher-Order Mode Perturbation", 43rd IEEE International Conference on Plasma Science (ICOPS 2015), Calgary, Alberta, Canada, June 19-23, 2016

Initial Plume Characterization of the CubeSat Ambipolar Thruster*

Timothy A. Collard, and J. P. Sheehan

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

Due to standardization, modularization, and shared launch costs the CubeSat architecture, based on multiples or fractions of a cube with 10 cm sides (one 10 cm cube is 1U), has reduced mission costs and accelerated spacecraft development cycles. These advantages have made CubeSats attractive options to commercial and scientific groups interested in a wide range of missions types, from imaging to satellite health monitoring to space weather [1]. However, current propulsion technology provides ΔV capabilities of < 300 m/s, allowing for limited on-orbit maneuvering [2]. The CubeSat Ambipolar Thruster (CAT) is designed to overcome this technology gap and enable high ΔV (≥ 1000 m/s) missions. These missions include geostationary orbit insertion from geotransfer orbit, interplanetary exploration, and long-lived low altitude orbits.

As part of the development path a power processing unit with a fixed match frequency of 9.96 MHz was integrated with CAT. Operation of the integrated prototype was limited to a high current, low voltage mode. This mode was stable over propellant flow rates of 2.5 - 3.5 mg/s and DC input power of 25 - 37 W. The plume was interrogated at varying input propellant and DC power conditions using emissive, Faraday, and resonance probes. The probe results were overlaid with magnetic nozzle measurements made with a 3-axis magnetometer.

As shown in Figure 1, interesting effects were observed in the plume, including the presence of ions beyond the magnetic nozzle. A potential structure within that pointed toward the thruster centerline was measured with an emissive probe. Resonance probe density measurements show decreasing density as the magnetic nozzle diverges downstream of the thruster. These results suggest interesting plasma phenomena occur within the plume, including possible detachment. Future diagnostic measurements will reveal the dominant physics driving CAT.

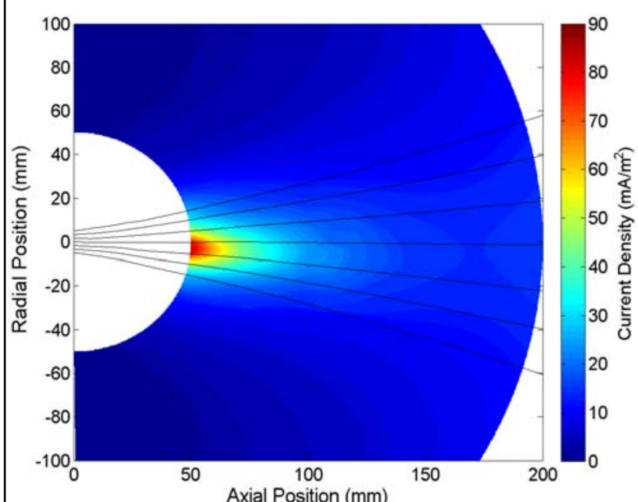


Figure 1 - Ion current density with CAT operating at $P_{dep} < 25.3$ W.

* This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1256260, the National Aeronautics and Space Administration (NASA) under Award No. NNX14AD71G, and the Defense Advanced Research Projects Agency (DARPA) under NASA Contract Number NNA15BA42C.

References

[1] Bouwmeester, J. and J. Guo "Survey of worldwide pico-and nanosatellite missions, distributions and subsystem technology." Acta Astronautica 67(7): 854-862. (2010).

[2] Mueller, J., et al. "Survey of propulsion technologies applicable to cubesats." Joint Army Navy NASA Air Force Meeting, Colorado Springs, CO, (2010).

Long pulse Soft X-ray Emission from Laser Irradiated Gold Foils*

J. S. Davis[a], Y. Frank[b], E. Raicher[b], M. Fraenkel[2], P. A. Keiter[a], S. R. Klein[a], R. P. Drake[a] and D. Shvarts[a]

(a) University of Michigan (davisjs@umich.edu)
(b) Soreq Nuclear Research Center, Israel

Long pulse soft x-ray sources (SXS) allow for flexibility in high-energy-density experimental designs by providing a means of driving matter to the high temperatures needed, for example to study radiation waves in different materials. SXSs can be made by using lasers to heat a high-Z thin foil, which then acts as a quasi-blackbody emitter. Previous studies of the x-ray emission characteristics of gold foils have focused on laser pulses of ~1ns or less. We performed experiments using a 6.0ns laser pulse with energy of 2kJ on the Omega-60 system to generate and characterize multi-ns laser heated Au foils of thicknesses between 0.5-2.0µm. We measured the 2D spatial profile of the emission with a soft x-ray camera and the time history of the emission with the Dante photodiode array. Effective temperatures for emission were calculated using the Dante measurements and those calculations were used to make comparisons between peak effective temperatures and foil thickness.

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

Atomic Bound States and Scattering in Strongly Coupled Plasmas Using Effective Momentum-dependent Potentials*

Gautham Dharuman [a], John Verboncoeur [a,b], Andrew Christlieb [b,c] and Michael S. Murillo [b]

(a) Dept. of Electrical and Computer Engineering, Michigan State University (dharuman@msu.edu)
(b) Dept. of Computational Mathematics, Science and Engineering, Michigan State University (johnv@egr.msu.edu,
christli@msu.edu, murillom@msu.edu)
(c) Dept. of Mathematics, Michigan State University

Non-equilibrium high energy density experiments have time evolving ionization and partial degeneracy, and modeling requires simulations spanning large length and time scales obviating the direct use of the time-dependent Schrodinger equation. Therefore, efficient approximate methods are needed. We have examined the accuracy of one such method based on an effective classical-dynamics approach employing effective momentum dependent potentials (MDPs) within a Hamiltonian framework that enables large-scale simulations. We have found that a commonly used formulation, based on Kirschbaum-Wilets (KW) MDPs [1] leads to very accurate ground state energies and good first/second-ionization energies. The continuum scattering properties of free electrons were examined by comparing the momentum-transfer cross section (MTCS) predicted by KW MDP to a semi-classical phase-shift calculation. Optimizing the KW MDP parameters for the scattering process yielded poor MTCSs, suggesting a limitation of the use of KW MDP for plasmas. However, our new MDP yields MTCS values in much better agreement than KW MDP.

* Work supported by the Air Force Office of Scientific Research

References

[1] Phys. Rev. A 51, 266 (1995).

Optical Emission Spectroscopy Investigation of an Atmospheric Pressure Plasma Glow that is Associated with Self-organization Pattern on Liquid Surface

Yao E. Kovach[a], Maria C. Garcia[b] and John E. Foster[a]

(a) Dept. of Nuclear Engineering and Radiological Sciences, University of Michigan (yaok@umich.edu, jefoster@umich.edu)
(b) Department of Applied Physics, University of Cordoba (fa1gamam@uco.es)

A helium plasma discharge glow, which works under atmospheric pressure, has been developed for analysis of self-organization anode pattern formation on a liquid surface of salted water. In order to characterize the plasma glow with self-organized pattern behavior, its gas temperature, electron density and species composition have been determined by means of optical emissions spectroscopy (OES) techniques.

In this work, the operation conditions such as inner-electrode distance (20 mm), gas flow rate (200 sccm), liquid conductivity (12 mS/cm), and applied voltage (1.3, 1.7, 2.0, 2.2, and 2.5 kV) with respective discharge current were consciously controlled. Pattern shape depended on voltage and current conditions. For all the cases studied, the light emitted by the plasma at different axial positions was analyzed using a spectrometer of 300 cm of focal length equipped with an ICCD camera. As an example, figure 1 represents an experimental result of gear-shaped self-organized anode pattern on liquid surface. The orange colored glow area shows a sodium clouds due to the water vaporization, which matches with the sodium emission result from measured OES data. Overall, this experiment provides a valuable studying to understand plasma chemistry. Further more, it may help find a clue of the origin of self-organization anode pattern formation.

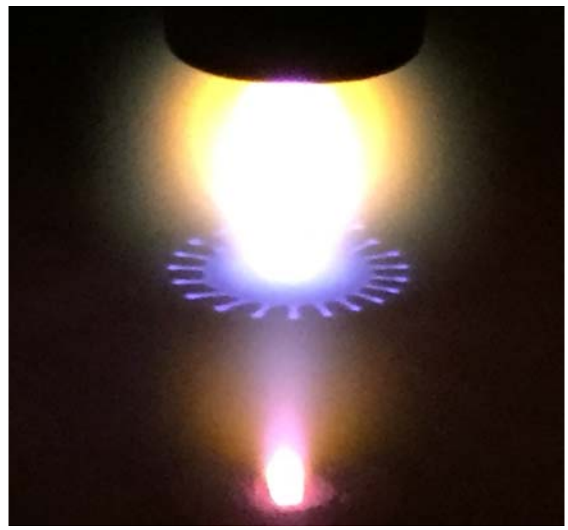


Figure 1 – A self-organized anode pattern with plasma glow at 20 mm Gap length, applied voltage of 2.0 kV and 76 mA discharge current.

Inductive and Capacitive Power Distribution and Impact on Plasma Properties in Inductively Coupled Plasma Reactors*

Steven J. Lanham[a] and Mark J. Kushner[b]

University of Michigan, Ann Arbor, MI 48109 USA

(a) Department of Chemical Engineering (sjlanham@umich.edu)
(b) Department of Electrical Engineering (mjkush@umich.edu)

Inductively coupled plasma (ICP) reactors are used in the microelectronics industry to process wafers and create the features for integrated circuits. In ICP reactors, an antenna (the coil) outside the reactor chamber produce inductive electric fields that deposit power into the plasma. Under ideal conditions, the deposited power is purely inductive (H-mode discharge) but electrostatic coupling between the coil and plasma (E-mode) becomes important when operating with low current [1]. The amount of capacitive coupling from the antenna can be important to capture the discharge physics.

Total power from the antenna in ICP reactors consists of balancing resistive losses, inductively deposited power, and capacitive coupling. For a set amount of total power delivered from the generator, the distribution between these components varies greatly depending on operating conditions. For instance, the applied coil frequency can greatly affect the power distribution [2]. Low frequencies, e.g. single MHz frequencies, feature almost pure inductive power with large resistive losses in the antenna. Higher frequencies result in increased capacitive power and decreased resistive losses.

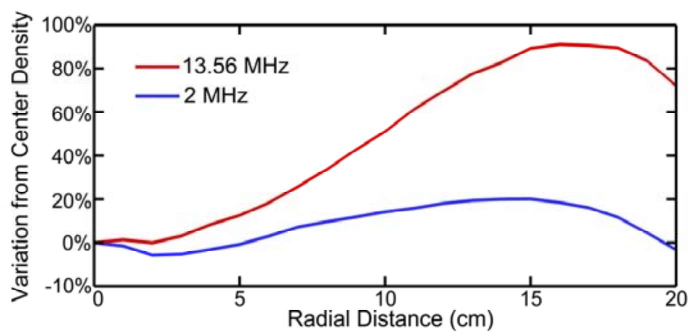


Figure 1 – HPEM simulation results for the percent variation of electron density 1 cm above a wafer in an ICP reactor for an Ar plasma operating at different frequencies.

In this work, a computational investigation of the distribution of power in ICP reactors between inductive and capacitive was performed using the Hybrid Plasma Equipment Model (HPEM), a 2-dimensional hydrodynamics plasma simulator [3]. The proportioning of deposited power can have a large impact on plasma properties. Specifically, plasma uniformity across a wafer can greatly depend on the coil frequency (see Figure 1). Applications such as material etching require uniform flux of reactive species across the wafer, and could greatly benefit from this work.

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

References

[1] U. Kortshagen, N. D. Gibson and J. E. Lawler, J. Phys. D. Appl. Phys. **29**, 1224 (1996).

[2] E. F. Jaeger, L. A. Berry, J. S. Tolliver, J. S. and D. B. Batchelor, Physics of Plasmas, **2**, 2597 (1995).

[3] M. J. Kushner, J. Phys. D. Appl. Phys. **42,** 194013 (2009).

Gas-Phase Synthesis of Gallium Nitride (GaN) Nanocrystals using Non-Thermal Plasma

Rajib Mandal and Rebecca J. Anthony

Department of Mechanical Engineering, Michigan State University, East Lansing, MI 48824
(ranthony@msu.edu)

Bulk Gallium Nitride (GaN) is the standard light-emitting material, very efficient for Light Emitting Diodes (LEDs) and has been in use for many years. This material is very attractive due to its high-brightness and thermal stability. GaN is a direct band gap semiconductor with 3.4 eV band gap energy enabling its use in ultraviolet/blue light emission technologies. Relative non-toxicity of GaN compared to other popular semiconductors such as cadmium selenide (CdSe) gives it distinct advantage. The applicability of GaN nanoparticles lies in high-brightness sloid-state lighting devices. Doping of GaN and incorporation of other semiconductors will enable these devices to be applicable in visible spectrum as well.

Here we present a study on synthesis of high-quality GaN nanocrystals using a fully gas-phase process. We have used a low-pressure nonthermal plasma reactor[1-2] for the synthesis of GaN directly from gaseous precursors and deposited onto the glass substrate without any additional steps. The plasma reactor has some advantages over other available methods, namely, size monodispersity, easy control on nanocrystal size and the ability to deposit the NCs from the gas phase without removal from the reactor. It is also inexpensive and can be processed rapidly. Some studies have been performed with microwave plasma but it is very complex in nature. Thus, radiofrequency (RF) plasma could be an attractive alternative.

An RF nonthermal plasma reactor is comprised of a borosilicate glass tube with three ring electrodes encircling the tube externally. Vapor-phase precursors and carrier gases were flown through at relatively low pressure (typically 5-15 Torr) with RF power ranging from 60W-150W. At low pressure or elevated temperature, the vapor of Trimethyl Gallium (TMGa) entered the gas flow as a source of gallium and ammonia has been flown as a source of nitrogen. Any inert gas, like argon or nitrogen, can be helpful in carrying the metal-organic precursor into the system. For example, argon acts as a valuable source of electrons and ions as it ionizes in the plasma. In this way, it promotes dissociation reactions of the precursor and provides exothermic three-body reactions to heat the forming NCs, aiding crystallization[3].

One of the main objectives of this work was to maximize the crystal fraction of the GaN NCs for full control over optoelectronic properties of NCs. Crystallinity of the GaN nanocrystals were studied by X-Ray diffraction (XRD) using a Bruker Diffractometer. The nanocrystals were also studied using transmission electron microscopy (TEM) on a JEOL 2200FS ultra-high resolution TEM. Photoluminescence from the GaN nanocrystals was measured using the 325 nm emission from a LED.

References

[1] L. Mangolini, E. Thimsen, and U. Kortshagen, Nano Letters, **5**, 655 (2005).
[2] R. Anthony and U. Kortshagen, Physical Review B, **80**, 115407 (2009).
[3] L. Mangolini and U. Kortshagen, Physical Review E, 79(2):026405 (2009).

Ionic Liquid Ferrofluid Electrospray*

Kurt J. Terhune, Brandon A. Jackson, and Lyon B. King

Michigan Technological University (kjterhun@mtu.edu)

The present focus of the Ion Space Propulsion Laboratory at Michigan Tech revolves around ionic liquid ferrofluid (ILFF) electrospray propulsion, which substitutes traditional IL propellant for a new magnetically susceptible propellant first developed by Jain et al.[1] Ionic liquids (ILs) are room-temperature molten salts with high electrical conductivity and almost zero vapor pressure, making them ideal for operating in a vacuum. Because they are comprised of both anions and cations they can be manipulated by electric fields.[2] Furthermore, since the new propellant is magnetically susceptible, subjecting it to a strong magnetic field causes the magnetic moments within the particles of the fluid to align with the magnetic field lines. Perturbations along a free surface of the colloid cause local concentrations of the magnetic field, causing the liquid to bulge, a phenomenon known as the Rosensweig instability.[3, 4] The goal of our research is to understand how electric and magnetic fields work together to cause electromagnetic spraying instability at the apex of a Rosensweig instability structure.

When an ILFF free surface is subjected to a strong electric field the meniscus will deform into a sharp peak until a threshold voltage is reach, at which time a jet of ions is emitted from the peak apex. This onset voltage, V_c of ion emission is the result of the electric field stress at the apex overcoming the capillary surface stress; for a meniscus with radius, *r*, and with the field formed by an extractor electrode at a distance, *d*, from the apex, onset is approximated according to Prewett & Mair as $V_c = \ln(2d/r)\sqrt{\sigma r/\varepsilon_0}$.[5] For a magnetically susceptible fluid, an additional stress from the magnetic field has an effect on the meniscus that has been shown to alter the threshold voltage of ion emission.

After onset of emission the free surface emits a continuous and steady beam of charged particles in a process known as electrospray. The average mass-to-charge ratio (m/q) of the beam has strong implications on the performance of the emitter for spacecraft propulsion. As such, acquiring the m/q distribution within an electrospray using the ILFF propellant is important to mission design, as is understanding the affect that an applied magnetic field would have on the m/q.

In this poster we report three primary findings. 1) The mass-to-charge ratio of particles within an ILFF electrospray beam. These were made using a time-of-flight mass spectrometer with a range of 0-1,000,000 amu/e. 2) Expansion of the operational range of ILFF electrosprays through the application of an external magnetic field. We measured significant changes in the onset potential for ion emission along with a reduction in the require flowrate for stable emission. 3) A predictive model for the ILFF meniscus geometry and ion emission under combined electric and magnetic fields.

* Work supported by a NASA Space Technology Research Fellowship

References

[1] Jain, N., et al., *Stable and Water-Tolerant Ionic Liquid Ferrofluids.* ACS Applied Materials & Interfaces, 2011. **3**(3): p. 662-667.

[2] Baker, G.A., et al., *An analytical view of ionic liquids.* Analyst, 2005. **130**(6): p. 800-808.

[3] Rosensweig, R.E., *Magnetic Fluids.* Annual Review of Fluid Mechanics, 1987. **19**: p. 437-461.

[4] Boudouvis, A.G., et al., *Normal field instability and patterns in pools of ferrofluid.* Journal of Magnetism and Magnetic Materials, 1987. **65**(2–3): p. 307-310.

[5] Prewett, P.D. and G.L.R. Mair, *Focused ion beams from liquid metal ion sources*1991: Research Studies Press.

The Role of Hot Electrons in the Creation of Hollow Atoms by Relativistic Laser Plasma Interaction

Amina Hussein[a], J. D. Hager[b], K. A. Flippo[b], K. Krushelnick[a], J. L. Kline[b], B. C. Tappan[b], W. L. Boncher[b], F. Elsner[c], A. Nikroo[c,d]

(a) University of Michigan (amina.e.hussein@gmail.com)
(b) Los Alamos National Lab
(c) General Atomics
(d) Lawrence Livermore National Lab

An investigation of X-ray spectra resulting from short-pulse laser-matter interactions at relativistic laser intensities (>3 x 10^{30} W/cm^2) yielded evidence of the production of hollow atoms through enhanced K-beta emission. Experiments were conducted using at the Trident Laser Facility to increase the conversion efficiency of short-pulse, copper K-alpha X-ray backlighter sources. New target designs were tested to optimize resonance absorption, produce a higher number of hot electrons, and maximize x-ray radiation. X- ray emission from irradiated copper thin films and copper foams were diagnosed using a Highly Ordered Pyrolytic Graphite (HOPG) crystal. At highly relativistic intensities, K- beta emission was found to exceed K-alpha emission, while the laser-electron conversion efficiency scaling of K-alpha agreed with previous results of K-alpha production. The observation of increased inner shell emission in the highly relativistic regime is consistent with greater hot electron populations causing multiple inner-shell transitions.

Ion Emission Energetics from a Charged Hollow Cathode Plasma Contactor System*

Grant Miars[a], Omar Leon[b], Brian Gilchrist[a], and Gian Luca Delzanno[c]

(a) University of Michigan, Department of Electrical Engineering (gmiars@umich.edu, gilchrst@umich.edu)
(b) University of Michigan, Applied Physics Program (omarleon@umich.edu)
(c) Los Alamos National Laboratory, Applied Mathematics and Plasma Physics (delzanno@lanl.gov)

Simulations suggest that a hollow cathode is able to balance the current of active electron beam emission in the absence of a background plasma.[1] In this system, ions are emitted from the quasi-neutral contactor plume surface to balance the electron beam current. Maximum ion emission from the plume surface is space-charge limited and determined by the ion drift velocity, ion temperature, spacecraft potential, and plasma sheath thickness according to the Child-Langmuir Law. Based on these parameters and the surface area of the quasi-neutral plume, one can determine if ion emission is capable of balancing the electron beam current.

Below we present experimental results from a ground-based hollow cathode system which investigates the relationship between spacecraft potential and the ion energetics which define maximum ion emission. The hollow cathode is charged to various positive voltages to reproduce the effects of an electron beam charged spacecraft system. Ion drift velocities and temperatures are presented for the axial and radial direction using drifting Maxwellian fits of ion energy distribution functions (IEDFs) obtained from retarding potential analyzers (RPAs). Planar probes placed along the chamber walls measure the emission current density and approximate the ion drift energy once it has transited the accelerating sheath. Conclusions about the ion energetics are drawn and the implications for electron beam charged spacecraft neutralization in the absence of a background plasma are explored.

* Work supported by the Center for Space and Earth Science & Los Alamos National Laboratory

References

[1] G. L. Delzanno, J. E. Borovsky, M. F. Thomsen, and J. D. Moulton, J. Geophys. Res. Space Physics. **120,** (2015).

Electrode Configurations in Atmospheric Pressure Plasma Jets*

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

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

Atmospheric pressure plasma jets (APPJs) have been used for emerging medical applications such as the treatment of chronic wounds [1] and inducing apoptosis in cancer cells [2]. Many of these results have been attributed to the production of reactive oxygen and nitrogen species (RONS) which are generated in the plasma, solvate in the biological liquid, and induce a cellular or systemic response. Studies on the behavior and effects of these jets have been performed in a great number of research groups, so the APPJ designs are far from standard. Most APPJs consist of a dielectric tube with at least one powered electrode in or on the dielectric tube. Rare gas, with or without a small admixture of reactive gas (<2%) is flowed through the tube, and interacts with the ambient air. In this paper, we will examine the effects of different electrode configurations and ground plane placement on the production of RONS in APPJs sustained in He flowing into humid air.

APPJs produce an ionization wave (IW) which usually propagates from the powered electrode toward any electrical grounds that are present in the system. In APPJs, the electrode position influences the IW propagation and location of power deposition. In this paper, we use a 2-D plasma hydrodynamic model, *nonPDPSIM*, to analyze the effect of electrode configuration on the ionization wave and RONS production.

The electron density and oxygen atom density shown in Fig. 1 indicate that the position of the powered electrode can significantly affect both the IW and the RONS production. When the powered electrode is closer to the tube outlet, more of the power deposition occurs in regions with higher humid air density.

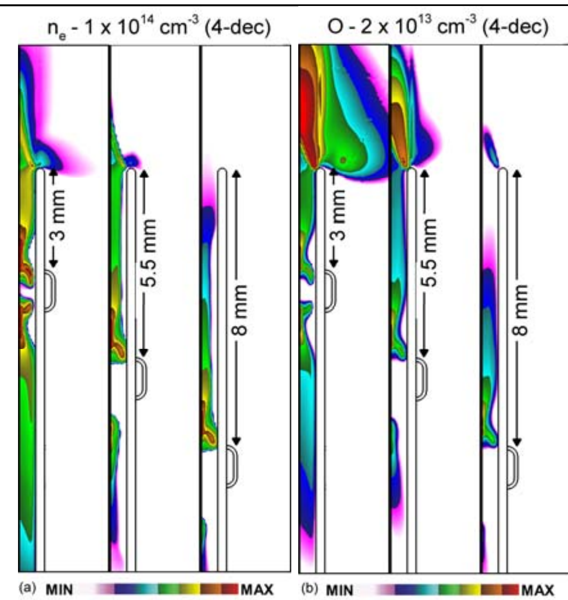


Figure 1 – The (left) electron density and (right) O atom density after a 200 ns voltage pulse at -18 kV. The placement of the powered electrode is varied from 3 mm to 8 mm.

* Work was supported by DOE Office of Fusion Energy Science (DE-SC0001319, DE-SC0014132), National Science Foundation (CHE-1124724, PHY-1519117) and the NSF Graduate Research Fellowship Program.

References

[1] S. Arndt, P. Unger, E. Wacker, T. Shimizu, J. Heinlin, Y. F. Li, H. M. Thomas, G. E. Morfill, J. L. Zimmermann, A. K. Bosserhoff and S. Karrer, PLoS One **8,** 1 (2013).

[2] N. Kaushik, N. Uddin, G. B. Sim, Y. J. Hong, K. Y. Baik, C. H. Kim, S. J. Lee, N. K. Kaushik and E. H. Choi, Sci. Rep. **5,** 8587 (2015).

Boundary Conditions in a Two-dimensional, Axisymmetric, Direct Kinetic Hall Thruster Simulation*

Astrid L. Raisanen[a], Kentaro Hara[b] and Iain D. Boyd[a]

(a) University of Michigan (astridr@umich.edu, iainboyd@umich.edu)
(b) Texas A&M University (khara@tamu.edu)

A two-dimensional, axisymmetric, hybrid-direct kinetic (DK) simulation is under development for use in Hall thruster applications. The simulation employs a two-dimensional Vlasov solver coupled with a quasi one-dimensional electron fluid solver to model the plasma discharge in a Hall thruster channel and near-field plume. The DK solver is an adaptation of that used in Hara's previous work [1], and the numerical method is outlined in the recent work by Raisanen *et al*.[2] The present study focuses on the implementation of boundary conditions in the thruster simulation domain.

Within the DK simulation, there are presently four types of boundary conditions in physical space, which are shown in Fig. 1. The boundary conditions include: outflow only; outflow with allowance of inflow due to a nonzero background pressure; specular reflection at the thruster centerline; and wall boundaries at which neutral atoms are diffusely reflected, and ions recombine to reflect as neutral atoms.

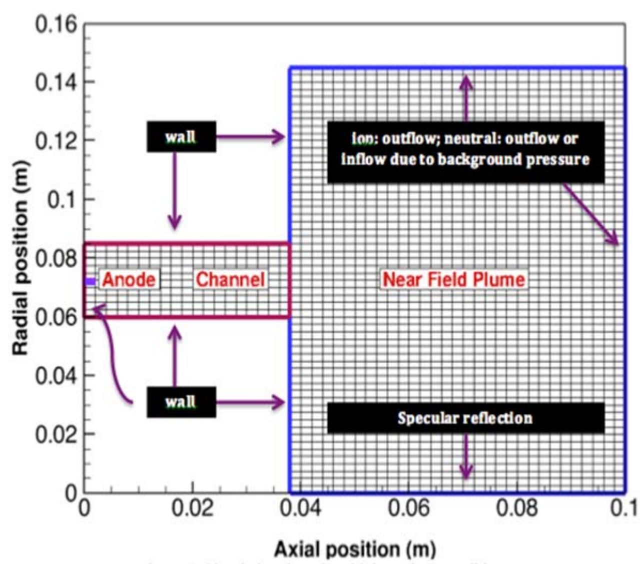


Figure 1 – Simulation domain with boundary conditions.

The DK algorithm uses a finite volume MUSCL scheme with a modified Arora-Roe limiter to calculate the flux throughout the domain.[3] [4] This study discusses the treatment of the flux at the boundaries of the domain and comments on the numerical implementation within the simulation.

* Work supported by the Air Force Office of Scientific Research Grant No. F95550-09-1-0695

References

[1] Hara, K., Development of Grid-Based Direct Kinetic Method and Hybrid Kinetic-Continuum Modeling of Hall Thruster Discharge Plasmas, Ph.D. Thesis, University of Michigan, 2015.

[2] Raisanen, A.L., Hara, K., and Boyd, I.D., "Comparing Two-Dimensional, Axisymmetric, Hybrid-Direct Kinetic and Hybrid Particle-in-Cell Simulations of the Discharge Plasma in a Hall Thruster," AIAA Paper 2016-4620, Salt Lake City, UT, July 2016.

[3] Van Leer, B., "Towards the ultimate conservative difference scheme. IV. A new approach to numerical convection," *Journal of Computational Physics*, Vol. 23, No. 3, 1977, pp. 276-299.

[4] Arora, M. and Roe, P.L., "A Well-Behaved TVD Limiter for High-Resolution Calculations of Unsteady Flow," *Journal of Computational Physics*, Vol. 23, No. 1, 1977, pp. 3-11.

Using the OMEGA Laser to Study Accretion Shocks on Forming Stars*

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

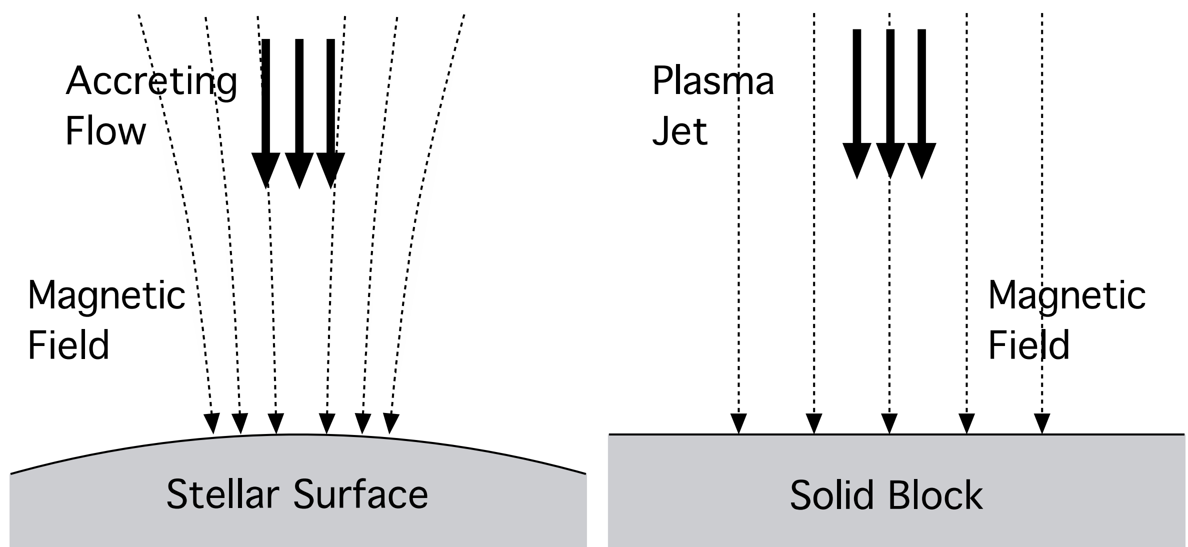
(a) University of Michigan (rpyoung@umich.edu)
(b) Laboratory for Laser Energetics
(c) Lawrence Livermore National Laboratory
(d) Massachusetts Institute of Technology
(e) Rice University

We present a series of laboratory-astrophysics experiments to better understand shocks that form during stellar accretion. During star formation, material is "funneled" from the accretion disk to the star's surface along magnetic field lines, creating accretion shocks (left side of the figure). However, there are open questions about the structure and evolution of these shocks and about the role of the star's magnetic field.

To better understand the system, we have designed a scaled experimental version (right side of figure). We create a plasma jet (the "accreting flow") and drive it into a solid block (the "stellar surface") in the midst of a parallel, externally-generated magnetic field. Our primary diagnostics are proton radiography and visible light imaging.

At this symposium, we discuss the design process and present results from two shot days and discuss them as well as difficulties we have encountered in executing this experiment.

* This work is funded by the U.S. Department of Energy, through the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0002956, and the National Laser User Facility Program, grant number DE-NA0002719, and through the Laboratory for Laser Energetics, University of Rochester by the NNSA/OICF under Cooperative Agreement No. DE-NA0001944.



The Influence of the Substrate Holder Depth on the Surface Morphology and Crystal Shape of Single Crystal Diamonds Grown via MPACVD

Amanda Charris, Shreya Nad and Jes Asmussen

Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA (charrish@msu.edu)

Single crystal diamonds (SCDs) exhibit exceptional and unique properties which are promising for several applications, such as optical, mechanical, and high-power electronics. High-quality SCDs of a large size are required for commercialization. Currently, commercially available SCDs are limited in size and quality. Typically, SCDs are available in sizes of 1 cm^2 or smaller. The SCD quality is dramatically reduced by the polycrystalline (PCD) rim that grows on the top surface. This rim causes stress, dislocations, and other morphological defects. Thus one current challenge is to grow thick SCD with a large and expanding top surface area without a PCD rim. This is the objective of our research activities.

SCD substrates were successfully synthesized using an optimized pocket holder design as discussed previously [1]. The pocket holder design created an appropriate thermal environment to shield the seed from the intense microwave discharge and the impressed microwave EM fields. Dimensions of the pocket holders consisted of a width of $w = \sim 1$ mm and depths varying as follows: $d_1 = 2.0$ mm, $d_2 = 2.3$ mm, $d_3 = 2.6$ mm and $d_4 = 2.9$ mm. The synthesis procedure was carried out via microwave plasma assisted chemical vapor deposition (MPACVD) in a 2.45 GHz microwave cavity plasma reactor C [2] at 240 Torr and high power density of ~ 100 W/cm^3. SCDs were grown on 3.5mm *x* 3.5mm *x* 1.4mm HPHT type 1b, (100)-oriented single crystal diamond seeds for 40 – 55 hours with H_2 flow rate of 400 sccm and 5% methane concentration.

The deposited SCD had a growth rate of 30 μm/h and normalized lateral area gains of 1.92 times. By continuously adjusting incident microwave power (P_{inc}), the substrate temperature (T_s) was held at ~ 1020^{o}C ±5°C over the entire process cycle. The process cycle was stopped before the growing SCD penetrated into the discharge. Under these growth conditions, all the morphologies exhibited a smooth and flat enlarged surface without a PCD rim. Optical and scanning electron microscopy (SEM) were performed to analyze the surface morphology and the crystal shapes of the SCD grown substrates. The lateral surface area gain versus the pocket depth was measured. The quality of these grown SCD substrates was indicated by their low birefringence and high purity; i.e ~ 120 ppb nitrogen impurity levels as measured by SIMS analysis. Therefore, a new MPACVD SCD process was developed where thick SCD is grown without an accompanying PCD rim.

References

[1] S. Nad, Y. Gu, and J. Asmussen, "Growth strategies for large and high quality single crystal diamond substrates," *Diam. Relat. Mater.*, vol. 60, pp. 26–34, 2015

[2] Y. Gu, J. Lu, T. Grotjohn, T. Schuelke, and J. Asmussen, *Diam. Relat. Mater.*, vol. 24, pp. 210–214, 2012.

[3] A. Charris, S. Nad, J. Asmussen, "The influence of different growth variables on the crystal shapes of MPACVD grown single crystal diamond substrates" *ICDCM, Le Corum, Montpellier, France*

Investigation of the Evolution of Plasma Injection Events within Saturn's Magnetosphere*

Abigail R. Azari[a], Michael W. Liemohn[a], Xianzhe Jia[a], Donald G. Mitchell[b], Abigail M. Rymer[b], and Jon D. Vandegriff[b]

(a) University of Michigan (azari@umich.edu, liemohn@umich.edu, xzjia@umich.edu)
(b) Johns Hopkins University Applied Physics Laboratory

Saturn's plasma environment is unique within our solar system and provides intriguing observations of planetary plasma physics. While Earth's magnetosphere is primarily composed of plasma from the solar wind and Earth's upper atmosphere, Saturn's magnetospheric plasma is also sourced by cyrovolanic outgassing from Enceladus, and experiences much larger co-rotational forces due to Saturn's rapid (~11h) spin rate. These effects contribute to the observed injection of energetic particles from the outer reaches of the magnetosphere to the middle and inner magnetosphere through a Rayleigh-Taylor like plasma instability. Commonly termed interchange injections, these events provide fascinating insights into the behavior of rotating space plasmas.

There is still much uncertainty as to the radial extent of these observed instabilities. For example, radially localized isolated flux tubes separated from the outer magnetosphere after initialization, or if they occur in channels and are physically attached to the outer magnetosphere, spanning many radial distances. These two morphologies can be related to the stages of linear, non-linear, and turbulent type Rayleigh-Taylor instabilities.

I will present an evaluation of two clusters of interchange injection events, observed ~14-18 hours apart by the Cassini spacecraft, for the potential of the two events originating from the same unstable plasma configuration. The second cluster of events occurs approximately within the right time frame to have co-rotated back within Cassini's view. This research has applicability to the study of plasma instabilities in rotating systems and to other astrophysical plasmas.

* This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1256260. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This work was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program - Grant NNX15AQ63H.

Investigation of Channel Interactions in a Nested Hall Thruster*

Sarah Cusson[a], Marcel Georgin[b], Ethan Dale[a], Vira Dhaliwal[a], and Alec Galimore[a]

(a) Department of Aerospace Engineering, University of Michigan (cusson@umich.edu)
(b) Applied Physics Program, University of Michigan (georginm@umich.edu)

Nested Hall thrusters, which concentrically nest multiple discharge channels together, are an attractive option for scaling Hall thrusters to high power. Their ability to maintain high thrust to power ratios, reduce mass to power ratios and throttle over large ranges makes them ideal for high power missions such as cargo missions to Mars. However, the underlying physics of how having multiple discharges in such proximity affects the device is not well understood.

Previous studies on nested Hall thrusters [1], have shown discrepancies between predicted multi-channel operation based on single-channel operation and actual multi-channel operation. These results suggest that the channels of nested Hall thrusters are interacting to affect the performance of these devices, probably due to increased neutral pressure near the thruster. The mechanism by which this is occurring is the subject of this study. Background neutral ingestion from the facility, neutral ingestion from the adjacent channel, and movement of the acceleration region leading to changes in divergence angle are the plausible candidates.

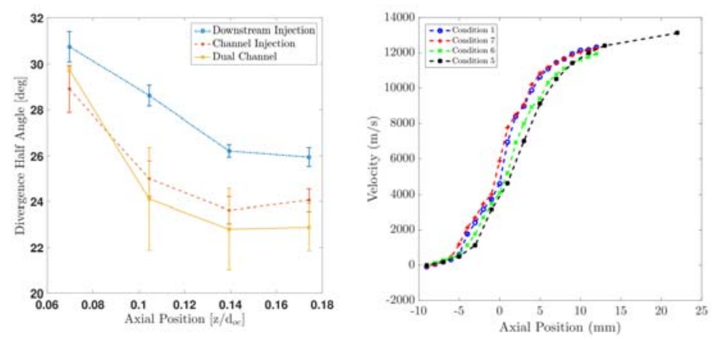


Figure 1 – The figure on the left shows divergence angle changes in the outer channel for dual-channel mode versus single-channel mode which suggests acceleration region movement. The figure on the right shows acceleration region movement for the outer channel confirming that increased near-field pressure leads to a decreased divergence angle and increased performance.

Thrust, beam current, divergence angle, and laser-induced fluorescence measurements were taken in order to investigate this phenomena. Chamber pressure was kept constant throughout the experiment to eliminate background neutral ingestion as a source of increased efficiency. Results indicate the thrust and efficiency increases in multi-channel operation versus the superposition of single channel operation. The beam current increases indicating neutral ingestion from the other channel is occurring. Additionally, divergence angle decreases suggest acceleration region movement. Laser-induced fluorescence confirms that in multi-channel operation the acceleration region is pushed inwards resulting in a decreased divergence angle.

* This work was partially funded by NASA Space Technology Research Fellowship grant numbers NNX15AQ43H, NNX15AQ37H, and NNX14AL65H

References

[1] Liang, R., *The Combination of Two Concentric Discharge Channels into a Nested Hall-Effect Thruster* , Ph.D. thesis, University of Michigan, Ann Arbor, MI, 2013.

Gas-phase Nanoparticle methods for Processing Silicon Nanorod Formation

A. Izadi and R. J. Anthony

Mechanical Engineering Department, Michigan State University, East Lansing, MI, 48824 (izadialb@msu.edu)

Silicon (Si) nanocrystals have been focused recently for their tunable optical properties, which arise due to quantum confinement. While spherical Si nanocrystals have been explored for a couple of decades, other morphologies have attracted a lot interest. Si nanorods (SiNRs) have the potential to exhibit different optoelectronic properties compared to their spatially isotropic counterparts, including polarized light emission and enhanced charge transport. Among the most attractive synthesis methods for Si nanocrystals is to use a nonthermal plasma reactor, which allows controllable nanocrystal physical and optoelectronic properties in an efficient gas-phase route. Synthesizing SiNRs in this method is challenging, though, as the process yields spherically isotropic nanomaterials. Here we present a method to streamline SiNR growth even further by combining hot-wire gold nanoparticle synthesis with plasma-based nanorod growth for freestanding SiNRs produced entirely in the gas-phase.

This method is composed from two parts. First, we initiate formation of gold nanoparticles by a hot-wire method. Second, we use the gold nanoparticles to catalyze the formation of SiNRs. To begin, we took a thin platinum wire, plated with gold, and supplied it with DC electrical power at 10-15 W under argon flow and reduced pressure. The coated gold on the wire is heated resistively and the gold vapor enters the gas flow, coalescing to form small nanoparticles. We collected and characterized the AuNPs using transmission electron microscopy (TEM). The AuNPs are then carried into the secondary stage of the reactor using a flow of argon gas from top side. In this step, we add silane gas (SiH_4) and supply RF power via dual ring electrodes encircling the glass reaction tube. The premise is that the RF power will excite a plasma, which causes the AuNP temperature to increase - then, adding the SiH_4 can cause a eutectic alloy between gold and silicon to form and the SiNRs to grow from the catalyst AuNPs. Early results indicate that the AuNPs are mixing with the SiH_4 and forming combined nanostructures, as observed using TEM. We also investigated the formation of a high ion density region (filament) and characterized parameters of the plasma based on that. Our future work will focus on characterizing the plasma process, including optical emission spectroscopy and electrical probe measurements, to diagnose the conditions in the plasma and improve our ability to engineer this process towards controllable growth of high-quality SiNRs in this all-gas-phase approach.

.

Time-Resolved Imaging of Micro-Plasmas as a Function of Dielectric Media*

Kenneth W. Engeling[a], Juliusz A. Kruszelnicki[a], John Foster[a], and Mark Kushner[b]

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

Plasma production in microporous media has potential to enable a number of technologies ranging from flameless combustion to environmental hazard mitigation addressing air borne pollutants. Packed bed reactors (PBRs) are one such technology that relies on plasma production in microporous media. The physics of plasma production and transport in such media however remains poorly understood. In order to better understand the plasma propagation and plasma driven chemical reaction within microporous media, absorption spectroscopy and time-resolved imaging diagnostics are being utilized. Using these diagnostics sensitivities to applied voltage, voltage frequency, and dielectric material type. We report on plasma driven species formation and plasma discharge spatial structure and evolution characteristics found in the 2-dimensional representation of a PBR.

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

Effects of Pulse-to-pulse Residual Species on Discharges in Repetitively Pulsed Discharges Through Packed Bed Reactors*

Juliusz Kruszelnicki[a], Kenneth Engeling[a] John Foster[a], and Mark J. Kushner[b]

(a) University of Michigan, Dept. of Nuclear Engineering and Radiological Sciences, Ann Arbor, MI 48109-2104, USA (jkrusze@umich.edu, kenengel@umich.edu, jefoster@umich.edu)
(b) University of Michigan Dept. of Electrical Engineering and Computer Science,1301 Beal Avenue, Ann Arbor, MI 48109-2122, USA (mjkush@umich.edu)

Atmospheric pressure dielectric barrier discharges (DBDs) sustained in packed bed reactors (PBRs) are being investigated for remediation of toxic gases, CO_2 removal and conversion of waste gases into higher value compounds. These discharges are repetitively pulsed having varying flow rates and internal geometries, which results in species from the prior pulse still being in the discharge zone at the time the following discharge pulse occurs. Typically, a non-negligible residual plasma remains, which effectively acts as pre-ionization. This residual charge changes the discharge properties of subsequent pulses, and may impacts important PBR properties such as chemical selectivity and energy efficiency. Similarly, the residual neutral reactive species produced during earlier pulses will impact the reaction rates on subsequent pulses. In this paper, we report on the results of a computational investigation of a 2-D PBR using the multi-fluid plasma hydrodynamics simulator *nonPDPSIM*.

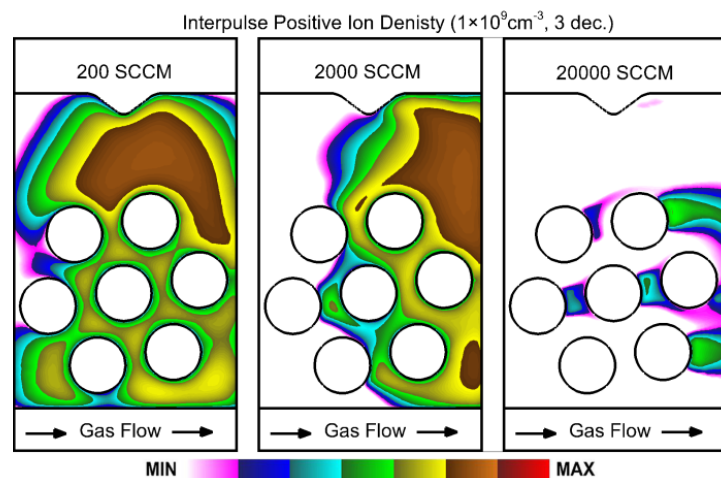


Figure 1 – Densities of positive ions during the inter-pulse for 1 kHz unipolar, -30 kV pulse, at different flow rates.

It was found that with gas flow, the pulse repetition frequency has a significant impact on the distribution of pre-ionization as the removal charged species from the discharge region primarily takes place during the inter-pulse period by flow. The lower the ratio of pulse-on to pulse-off times, the higher and more homogenous the density of charges throughout the reactor. Similarly, increased gas flow rates lead to more rapid convection of charged species out of the reactor for a given pulse frequency. Low flow rates, and high repetition rates lead produce more microdischarges throughout the reactor as break-down conditions (electron density, E/N) exist in a greater number of locations. Higher likelihood for breakdown also correlates with increased propagation speeds of the discharges, and higher electron densities and production of reactive species. However, when local stagnation points of certain species (e.g. Ozone) developed, regional saturation led to a drop in production of that species. These results point to the need to carefully examination of both: repetition and flow rates in any effort aiming to maximize plasma PBR efficiency.

* Work supported by the National Science Foundation (PHY- 1519117) and Department of Energy Office of Fusion Energy Science (DE-SC0001319, DE-SC0014132).

Determining the Quasi-Neutral Plasma Plume Region in the Presence of a Biased Hollow Cathode*

Omar Leon[a], Grant Miars[b], Brian Gilchrist[b], and Gian Luca Delzanno[c]

(a) The University of Michigan, Applied Physics Program (omarleon@umich.edu)
(b) The University of Michigan, Department of Electrical Engineering (gmiars@umich.edu & gilchrst@umich.edu)
(c) Los Alamos National Laboratory, Applied Mathematics and Plasma Physics (delzanno@lanl.gov)

Simulations developed at Los Alamos National Laboratory (LANL) are used to determine the effectiveness of a hollow cathode plasma plume to electrically neutralize an electron emitting spacecraft in the magnetosphere. These simulations suggest that the plasma plume will be unable to neutralize a charged spacecraft until the quasi-neutral region is large enough to overcome space charge limited conditions.[1] This is a direct result of the fact that the net ion current increases with increasing plume size as the ions are able to spread out over a larger surface area. However, when the spacecraft is positively charged, the plume's electrons are attracted toward the spacecraft decreasing the size of the quasi-neutral region.

To verify the effect of the spacecraft bias on plume size and validate these simulations, experimental measurements of the plasma sheath were taken while biasing a simulated spacecraft to various charging levels in a vacuum chamber. Langmuir probes were used to study the ratio of ion and electron densities at different positions relative to the cathode orifice. As the probe exits the quasi neutral region, the density ratio will diverge from unity at which point the sheath thickness can be determined. These measurements were validated using an emissive probe where the potential drop off toward chamber ground is used to infer the sheath thickness.

* Work supported by the Center for Space and Earth Science, Los Alamos National Laboratory, and the MIPSE Graduate Fellowship

References

[1] G.L. Delzanno, J.E. Borovsky, M.F. Thomsen, J.D. Moulton, and E.A. MacDonald, J. Geophys. Res. Space Physics **120**, **(**2015)

Numerical Modeling of LLNL's Au-Sphere Experiments on the OMEGA Laser*

K.H. Ma[a], E. Raicher[b], Y. Frank[b], M. Fraenkel[b], E. Johnsen[a], R.P. Drake[a], D. Shvarts[a, b]

(a) University of Michigan, Ann Arbor, MI USA
(b) Soreq Research Center, Israel

Experiments performed by LLNL on OMEGA studying X-ray conversion efficiencies of high-Z materials in spherical configurations, aimed to confirm hohlraum modeling, resulted in the use of a "liberal" electron heat flux limiter value of 0.15 to match simulations with these measurements[1]. This conclusion was re-examined and another model accounting for the effect of Ion Acoustic Turbulence on the thermal electron flux limitation was proposed[2]. Our work continues to explore relevant physical parameters in modeling these experiments using the HYADES and FLORENCE codes[3]. The sensitivity of laser absorption, X-ray emission and corona electron temperature to the electron flux limiter, inverse bremsstrahlung coefficient, resonant absorption in the critical layer, LTE and NLTE atomic physics and a numerical convergence study due to steep density and electron temperature profiles at the critical layer will be discussed. Additionally, alternative experimental designs, such as an "onion" configuration of plastic and gold as well as different laser illumination patterns, were studied.

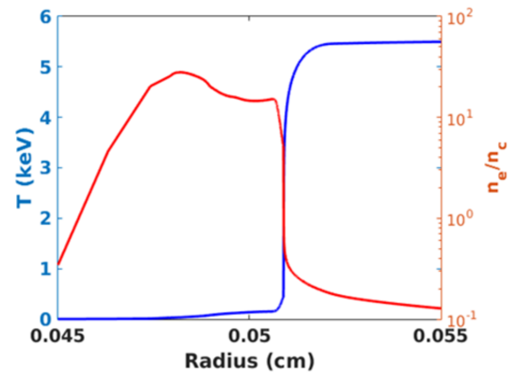


Figure 1 – Electron temperature and normalized electron density profiles for f = 0.03 around the critical density at the end of the laser pulse.

* Supported by the LLNL under subcontract B614207 to DE-AC52-07NA27344

References

[1] Dewald, E.L., et al., *Phys. of Plasmas 15*, 072706 (2008).
[2] Rosen M.D. et al., presented at the 2015 APS/DPP conference.
[3] Y. Frank et al**., Phys**. Rev. E 92, 053111 (2015)

Kinetic Global Modeling of Rare Gas Lasers*

Guy Parsey, John Verboncoeur and Andrew Christlieb

(a) Michigan State University ({parseygu, johnv, christli}@msu.edu)

Akin to diode-pumped alkali metal lasers, electronically excited states of rare gases (e.g. Ar and Kr) have been shown to operate as chemically inert three-level gain media for an optically pumped laser system.[1] As opposed to vaporization heating, these systems rely on electric discharge to efficiently maintain a population of metastable states acting as the bottom laser level. We propose that a modified electron energy distribution (EEDF) in the electric heating can be used to tune optically pumped rare gas laser (OPRGL) efficiencies. The EEDF factors into all plasma phase chemistry within the underlying reaction network, and is assumed to be maintained by discharge and electron sources.

Reaction data for noble species is predominantly acquired from publicly available sources in conjunction with rates found in the literature for reaction network completeness.[2,3] Using parameter scanning methods within the kinetic global modeling framework (KGMf), optimized static EEDFs are found for metastable production and increasing OPRGL operational efficiencies. Found EEDFs are then tested with the inclusion of a Boltzmann equation solver for self-consistent evaluation of EEDF response to electron sources, pumping mechanisms, and laser reaction dynamics.

Finally, we investigate the feasibility of using a modified EEDF to drive a rare gas laser system without the need for optical pumping. Relying on a mix of tuned microwave discharge and external electron sources, the energy efficiency of RGL systems is compared between optically-pumped and electronic driving methods.

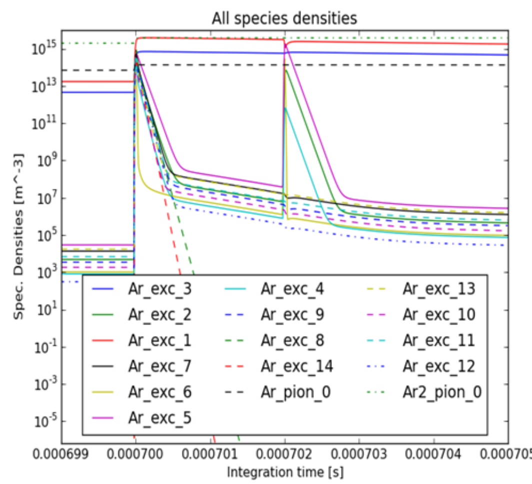


Figure 1 – Equilibrated argon species responding to MW discharge followed by optical pumping pulse.

* Work supported by AFOSR and MSU SPG

References

[1] J. Han and M.C. Heaven, Opt. Lett. **37**, 2157 (2012)
[2] Biagi-v8.9 database, www.lxcat.net, retrieved on July 4th, 2012
[3] NIST, www.nist.gov/pml/data/asd, retrieved on July 13th, 2012

Schlieren High Speed Imaging of Fluid Flow in Liquid Induced by Plasma-driven Interfacial Forces*

Janis Lai and John E. Foster

Dept. of Nuclear Engineering and Radiological Sciences, University of Michigan (janislai@umich.edu)

Effective plasma-based water purification depends heavily on the transport of plasma-derived reactive species from the plasma into the liquid. Plasma interactions at the liquid-gas boundary are known to drive circulation in the bulk liquid. This forced circulation is not well understood. A 2-D plasma-in-liquid water apparatus is currently being investigated as a means to study the plasma-liquid interface to understand not only reactive species flows but to also understand plasma- driven fluid dynamic effects in the bulk fluid. Using Schlieren high speed imaging, plasma-induced density gradients near the interfacial region and into the bulk solution are measured to investigate the nature of these interfacial forces. Plasma-induced flow was also measured using particle imaging velocimetry.

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

Customizing Arrays of Microplasmas for Controlling Properties of Electromagnetic Waves*

Chenhui Qu, Peng Tian and Mark J. Kushner
University of Michigan, Dept. Electrical Engr. & Comp. Sci, Ann Arbor, MI 48109-2122 USA
(chenqu@umich.edu, tianpeng@umich.edu, mjkush@umich.edu)

Microplasma arrays are being investigated to manipulate the propagation of electromagnetic waves [1]. Such applications require control of plasma properties, such as their absorption, dielectric and metamaterial properties. These microplasma arrays often operate at intermediate pressures of 10s to 100s of Torr. *pd* scaling then implies plasma cavities of hundreds of microns. Controlling cross-talk between microplasma units is a challenge since normally they are not physically isolated to reduce absorption or diffraction by structural components.

Plasma properties of 1-D and 2-D microplasma arrays excited by pulsed dc-bipolar/unipolar waveforms were computationally investigated. Results will be discussed for investigations aimed at maximizing the time averaged electron density and dynamic range during pulses, and controlling cross-talk between microplasmas that are not physically isolated. The basic geometry is four microplasma cells operating in 60 Torr Ar generated with 300 V unipolar pulses of 100 ns duration. The electron density peaks up to 2×10^{14} cm^{-3} with the cathode fall region forming near the exposed cathode. Beam ionization by secondary electrons from the cathode is the major source of electrons. In the base case, the influence of the crosstalk on plasma behavior is weak, which makes it possible to control plasma cells separately.

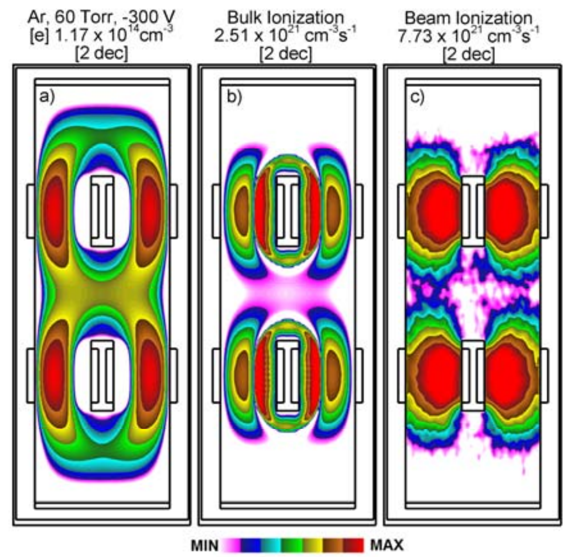


Figure 1 – a) Electron density, b) Bulk ionization and c) Beam ionization densities of base case in *Ar* gas with pulse repetition frequency *PRF* = 10 *MHz*, peak voltage V_{peak} = -300 *V*, duty-cycle *D* = 30% and pressure *P* = 60 *Torr*.

Predicted plasma properties were used to gauge the ability of microplasma arrays in waveguides to act as an EM wave filter. Simulations of transmission power under such conditions were made using the commercial code HFSS. In the simulation a 65 GHz wave was propagated through a WR-12 waveguide with 0.5 mm thick, 7 × 15 plasma array oriented perpendicular to the axis. The transmission power can be controlled from 100% to 45% as successive rows of the microplasma array are activated. There are indications of resonant behavior as the plasma density increases well above the critical value. These results show the capability of microplasma arrays to influence EM wave transmission and the potential of using plasma arrays as programmable EM filters.

* Work supported by DARPA, the DOE Office of Fusion Energy Sciences (DE-SC0001319, DE-SC0014132) and NSF (PHY-1519117)

References

[1] Osamu Sakai and Kunihide Tachibana, *Plasma Sources Sci. Technol.* **21** 013001(2012).

Experimental Design to Understand the Interaction of Stellar Radiation with Molecular Clouds*

Robert VanDervort[a], Josh Davis[a], Matt Trantham[a], Sallee Klein[a], Yechiel Frank[b], Erez Raicher[b], Moshe Fraenkel[b], Dov Shvarts[a], Paul Keiter[a] and R. Paul Drake[a]

(a) University of Michigan (dervort@umich.edu)
(b) Soreq Research Center, Israel

Enhanced star formation triggered by local O and B type stars is an astrophysical problem of interest. O and B type stars are massive, hot stars that emit an enormous amount of radiation. This radiation acts to either compress or blow apart clumps of gas in the interstellar media. For example, in the optically thick limit, when the x-ray radiation in the gas clump has a short mean free path length the x-ray radiation is absorbed near the clump edge and compresses the clump. In the optically thin limit, when the mean free path is long, the radiation is absorbed throughout acting to heat the clump. This heating explodes the gas clump. Careful selection of parameters, such as foam density or source temperature, allow the experimental platform to access different hydrodynamic regimes. The stellar radiation source is mimicked by a laser irradiated thin gold foil. This will provide a source of thermal x-rays (around ~100 eV). The gas clump is mimicked by a low-density foam around 0.12 g/cc. Simulations were done using radiation hydrodynamics codes to tune the experimental parameters. The experiment will be carried out at the Omega laser facility on OMEGA 60.

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

Relativistic Magnetic Reconnection in High-intensity Laser-plasma Interactions*

P. T. Campbell[a], A. Raymond[a], C. Zulick[a], A. Mckelvey[a], H. Chen[b], V. Chvykov[c], C. Dong[d], W. Fox[d], A. Maksimchuk[a], C. Mileham[e], P.M. Nilson[e], C. Stoeckl[e], A.G.R. Thomas[a], M. Wei[f], L. Willingale[a], V. Yanovsky[a], K. Krushelnick[a]

(a) Center for Ultrafast Optical Science, University of Michigan (campbpt@umich.edu)
(b) Lawrence Livermore National Laboratory
(c) ELI-ALPS
(d) Princeton Plasma Physics Laboratory
(e) Laboratory for Laser Energetics
(f) General Atomic

In experiments performed with the HERCULES laser at the University of Michigan and the OMEGA EP laser at the Laboratory for Laser Energetics, two short pulse beams were focused to high intensities on foil targets. Relativistic electrons produced during the interaction drive fast reconnection of self-generated magnetic fields. Energetic electrons accelerated during the reconnection event were measured by a multichannel magnetic electron spectrometer. A spherically bent crystal imaged the K_α x-ray emission induced by fast electrons deflected into the target. In future work, the effects of a preformed plasma on this relativistic magnetic reconnection will be investigated by using a long pulse UV beam to ablate the front surface of layered targets. The density and reconnection dynamics in the preformed copper or CH plasma will be diagnosed with a 4ω optical probe.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0002727.

Sheath Capacitance Effects in High-speed Langmuir Probes*

Ethan T. Dale, J. P. Sheehan and Alec Gallimore

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

High-frequency phenomena are abundant in low-temperature plasma devices but many plasma diagnostics make comparatively slow measurements that are not capable of capturing this high-speed behavior. One of the most common diagnostics, the Langmuir probe, can be adapted for operation at frequencies in excess of 100 kHz.[1] For a Hall thruster, an electrostatic plasma propulsion device with crossed electric and magnetic fields, this permits the time-resolved characterization of ~10 kHz oscillations like the so-called "breathing mode", the presence of which is known to impact thruster performance.[2] However, operating a Langmuir probe at high frequencies introduces electrical effects that tend to distort the measured I-V trace, requiring considerable post-processing.

One such effect is related to the capacitance of the sheath that forms between the probe tip and the bulk plasma. This effect was investigated for Langmuir probes operated in a Hall thruster plume. Sheath capacitance displacement current was estimated from sequential I-V traces, and the resulting data was used to compute the sheath capacitance itself, an example of which is shown in Figure 1. Existing theory relating sheath capacitance to bulk plasma parameters was applied to the experimental measurements and the outcome compared to the plasma properties yielded by traditional I-V trace analysis.[3]

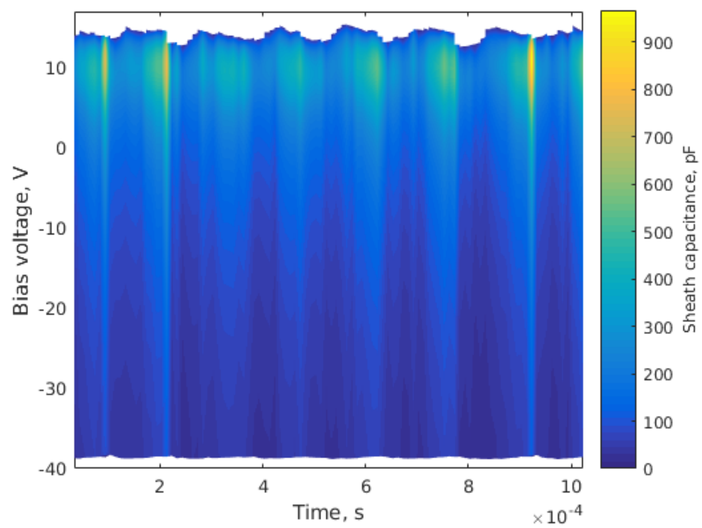


Figure 1 – Sheath capacitance throughout a Langmuir probe sweep, as a function of time. The maximum bias voltage at a given time is an indication of the plasma potential.

The possibility of using the sheath capacitance to estimate plasma potential was also explored. Beyond the assumptions required to calculate the sheath capacitance current, only a zero crossing in that current signal must be found to determine the plasma potential. This may reduce error in these measurements considerably compared to traditional Langmuir probe analysis techniques. High-speed plasma potential measurements made with both methods were compared to more precise low-speed data, and it was found that all three techniques agree within error.

* Work supported by NASA Space Technology Research Fellowship grant NNX14AL65H.

References

[1] R. Lobbia and A. Gallimore, Rev. Sci. Instrum. **81**, 073503 (2010).
[2] M. Sekerak et al., J. Prop. Power **32**, 903 (2016).
[3] F. Chen, Plasma Sources Sci. Technol. **15**, 773 (2006).

Generalized Mesh-based Ewald Decomposition for Molecular Dynamics Simulation of Correlated Plasmas with Screened Coulomb Interactions

Gautham Dharuman[a], Liam G. Stanton[b], James N. Glosli[c] and Michael S. Murillo[d]

(a) Dept. of Electrical and Computer Engineering, Michigan State University (dharuman@msu.edu)
(b) Center for Applied Scientific Computing, Lawrence Livermore National Laboratory (stanton6@llnl.gov)
(c) Condensed Matter and Materials Division, Lawrence Livermore National Laboratory (glosli1@llnl.gov)
(d) Dept. of Computational Mathematics, Science and Engineering, Michigan State University (murillom@msu.edu)

Molecular dynamics (MD) is a high fidelity approach for understanding moderate to strongly correlated plasmas like ultracold neutral plasmas [1], dusty plasmas [2] and warm dense matter [3]. For scenarios where electrons have relaxed forming screening clouds around the ions, the plasma can be modeled as a system of screened ions interacting through an effective potential [4]. Depending on the nature of the screening, the effective potential can span from long to moderate to short range [4]. The limiting step in MD is force calculation that scales naively as O(N^2), but, efficient algorithms have been developed like Linked-Cell-List (LCL) [5] for short range interaction with O(N) scaling and Particle-Particle-Particle-Mesh (PPPM) [5] which is a mesh-based Ewald method for long range Coulomb interaction with O(N log N) scaling. However, for moderate range interaction it raises a question of which of the two algorithms would have better computational efficiency. We generalized PPPM to systems described by an arbitrary dielectric response function, and from this generalization we optimized to find a boundary in the space of simulation size and screening that demarcates PPPM from LCL in terms of computational efficiency [6]. We examine the implications of different choices of screening function on the cost of computing dynamic structure factor that provides insight into plasma dynamics spanning small to large wavelengths and frequencies [6].

References

[1] T.C. Killian, Science 316, 705 (2007).
[2] H. Thomas et al., Phys. Rev. Lett. 73, 652 (1994).
[3] T. G. White et al., Phys. Rev. Lett. 111, 175002 (2013).
[4] L. G. Stanton and M. S. Murillo, Phys. Rev. E 91, 033104 (2015).
[5] R. W. Hockney and J. W. Eastwood, *Computer Simulation using Particles* (CRC Press, New York, 1988).
[6] G. Dharuman et al., *submitted.*

Effects of Temperature Dependence of Electrical and Thermal Conductivities on the Heating of a One Dimensional Conductor*

Foivos Antoulinakis[a], David Chernin[b], Peng Zhang[a] and Yue Ying Lau[a]

(a) University of Michigan (foivos@umich.edu)
(b) Leidos, Inc (DAVID.P.CHERNIN@leidos.com)

Dependence of electrical conductivity on temperature gives rise to electrotheramal instability, an important instability for Z-pinches [1]. In other areas, ohmic heating limits the operation of nanoscale circuits such as graphene electronics, carbon nanofiber based field emitters, and nanolasers [2]. For many applications, it is important to consider the temperature dependence of the thermal and electrical conductivities when calculating the effects of ohmic heating. We examine the effects of linear temperature dependence of the electrical and thermal conductivities on the heating of a one-dimensional conductor by solving the coupled non-linear steady state electrical and thermal conduction equations. We find that there are conditions under which no steady state solution exists. In the special case in which the temperature dependence of the electrical conductivity may be neglected, we have obtained explicit expressions for these conditions. The maximum temperature and its location within the conductor are examined for various boundary conditions. We note that the absence of a steady state solution may indicate the possibility of thermal runaway.

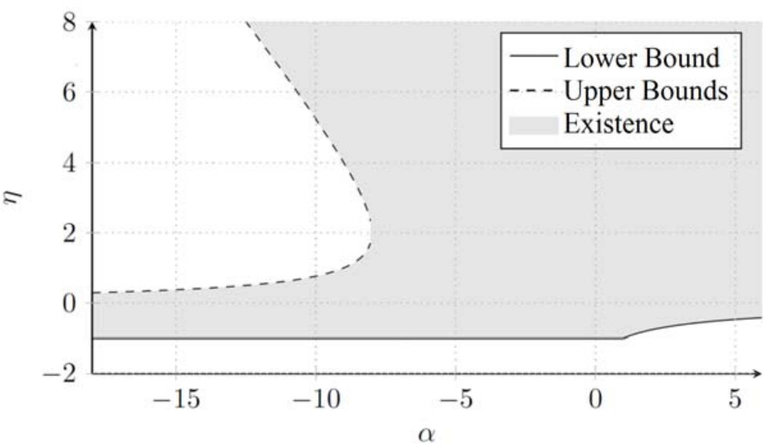


Figure 1 - Bounds for the existence of steady-state solution when the electrical conductivity is assumed constant and the thermal conductivity (κ) is linearly dependent on temperature. η is proportional to $d\kappa/dT$ and α depends on the voltage and temperature differences that are imposed at the two ends of the one dimensional conductor.

* Work supported by AFOSR No. FA9550-14-1-0309, and by L-3 Communications.

References

[1] K. J. Peterson, et al., Phys. Plasmas, **20**, 056305 (2012).
[2] P. Zhang, et al., IEEE J. Quantum Electronics, **52**, 2000207 (2016).

Production of 100 MeV Gamma Rays Through Inverse Compton Scattering on a Laser Wakefield Accelerator

Keegan Behm[a], J. Cole[b], E. Gerstmayr[b], SPD. Mangles[b], C. Murphy[c], C. Ridgers[c], AGR. Thomas[a], JC. Wood[b], K. Krushelnick[a]

(a) Center for Ultrafast Optical Science, University of Michigan (ktbehm@umich.edu)
(b) Plasmas Group, Imperial College of London, UK
(c) Laser-Plasmas Group, The University of York, UK

Research for high energy photon sources has been continuing since the discovery of X-rays in 1895. Here we present data showing the production of gamma rays as high as 100 MeV through inverse Compton scattering of a laser wakefield accelerated (LWFA) electron beam. One of the reasons for studying high energy photon sources on an all-optical device is because they have a high degree of tunability and it is possible to eliminate timing jitter between various arms of th experiment. At the Astra-Gemini laser system at Rutherford Appleton Labs (RAL), we collided an 800 MeV electron beam with a counter-propagating ultra-short pulse with a maximum a_0 of 20 [1]. The goal fo this experiment was to measure a radiation reaction due to the immense energy radiated away by the electron beam [2].

A CsI crystal array positioned parallel to the photon beam was used to detect the high energy gamma rays and provide information about the penetration depth of the gammas and the vertical divergence. Figure 1 shows an example of the data obtrained from the fluorescing CsI crystals within the detector array. With this detector we can analyze correlations between vertical divergence of photon flux and characteristics of the electron beam such as charge or maximum electron energy.

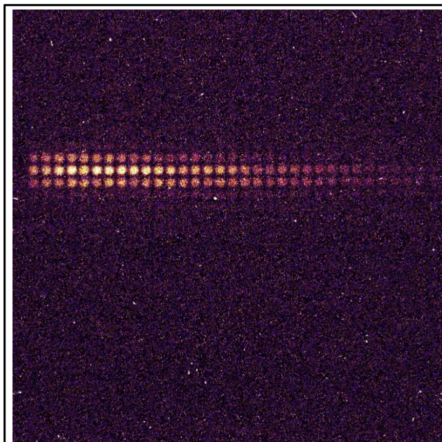


Figure 1- Fluorescing light from a CsI crystal array detecting gamma rays.

References

[1] Sarri, G., et al. "Ultrahigh brilliance multi-MeV γ-ray beams from nonlinear relativistic thomson scattering." *Physical review letters* 113.22 (2014): 224801.
[2] Di Piazza, A., K. Z. Hatsagortsyan, and Christoph H. Keitel. "Quantum radiation reaction effects in multiphoton Compton scattering." *Physical review letters* 105.22 (2010): 220403.

KGMf – Model Class and Boltzmann Equation Solver

Janez Krek, Guy Parsey and John Verboncoeur

(a) Michigan State University ({krek,parseygu,johnv}@msu.edu)

Kinetic global models are a convenient way to explore complicated chemistry in multi-species systems and to perform parameter scanning over a range of specified targets. The Kinetic Global Model framework (KGMf), a Python-based framework developed at Michigan State University, offers users great flexibility in defining various system parameters, such as power input, included/excluded species, included reactions between species, arbitrary defined electron energy distribution function (EEDF), etc. All parameters can be defined as system variable dependent functions or as a constants. The KGMf was used to simulate microwave assisted jet flame [1], multi-phase chemistry [2], and rare gas metastable laser reaction kinetics [3]. To use the KGMf, one needs a non-trivial proficiency in Python and has to provide a static, but arbitrary defined, EEDF. We attacked the first limitation by introducing simplified interaction with the KGMf via Model class and the latter by adding Boltzmann equation solver for computing the EEDF.

The KGMf takes full advantage of Python as a programming language, e.g. dynamic defined arrays, results type, size and structure vary depending on input file(s). To fully utilize the KGMf, users are required to have good knowledge of Python, preferably with some programming background. To ease use of the KGMf we implemented Model class to serve as an interface between the user and current KGMf functionality. The Model class simplifies usage of the KGMf by doing some checking/corrections in back-end, hidden away from the user. The main motivation was to enable use of the KGMf without the steep learning curve of a programming language while offering long time users same functionality and scripts used up till now.

As a part of input parameters, the KGMf currently offers the possibility to define an EEDF as an arbitrary defined function, either as a constant value or as a system variable dependent function. In adding a Boltzmann equation solver to the KGMf, presently we are using BOLOS[4] (open-source solver written completely in Python), one could leave the KGMf to self-consistently evaluate / compute the EEDF in every simulation time step rather that specifying it at the beginning of each run. This makes simulations more realistic, but at the cost of increased computational expense. Newly introduced Boltzmann equation solver capability of KGMf is only used when enabled by a parameter in the KGMf input file.

References:

[1] G. Parsey, Y. Güçlü, J. Verboncoeur and A. Christlieb, ICOPS, doi: 10.1109/PLASMA.2013.6634762 (2013)
[2] G. Parsey, Y. Güçlü, J. Verboncoeur and A. Christlieb, ICOPS, doi: 10.1109/PLASMA.2014.7012415 (2014)
[3] G. Parsey, J. Verboncoeur, A. Christlieb and Y. Güçlü, ICOPS, doi: 10.1109/PLASMA.2015.7179543 (2015)
[4] A. Luque, https://pypi.python.org/pypi/bolos (2004)

An Investigation of the Role of Near-anode Plasma Conditions on Anode Spot Self-organization in Atmospheric Pressure DC Glows

Yao E. Kovach and John E. Foster

Dept. of Nuclear Engineering and Radiological Sciences, University of Michigan (yaok@umich.edu, jefoster@umich.edu)

In previous work, plasma self-organization patterns were experimentally observed on both liquid surface and metal anode surface in atmospheric pressure glows. However, the origin of the self-organized pattern formation is still poorly understood and is currently under study. In this work, it was observed that the discharge current is the dominant parameter controlling the onset of the self-organization of the plasma attachment on a liquid anode. On the other hand, it is observed that inter-electrode spacing is the key parameter that controls plasma self- organization on metal anodes. Presented here are experiments aimed at understanding how these parameters control conditions at the anode surface, which ultimately result in self-organization. Here we determine the effects of space charge at the anode surface and also estimate the anode fall voltage in response to discharge parameter variations. Additionally electron microscopy is used to assess anode morphological changes resulting from the self-organization plasma attachments.

Exploring Astrophysically Relevant Bow Shocks Using MIFEDS and the OMEGA Laser*

Joseph Levesque[a], Carolyn Kuranz[a], Rachel Young[a], Mario Manuel[a], Sallee Klein[a], Gennady Fiksel[a], Matthew Trantham[a], Patrick Hartigan[b], Andy Liao[b], and Chikang Li[c]

(a) University of Michigan, Ann Arbor (jmlevesq@umich.edu, ckuranz@umich.edu, rpyoung@umich.edu, mmanuel@umich.edu, salleer@umich.edu, gfiksel@umich.edu, mtrantha@umich.edu)
(b) Rice University (hartigan@rice.edu, andy.liao@rice.edu)
(c) Massachusetts Institute of Technology (li@psfc.mit.edu)

We present current experiments using the Omega Laser Facility and their magneto-inertial fusion electrical discharge system (MIFEDS) to observe the effect of magnetic pressure on bow shock dynamics in an astrophysically relevant regime. Astrophysical bow shocks are an interesting phenomenon in which a shock forms when incident supersonic flow encounters a sufficiently magnetized medium surrounding an object. The most well-known example of this phenomena is the interaction of the solar wind with the Earth's magnetic field, which creates our magnetosphere. In our experiment the magnetosphere will be emulated by a current flowing through a curved wire to create an azimuthal magnetic field. To create the analogous solar wind, lasers rear-irradiate two opposing graphite targets so the plasma outflows collide and then expand along the collision plane toward the magnetized wires. We use the UV Thomson scattering diagnostic technique to determine plasma parameters along with optical imaging and proton radiography to characterize the plasma flow and the bow shock that forms.

* This work is supported by the U.S. DOE, through NNSA grants DE-NA0002956 (SSAA) and DE-NA0002719 (NLUF), by the LLE under DE-NA0001944, and by the LLNL under subcontract B614207 to DE-AC52-07NA27344.

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

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

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

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

For intense, ps scale lasers, propagation through underdense plasmas results in forces which expel electrons from along the laser axis, resulting in the formation of channels. [1] Electrons can then be injected from the channel walls into the laser path, which results in the direct laser acceleration (DLA) of these electrons and the occurrence of an electron beam of 100's of MeV. [2] Experiments performed at the OMEGA EP laser studied the formation of a laser channel in an underdense CH plasma, as well as the spatial properties and energy of an electron beam created via DLA mechanisms. The 4 omega optical probe diagnostic was used to characterize the density of the plasma plume, while proton radiography was used to observe the electromagnetic fields of the channel formation. These electric fields as well as the spectra of the accelerated electrons have been studied across different plasma density profiles. The channel behavior and electron spectra are compared to 2D particle-in-cell simulations.

* This work was supported by the National Laser Users' Facility (NLUF) ,DOE.

References

[1] Willingale et al., Physical Review Letters, 106, 105022 (2011)
[2] Willingale et al., New Journal of Physics, 15, 025023 (2013)

Advanced Ignition Technologies for Heavy-Duty Natural-Gas Engines*

Ahmet Mazacioglu, Michael Gross, and Volker Sick

Department of Mechanical Engineering
University of Michigan, Ann Arbor, MI 48109 USA
(mazaci@umich.edu, mcgross@umich.edu, vsick@umich.edu)

Achieving high thermal efficiency and low pollutant emissions are the two most important goals of engine research worldwide. Heavy-duty trucks currently use primarily compression-ignition (CI) engines due to their efficiency and low maintenance requirements. However, the Diesel fuel used in CI engines yields polluting combustion products that require costly and complicated after-treatment. There is a growing demand to replace Diesel fuel with natural gas (NG), which produces lower emissions. However, NG has a significantly higher autoignition temperature (580 °C) than Diesel fuel (210 °C); hence it is not suitable for CI use. On the other hand, the superior anti-knock property of NG (Motor Octane Number 122, [1]) makes it a good fuel for spark-ignition (SI) engines. Additionally, it is preferred to burn NG in lean conditions to minimize fuel consumption and also to use exhaust-gas recirculation (EGR) to further reduce emissions of oxides of nitrogen (NO_x). However, reaching all these goals is challenging, because common spark-ignition techniques are not specifically optimized for heavy-duty NG combustion, let alone its lean and EGR-diluted versions.

In an experimental program to identify improved ignition systems and implement them into an NG-operated heavy-duty engine, we have extensively surveyed ignition systems in use and under development, and we have identified (i) corona ignition [2] and (ii) turbulent jet ignition (TJI, [3]) as the technologies with the highest potential for our application. In conventional igniters, a single ~1-mm spark is generated and heats up the combustible mixture to the autoignition temperature to create a flame kernel that must grow across the chamber. By contrast, corona ignition utilizes ~5-25 mm non-equilibrium plasma streamers to ignite a larger volume and to distribute the input energy into the preferred electronic energy levels (rotational and vibrational, rather than translational) within the combustible mixture. TJI uses a pre-chamber in which a rich air/fuel mixture is ignited. High-energy, turbulent flames jet out of nozzles in the pre-chamber into the main chamber and ignite the air/fuel mixture contained therein. Ultra-lean mixtures can be ignited in this way.

We are building a dual-axis borescope/camera setup to study the ignition and resultant flame-kernel growth produced by these ignition systems in a modified production heavy-duty engine. We will characterize the performance of each system using infrared imaging in order to eventually guide the commercial implementation in truck fleets.

* Work funded by U.S. Department of Energy, under Award Number DE-EE0007307.

References

[1] G. Genchi and E. Pipitone, "Octane Rating of Natural Gas-Gasoline Mixtures on CFR Engine," 2014.

[2] A. Schenk, G. Rixecker, and S. Bohne, "Results from Gasoline and CNG Engine Tests with the Corona Ignition System EcoFlash," in *Laser Ignition Conference*, 2015, p. W4A. 4.

[3] E. Toulson, A. Huisjen, X. Chen, C. Squibb, G. Zhu, H. Schock, *et al.*, "Visualization of Propane and Natural Gas Spark Ignition and Turbulent Jet Ignition Combustion," *SAE International Journal of Engines*, vol. 5, pp. 1821-1835, 2012.

High Throughput Plasma Water Reactor*

Selman Mujovic and John Foster

University of Michigan, Dept. of Nuclear Engineering & Radiological Sciences, Plasma Science and Technology Laboratory (mujovics@umich.edu, jefoster@umich.edu)

The troublesome emergence of new classes of micro-pollutants, such as pharmaceuticals and endocrine disruptors, poses challenges for conventional water treatment systems. In an effort to address these contaminants and to support water reuse in drought stricken regions, new technologies must be introduced. The interaction of water with plasma rapidly mineralizes contaminants by inducing advanced oxidation in addition to other chemical, physical and radiative processes, such as precipitation, shockwaves and UV. The primary barrier to the implementation of plasma-based water treatment is process volume scale up.

In this work, we investigate a potentially scalable, high throughput plasma water reactor that utilizes a packed bed dielectric barrier-like discharge to maximize the plasma water interface. Here, the water serves as the dielectric medium. High-speed imaging and emission spectroscopy are used to characterize the reactor discharges. Changes in methylene blue concentrations and basic water parameters are mapped as a function of plasma treatment time. Experimental results are compared to electrostatic and plasma chemistry computations, which will provide insight into the reactor's operation so that efficiency can be assessed. The reactor's current and potential efficiencies will be compared to competing disinfection methods.

* NSF (CBET 1336375)

Etching of High Aspect Ratio Contacts in SiO_2 by Pulsed Capacitively Coupled Plasmas Sustained in $Ar/C_4F_8/O_2$ Mixtures*

Shuo Huang, Peng Tian, Chad Huard and Mark J. Kushner

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

As feature sizes continue to shrink and aspect ratios continue to increase in semiconductor processing, maintaining critical dimensions (CDs) of the features becomes more challenging. This is particularly the case for plasma etching of high aspect ratio contacts (HARC) in dielectrics such as SiO_2, in which aspect ratios of 50-100 are desired. Bowing and tapering of the features are continuing challenges resulting in deviation of the feature from an ideal anisotropic etching profile. By applying pulsed power in capacitively coupled plasmas with pulse repetition frequencies (PRF) of hundreds of Hz, the features receive different fluxes of radicals and ions having different ion energy angular distributions (IEADs) during the pulse-on and pulse-off subcycles. By carefully tuning PRF and duty cycle (DC), fluxes into the features alternately result in passivation and etching, which enables optimization of the etch profile.

We report on results from a computational investigation of etching of HARCs in SiO_2 sustained in a $Ar/C_4F_8/O_2$=75/15/10 mixture at 25 mTorr in a tri-frequency capacitiviely coupled plasma. Modeling of the reactor scale and surface chemistry was performed using the Hybrid Plasma Equipment Model (HPEM), from which the neutral and ion fluxes and IEADs to the wafer were obtained. The feature scale modeling was performed with the Monte Carlo Feature Profile Model. The reactor utilizes 3 frequencies, two lower frequencies of 10 MHz (2.5 kW) and 5 MHz (5 kW), and one higher frequency of 80 MHz, which alternates between 50 W and 1,200 W with a PRF of 200 Hz and 50% DC. Radical fluxes to the wafer are dominated by CF_x, O and F due to there being significant dissociation of the feedstock gases. Ion fluxes are dominated by Ar^+ and $C_nF_x^+$. The 80 MHz power dominantly produces polymerizing CF_x neutrals. At 50 W at 80 MHz, the polymerizing fluxes provide sidewall coverage and net etching occurs. For 1200 W, the polymerizing fluxes produced by 80 MHz dominate and an etch stop occurs. By alternating between etching and passivation during pulsing, the etch profile evolves more anisotropically and leads to more flattened etch front compared with continuous-wave (CW) power, as shown in Fig. 1.

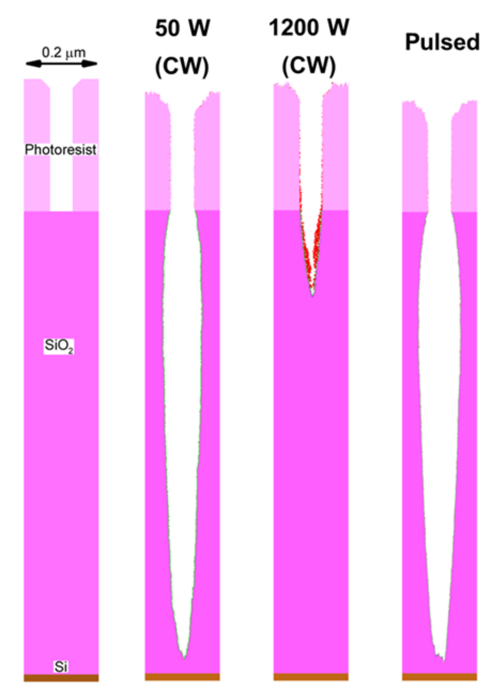


Figure 1 - Etch profile of HARC in SiO_2 when varying 80 MHz power: (left) 50 W (CW), (middle) 1,200 W (CW), (right) alternating between 50 W and 1,200 W with PRF=200 Hz and DC=50%.

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

Vortex Merger in a Supersonic, Dual-mode Kelvin-Helmholtz Instability Experiment*

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

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

Hydrodynamic instabilities play a dominant role in the transport of mass, momentum, and energy in nearly all plasma environments, including interstellar jets, solar convective zones, and at magnetospheric boundaries. In recent decades, the contribution of these instabilities has been underestimated in many high-energy-density systems such as core-collapse supernovae and fusion experiments. Since then, significant advances have been made to our diagnostic capabilities, simulation codes, and experimental techniques. We developed and applied a novel experimental platform to study the evolution of well-characterized single-mode and dual-mode seed perturbations evolving in a steady, supersonic flow for unprecedented durations [1,2].

The Kelvin-Helmholtz instability is a hydrodynamic instability that can produce vortical structures and turbulence in a system with shear flow. In a supersonic flow, when fluid compressibility becomes significant, the evolution of the instability and the resultant structure is altered. In a complicated multi-mode system, smaller vortices merge into larger, harmonic modulations. This merger process is the most important and unknown physical process that determines the evolution of the Kelvin-Helmholtz turbulent mixing zone, especially in a supersonic regime. We present the first observations and measurements of the Kelvin-Helmholtz instability vortex merger rate from well-controlled dual-mode initial conditions.

This experiment was performed at the OMEGA-EP facility by utilizing three laser beams to create an extended, 28 ns laser drive, sustaining a supersonic shockwave over a precision machined foam-plastic interface for roughly 70 ns. The primary diagnostic was x-ray radiography, using a spherical crystal imager to image the system with Cu K_α radiation at 8.0 keV.

* Supported by the U.S. DOE, through NNSA grants DE-NA0002956 (SSAA) and DE-NA0002719 (NLUF), by the LLE under DE-NA0001944, and by the LLNL under subcontract B614207 to DE-AC52-07NA27344.

References:

[1] W.C. Wan, G. Malamud, *et al.*, Physical Review Letters, **115**, 145001, (2015).
[2] G. Malamud, *et al.,* High Energy Density Physics, **9**, 672-686, (2013)

List of Participants

Last Name	First Name	Institution	Email
Antoulinakis	Foivos	UM	foivos@umich.edu
Azari	Abigail	UM	azari@umich.edu
Batson	Thomas	UM	tgbatso@umich.edu
Behm	Keegan	UM	ktbehm@umich.edu
Campbell	Paul	UM	campbpt@umich.edu
Charris	Amanda	MSU	charrish@msu.edu
Collard	Timothy	UM	collardt@umich.edu
Cusson	Sarah	UM	cusson@umich.edu
Dale	Ethan	UM	etdale@umich.edu
Davis	Joshua	UM	davisjs@umich.edu
Dharuman	Gautham	MSU	dharuman@egr.msu.edu
Engeling	Kenneth	UM	kenengel@umich.edu
Huang	Shuo	UM	shuoh@umich.edu
Huard	Chad	UM	chuard@umich.edu
Hussein	Amina	UM	amina.e.hussein@gmail.com
Izadi	Alborz	MSU	alborz.izadi@gmail.com; izadialb@msu.edu
Kovach	Yao	UM	yaok@umich.edu
Krek	Janez	MSU	krek@msu.edu
Kruszelnicki	Juliusz	UM	jkrusze@umich.edu
Lai	Janis	UM	janislai@umich.edu
Lanham	Steven	UM	sjlanham@umich.edu
Leon	Omar	UM	omarleon@umich.edu
Levesque	Joseph	UM	jmlevesq@umich.edu
Lietz	Amanda	UM	lietz@umich.edu
Ma	Kevin	UM	kevima@umich.edu
Mandal	Rajib	MSU	mandalra@egr.msu.edu
Mazacioglu	Ahmet	UM	mazaci@umich.edu
Miars	Grant	UM	gmiars@umich.edu
Mujovic	Selman	UM	mujovics@umich.edu
Parsey	Guy	MSU	guy.parsey@gmail.com
Qu	Chenhui	UM	chenqu@umich.edu
Raisanen	Astrid	UM	astridr@umich.edu
Raymond	Anthony	UM	aeraym@umich.edu
Rice	Scott	MSU	scott.a.rice@gmail.com; ricesco1@msu.edu
Terhune	Kurt	MTU	kjterhun@mtu.edu
Tian	Peng	UM	tianpeng@umich.edu
Vandervort	Robert	UM	dervort@umich.edu
Wan	Willow	UM	wwan@umich.edu
Young	Rachel	UM	rpyoung@umich.edu