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Western Michigan University**

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GRADUATE STUDENT SYMPOSIUM**

October 18, 2017

2:30 – 7:20 pm

North Campus, University of Michigan

1301 Beal Avenue

Ann Arbor, MI 48109-2122

Schedule

2:30 – 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 <i>Opening remarks</i>	1005 EECS
3:40 – 4:40	Special MIPSE Seminar: Dr. J. Tiberius Moran-Lopez National Nuclear Security Administration <i>Bridging HED Plasma Sciences to Stockpile Stewardship and Defense Applications</i>	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	<i>Best Presentation Award</i> ceremony	EECS atrium

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Abstracts

Kelvin-Helmholtz Evolution in Subsonic Cold Streams Feeding Galaxies

A.M. Angulo^a, S.X. Coffing^a, C.C. Kuranz^a, R.P. Drake^a, S.R. Klein^a,

M. Trantham^a, G. Malamud^b

(a) University of Michigan, Ann Arbor, MI

(b) Nuclear Research Center, Negev, Israel

The most prolific star formers in cosmological history lie in a regime where dense filament structures carried substantial mass into the galaxy to sustain star formation without producing a shock. However, hydrodynamic instabilities present on the filament surface limit the ability of such structures to deliver dense matter deeply enough to sustain star formation. Simulations lack the finite resolution necessary to allow fair treatment of the instabilities present at the stream boundary. Using the Omega EP laser, we simulate this mode of galaxy formation with a cold, dense, filament structure within a hotter, subsonic flow and observe the interface evolution. Machined surface perturbations stimulate the development of the Kelvin-Helmholtz (KH) instability due to the resultant shear between the two media. A spherical crystal imaging system produces high-resolution radiographs of the KH structures along the filament surface. The results from the first experiments of this kind, using a rod with single-mode, long-wavelength modulations, will be discussed.

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References

- [1] Avishai Dekel, Re'em Sari, and Daniel Ceverino, "Formation of Massive Galaxies at High Redshift: Cold Streams, Clumpy Disks, and Compact Spheroids", *Astrophysical Journal* 703, 785 (2009).
- [2] M. Krumholz, A. Burkert, "On the Dynamics and Evolution of Gravitational Instability-dominated Disks", *Astrophysical Journal* 724, 895 (2010)
- [3] S. Choudhury, "Nonlinear evolution of the kelvin-helmholtz instability of supersonic tangential velocity discontinuities", *Journal of Mathematical Analysis and Applications* 214, 561 (1997).

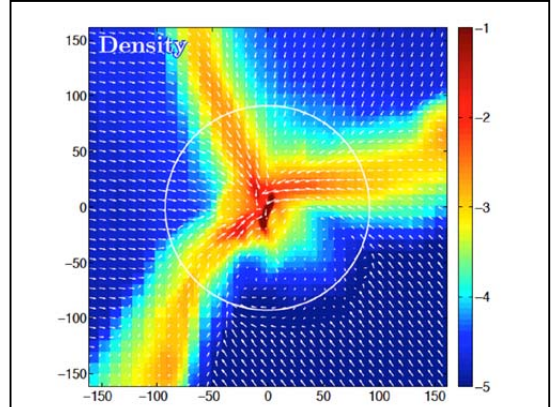


Figure 1 – Density slice from Dekel et al., showing atoms per cc within halo from their MareNreNostrum simulation.

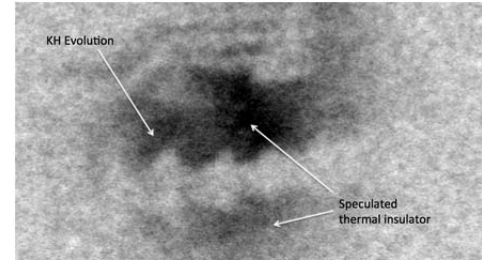


Figure 2 – Radiograph taken at 70 ns with a base thickness of 62 um, indicating KH evolution along the filament surface

Implementation of an Implicit 2V Rosenbluth-Fokker-Planck Operator*

Alexander R. Vazsonyi

Nonequilibrium Gas and Plasma Dynamics Lab, University of Michigan (vazsonyi@umich.edu)

Kinetic theory aims to describe gases on a macroscopic level by analyzing their motion on a microscopic level. The Boltzmann equation, the governing equation for dilute gases which may also be used to describe plasmas, features a right hand collision term which is notoriously difficult to solve both analytically and numerically. While low-density plasmas are often approximated as collisionless (the Vlasov equation), a higher level of fidelity may be achieved by accounting for the collisions that do occur. Several models of collisions in the Boltzmann equation exist; the Fokker Planck model, which assumes many grazing collisions and an inverse square potential, is considered here.

The Rosenbluth-Fokker-Planck operator model is a unique formulation which casts the equation in terms of the Rosenbluth potentials, Poisson equations which are relatively simple to solve numerically [1]. Drawing from the work of Taitano et al., a conservative, multi-species implementation of this equation has been applied [2]. This methodology forms a nonlinear residual and solves the system through use of a Jacobian-Free Newton Krylov (JFNK) method.

Test cases for single species were run and multi-species cases are currently being considered. For single species, a supplied distribution does, as expected, converge to a Maxwellian distribution as time marches on. Figure 1 demonstrates the algorithm's ability to maintain a Maxwellian, in this case with conservation of momentum for Argon; mass, and energy are also well conserved, and entropy increases monotonically. The algorithm's conservative properties are dependent on grid refinement, and the scheme, while implicit, is currently sensitive to time step. This dependence is to be minimized through future implementation of preconditioning in the JFNK solver.

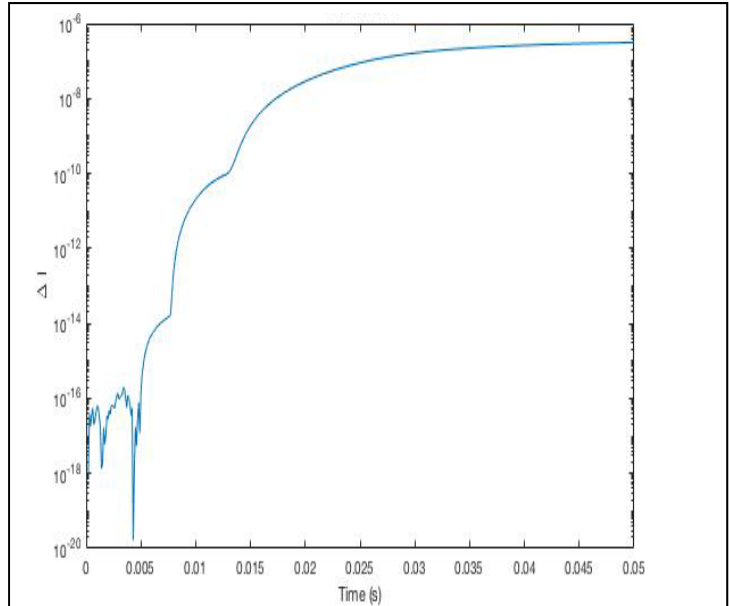


Figure 1 – Momentum change of Argon maintaining a Maxwellian; $dt = 1e-4$, run on a 32×16 grid.

* Work supported by the Air Force Research Laboratory

References

- [1] Rosenbluth, Marshall N., William M. MacDonald, and David L. Judd. "Fokker-Planck equation for an inverse-square force." *Physical Review* 107.1 (1957): 1.
- [2] Taitano, William T., et al. "A mass, momentum, and energy conserving, fully implicit, scalable algorithm for the multi-dimensional, multi-species Rosenbluth–Fokker–Planck equation." *Journal of Computational Physics* 297 (2015): 357-380.

Molecular Admixtures in Helium Atmospheric Pressure Plasma Jets*

Amanda M. Lietz^a and Mark J. Kushner^b

(a) University of Michigan, Dept. of Nuclear Eng. & Radiol. Science, Ann Arbor, MI, USA

(b) University of Michigan, Dept. of Electrical Eng. & Computer Science, Ann Arbor, MI, USA
(lietz@umich.edu, mjkush@umich.edu)

Atmospheric pressure plasma jets (APPJs) are low temperature plasma sources that can be used in ambient air, and have been of growing interest for biomedical applications. Treatment with these plasma sources can kill bacteria, improve wound healing, and selectively kill cancer cells.[1-2] These effects are mostly attributed to the reactive chemistry that is generated by dissociation of molecules. APPJs usually operate with a rare gas, and are allowed to mix with the ambient air. Sometimes molecular admixtures, such as O₂ or H₂O are added to the rare gas flow to increase the production of particular reactive oxygen and nitrogen species (RONS).

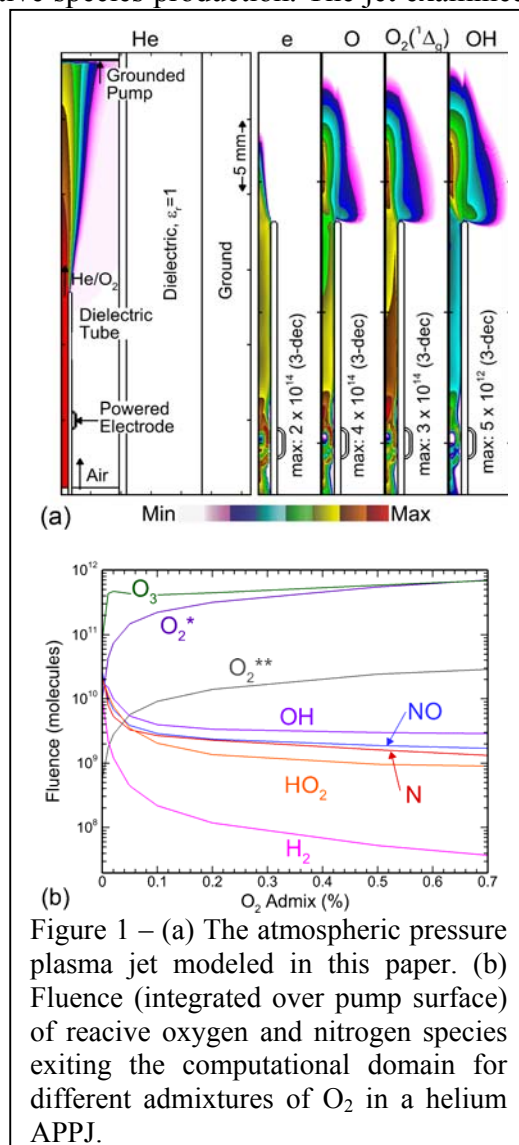
In this computational study, *nonPDPSIM*, a 2-dimensional plasma hydrodynamics model, is used to examine the effect of molecular admixtures on reactive species production. The jet examined in this case, shown in Fig. 1a, is a dielectric tube with a powered ring electrode, with He flowing through it at 2 slm. A -10 kV pulse is applied to the powered electrode for 120 ns, and an ionization wave begins at the powered electrode and propagates out of the tube into the He plume.

This APPJ was simulated for several admixtures of O_2 and H_2O . The RONS exiting the computational domain through the pump for different admixtures of O_2 are shown in Fig. 1b. As the O_2 admixture is increased, several species that are a direct result of O_2 , including O_2^* and O_2^{**} increase. More O_3 is also produced by the reaction $O + O_2 + M \rightarrow O_3 + M$. As the O_2 admixture increases, more of the electron energy is used to dissociate and excite O_2 , rather than other species such as H_2O and N_2 . As a result, OH , NO , N , HO_2 , and H_2 decrease with this admixture. The mechanisms responsible for the evolution of reactive species as the molecular admixtures are increased are discussed in this paper. A water vapor admixture is also analyzed.

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

References

- [1] M. G. Kong, et al. New J. Phys. **11**, 115012 (2009).
[2] N. Kaushik, et al., Nat. Sci. Reports. **5**, 8587 (2015).



Status of a DC Plasma Window for Sustained Gas Flow Reduction through a Narrow Channel*

Andrew LaJoie, Jian Gao, and Felix Marti

National Superconducting Cyclotron Lab, Michigan State University (lajoie@nsl.msu.edu)

The Plasma Window (PW) is a device that utilizes a steady state wall stabilized DC arc supported by a flowing He gas through a 6 mm diameter and approximately 10 cm long channel to sustain a large degree of pressure separation between high and low pressure chambers on either side of the channel.[1] This separation is accomplished without the need for solid interface material, and would allow for a high pressure He gas target (100s of torr) to be isolated from surrounding low pressure regions (100s of mtorr). This makes it an attractive complement to a gas charge stripper used in a heavy ion particle accelerator, but the exact mechanisms responsible for the large observed differential are currently inadequately understood, and obtaining a more coherent understanding of the mechanisms dictating the pressure drop would better enable optimizing the PW for the desired conditions.[2] Initial results from the PW test stand at the National Superconducting Cyclotron Laboratory for helium are presented as well as argon for comparison, progress and diagnostic development are described. Of primary interest are the pressure separation, gas flowrate, spectral data, and the heat load on the enclosure. The future addition of other diagnostics to further characterize the plasma and supporting gas is also briefly discussed.

* Work supported by National Science Foundation

References

- [1] A. Hershcovitch, Phys. of Plasmas 5, 2130 (1998).
- [2] J. A. Nolen and F. Marti, Rev. of Accel. Sci. and Tech. 6, 221 (2013).

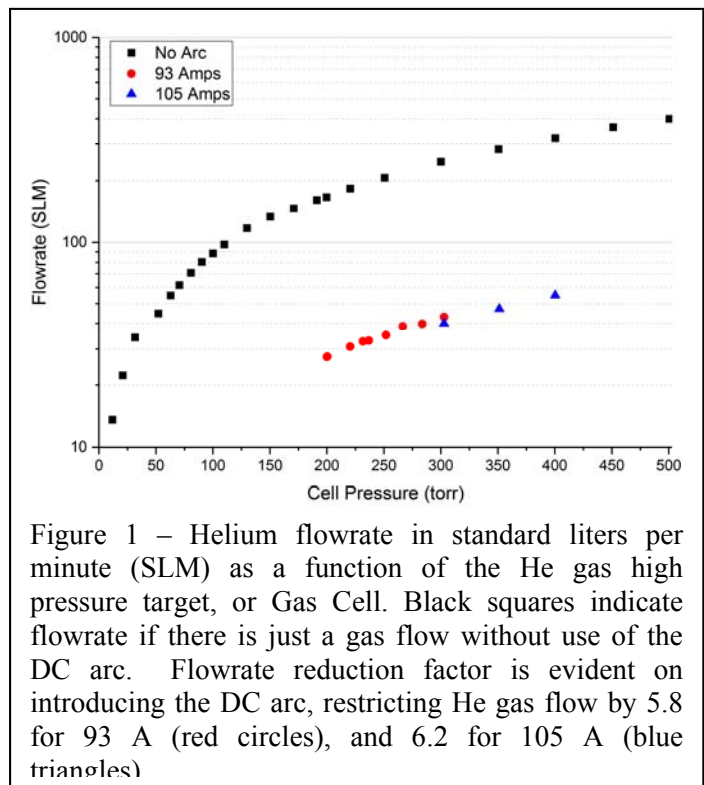


Figure 1 – Helium flowrate in standard liters per minute (SLM) as a function of the He gas high pressure target, or Gas Cell. Black squares indicate flowrate if there is just a gas flow without use of the DC arc. Flowrate reduction factor is evident on introducing the DC arc, restricting He gas flow by 5.8 for 93 A (red circles), and 6.2 for 105 A (blue triangles)

A Platform for X-Ray Thomson Scattering Measurements of Radiation Hydrodynamic Experiments on the NIF*

H. J. LeFevre^a, K. Ma^a, P. X. Belancourt^a, M. J. MacDonald^b, T. Doeppner^c, P. A. Keiter^a and C. C. Kuran^a

(a) University of Michigan Climate and Space Sciences and Engineering, hjlefe@umich.edu

(b) University of California, Berkeley CA

(c) Lawrence Livermore National Laboratory, Livermore CA

A recent experiment on the National Ignition Facility(NIF) radiographed the evolution of the Rayleigh-Taylor(RT) instability under high and low drive cases[1]. This experiment showed that under a high drive the growth rate of the RT instability is reduced relative to the low drive case. The high drive launches a radiative shock, increases the temperature of the post-shock region, and ablates the spikes, which reduces the RT growth rate. The plasma parameters must be measured to validate this claim.

We present a target platform for making X-Ray Thomson Scattering(XRTS) measurements on radiation hydrodynamics experiments on NIF to measure the electron temperature of the shocked region in the above cases. This is accomplished with a scattering geometry in the non-collective regime and a non-degenerate plasma. Specifically, we show that a previously fielded NIF radiation hydrodynamics platform can be modified to allow sufficient signal and temperature resolution for XRTS measurements. Photonics and synthetic XRTS spectra are provided to illustrate this point. In addition, a 3D model of the target design is presented to show the shielding coverage of the physics package.

* This work is funded by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-NA0002956 and the National Science Foundation through the Basic Plasma Science and Engineering program.

References

[1] C. C. Kuran et. al., “How high energy fluxes may affect Rayleigh-Taylor instability growth in young supernova remnants” (Pre-publication).

Scaling Laws of Rotating Magnetic Field Field-Reversed Configuration Thrusters

Joshua M. Woods, Benjamin A. Jorns and Alec Gallimore

University of Michigan, Ann Arbor, MI 48105, USA
(jmwoods@umich.edu)

The electrodeless Lorentz force field-reverse configuration thruster (FRC) is an electric propulsion concept that utilizes plasmoids confined in a field-reversed configuration for pulsed propulsion. FRCs are an attractive option for in-space propulsion due to their high specific impulse and ability to use a multitude of propellants [1]. While the principles of forming plasmoids in a field-reverse configuration for confinement have been well established in the fusion community, key aspects of their use as thrusters remains poorly understood. These include propellant utilization efficiency and thrust performance.

FRC thrusters generate a plasmoid by inducing azimuthal currents in a plasma column confined by a steady background axial magnetic field. At a threshold value, the magnetic field resulting from the flowing azimuthal current reverses the background axial field near the plasma centerline, resulting in a self-contained magnetic structure populated by a high density plasma [1]. This magnetic plasmoid is then accelerated by a Lorentz force that results when the azimuthal currents in the plasmoid interact with a gradual radial gradient in the background field. Multiple techniques exist for generating the azimuthal current including, but not limited to, using planar coils and the conical θ -pinch technique. In this study, the method for generating the azimuthal current is through the use of rotating magnetic fields (RMF). Given a sufficiently high RMF magnitude, the electrons become tied to and rotate synchronously with the field lines.

Research on FRC thrusters has steadily grown over the past decade. Prototypes of FRC thrusters exist and have been tested with a variety of propellants [1]. In addition, numerical analyses have been performed to investigate the scaling of FRCs with already formed plasmoids [2]. However, there are still open questions about how the thrust and mass utilization efficiencies depend on the thruster operating conditions. Current scaling laws that capture the formation and ejection of the plasmoid do not provide a relation to the RMF currents and how the presence of a plasmoid influences them [1].

This study details fundamental scaling laws for thruster operation. A magnetohydrodynamics hierarchy coupled with a basic circuit analysis is used to establish relationships for parameters that effect ideal thruster performance. Two models are discussed: one that does not consider the load on the circuit due to the plasmoid and another which does. Operating parameters of these devices such as current, voltage, and thruster geometry are related to performance parameters including impulse and efficiency.

References

- [1] Slough, John, David Kirtley, and Thoomas Weber, “Pulsed Plasmoid Propulsion: The ELF Thruster,” **IEPC-2009-265**, 31st International Electric Propulsion Conference, Ann Arbor, Michigan, September 20 – 24, 2009
- [2] Little, Justin, Barry Cornella, Anthony Pancotti, and David Kirtley, “Scaling of FRC Thrusters with Neutral Entrainment,” **AFRL-RQ-ED-TP-2016-302**, 8th JANNAF Spacecraft Propulsion Subcommittee Meeting, Phoenix, Arizona, December 5 – 9, 2016

3D MHD Simulations of Auto-Magnetizing Imploding Liners for ICF

J.M. Woolstrum^a, C. A. Jennings^b, G. A. Shipley^b, T. J. Awe^b, S. A. Slutz^b, N.M. Jordan^a, Y.Y. Lau^a, K. J. Peterson^b, R.D. McBride^a

(a) University of Michigan (jeffwool@umich.edu)

(b) Sandia National Laboratories

AutoMag [Slutz et al., Phys. Plasmas 24, 012704 (2017)] is a potential next step in the magnetized liner inertial fusion (MagLIF) program. In standard MagLIF, external coils are used to magnetize deuterium gas inside a metal cylindrical liner, which is imploded by the Z-machine at Sandia National Laboratories. In AutoMag, helical slots are cut into the liner and filled with dielectric insulator to form a solenoid, producing an axial magnetic field from the drive current and removing the need for external field coils. Alternatively with external field coils, AutoMag could produce a field-reversed configuration inside the liner. Recent work at Sandia has found that the breakdown of the dielectric material corresponds to the geometry of the liner/dielectric. We explore this finding in 3D resistive-MHD simulations, modeling geometries relevant to both the 20-MA Z facility, and to the 1-MA MAIZE facility at the University of Michigan.

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. DoE's NNSA under contract DE-NA0003525.

References

[1] Slutz et al., Phys. Plasmas 24, 012704 (2017)

The Effect of Pressure Variations on Micro-Discharge Formation in a 2-D Packed Bed Reactor

Kenneth W. Engeling, Juliusz A. Kruszelnicki, John Foster, and Mark Kushner

University of Michigan, Ann Arbor, MI

(kenengel@umich.edu, jkrusze@umich.edu, jefoster@umich.edu, mjkush@umich.edu)

Packed bed dielectric barrier discharge reactors (PBRs) are one of the technologies at the forefront of advanced plasma applications. PBRs are implemented in systems designed for ozone generation, plasma-aided combustion, dry reforming of methane, and plasma catalysis. Plasma formation and propagation occurs through the porous media of the PBR in the form of microdischarges and are a function of several parameters. To investigate the kinetic mechanisms of the micro-plasma formation, a 2-dimensional packed bed reactor was designed for optical analysis. The 2-d array of dielectric aggregate with varying dielectric constants is used to simulate and visualize plasma formation as a function of voltage, pressure, gas type, and spacing. The 2-d geometry is directly observed using fast cameras and emission spectroscopy. The plasma is sustained using a DC nano-pulsed power supply and an AC voltage typical of dielectric barrier discharges (DBDs). The results of this experiment allows for insights into higher dimensional systems of the same nature.

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

Experimental and Analytical Investigation of the Hollow Cathode Plume Mode

Marcel P. Georgin, Benjamin A. Jorns, and Alec D. Gallimore

University of Michigan

(georginm@umich.edu, bjorns@umich.edu, alec.gallimore@umich.edu)

Hollow cathodes are plasma devices that are commonly used in electric propulsion devices as electron current sources to initiate discharges and neutralize ion beams. While the high propellant efficiency of electric propulsion systems makes them attractive for deep space exploration, this advantage is balanced against the long lifetime requirements (>50 kHrs) of these EP systems to accomplish deep space exploration. To satisfy these requirements, hollow cathodes must be able to meet this stringent requirement. Although hollow cathodes are heavily relied on for electric propulsion technologies, we lack a first-principles understanding of some of the mechanisms that cause cathode erosion. Without this insight into the fundamental physics, electric propulsion devices that rely on hollow cathodes must depend on ground testing in vacuum chambers for flight qualification. This process is prohibitively expensive and time consuming and is a major hurdle for deep space missions that use electric propulsion systems. Furthermore, measurements have shown that ground test facilities do not always replicate the conditions in space and the effects of the facility are also not well understood. [1] Having a fundamental description of cathode erosion mechanisms is a critical step for flight qualification of electric propulsion devices through predictive numerical modeling. This qualification process would both reduce the costs for flight qualification and improve our understanding of how electric propulsion devices will perform on orbit.

The processes that cause erosion of the hollow cathode change depending on the operating regime of the cathode. Historically, cathodes have two operational modes: the spot mode and the plume mode.[2] The spot mode is the nominal operating condition of the cathode and is characterized by having low amplitude discharge current oscillations and relatively low erosion rates. The plume mode is a deleterious operation condition with large plasma oscillations resulting high erosion rates. [3] Although empirical scaling laws have been developed to avoid the plume mode, a first-principles description of the onset of the oscillations associated with this mode does not exist. This knowledge gap means that the onset of the plume mode cannot be predicted.

As an initial attempt to better understand the governing processes for this transition, we have conducted an experimental campaign to characterize the plume mode instability and a theoretical investigation to find a physical intuition for the onset of the wave. Experimentally, we have used electrostatic probe and high-speed imaging techniques to estimate the dispersion of the wave. Figure 1 shows the dispersion estimated using the probes indicating that the wave travels close to the ion drift velocity. The analytical description of the wave was generated using quasi-linear theory and predicts the scaling behavior for the wave growth and the dispersion of the plume mode oscillation.

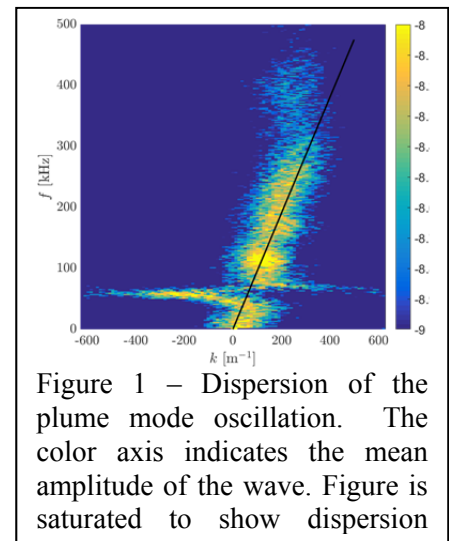


Figure 1 – Dispersion of the plume mode oscillation. The color axis indicates the mean amplitude of the wave. Figure is saturated to show dispersion

References

- [1] T. Randolph et. al., International Electric Propulsion Conference, **IEPC 93-93** (1993)
- [2] G.A. Csiky., NASA Technical Note (1969)
- [3] M. Domonkos et. al., Joint Propulsion Conference, **AIAA-99-2575** (1999).

Effect of Langmuir Probe Measurements on the Spacecraft Potential of Small Spacecraft*

Omar Leon^a, Walter Hoegy^b, Grant Miars^c, and Brian Gilchrist^c

(a) Applied Physics Program, University of Michigan (omarleon@umich.edu)

(b) Department of Climate and Space Sciences and Engineering, MI 48109 (hoegy@umich.edu)

(c) Department of Electrical Engineering and Computer Science
(gmiars@umich.edu, brian.gilchrist@umich.edu)

Historically, spacecraft had current collection areas much larger than their Langmuir probes, such that any change in current to the probe had negligible effects on the spacecraft electric potential. However, as spacecraft size decreases, the surface area of the probes and the spacecraft become comparable leading to non-negligible changes in the spacecraft's electric potential during probe operation. As the Langmuir probe is biased positive relative to the spacecraft, increased electron collection forces the spacecraft potential to become more negative. As a result, many Langmuir probe measurements including plasma potential and temperature are significantly affected [1]. Additionally, the current collected to the probe can approach an asymptotic limit if the spacecraft is unable to collect enough ion current to compensate for the probe's electron current collection.

A spacecraft charging model was created to study the effects of Langmuir probe operation on spacecraft in the ionosphere as a function of area ratios, angle relative to the ion drift velocity, and background plasma properties in support of the MiTEE-I CubeSat mission developed at the University of Michigan. This MiTEE model employs simple, analytic current collection schemes for a cylindrical Langmuir probe and spacecraft in a moving plasma. In this paper, the results of the model are presented and compared with Nascap-2k simulations to determine what missing physics must be included to obtain more accurate predictions.

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

References

[1] Brace, Larry H. "Langmuir probe measurements in the ionosphere." *Measurement Techniques in Space Plasmas: Particles* (1998): 23-35.

An Exact Hot-Tube Solution for Thin Tape Helix Traveling-Wave Tube*

Patrick Y. Wong^a, David P. Chernin^b, Y.Y. Lau^a, Ronald M. Gilgenbach^a and
Brad W. Hoff^c

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

(b) Leidos, Inc. (david.p.chernin@leidos.com)

(c) Air Force Research Laboratory (brad.hoff@us.af.mil)

The exact hot-tube dispersion relation for a thin tape helix traveling-wave tube (TWT) that is stratified by dielectrics (representing the support rods) is derived for the first time, based on its exact cold-tube solution [1]. This is an attempt to provide a reliable determination of the Pierce parameters, in particular the "AC space-charge" parameter QC , for a realistic TWT. The determination of QC remains an outstanding issue [2]. The numerical results from the exact formulation will be compared with other approximate models of TWT that are commonly used in the literature for QC [3].

A numerical solution to the exact hot-tube dispersion relation is provided. An example of a test case considered is shown on the right (Figure 1). Comparison of the solution to other approximate models commonly used in the literature, in particular the Branch and Mihran model and the sheath helix model used in the large-signal simulation code CHRISTINE [4] is provided (Figure 2).

From the numerical solution, an analytic theory was devised to ascertain the exact values of QC . In doing so, it was found that in addition to the Pierce gain (beam-circuit coupling) parameter C , detune parameter b , and loss parameter d , that characterize the operation of a given TWT, a new parameter qC is needed. While QC characterizes the interaction of the beam to the other circuit modes, its symmetric complement qC characterizes the interaction of the circuit modes to the beam modes.

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References

- [1] D. Chernin, et al., *IEEE Trans. ED* 46, 7 (1999).
- [2] D. H. Simon, et al., *Phys. Plasmas* 24, 033114 (2017).
- [3] G. M. Branch and T. G. Mihran, *IRE Trans. ED* 2, 3 (1955).
- [4] T.M. Antonsen, Jr. and B. Levush, NRL report NRL/FR/6840-97-9845 (1997).

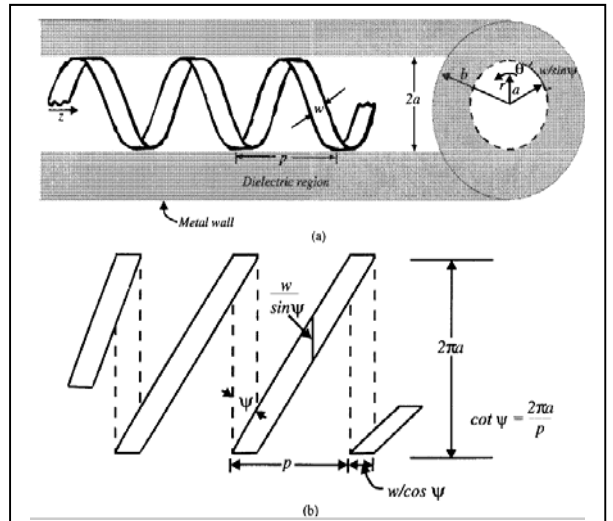


Figure 1 – A thin tape helix TWT stratified by a dielectric.

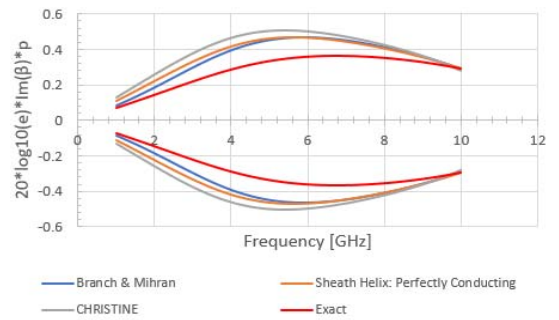


Figure 2 – Comparison of the exact solution to the hot-tube dispersion relation for the gain to other approximate models.

Instability of Power on Dynamics in Inductively Coupled Plasmas*

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 plasmas (ICPs) are used to generate high density plasmas (up to $n_e \sim 10^{12}$ cm⁻³) at low pressures (10s mTorr), useful for microelectronics manufacturing. Pulsing the power to the system is of interest as an additional means of control, offering partial separation of charged particle dynamics and long-lived chemical species [1]. One longstanding challenge for ICPs is igniting the plasma – the initial application of power to form the plasma. When pulsing, reignition of the plasma can be a repetitive difficulty rather than a singular event, and so becomes more important to understand and control.

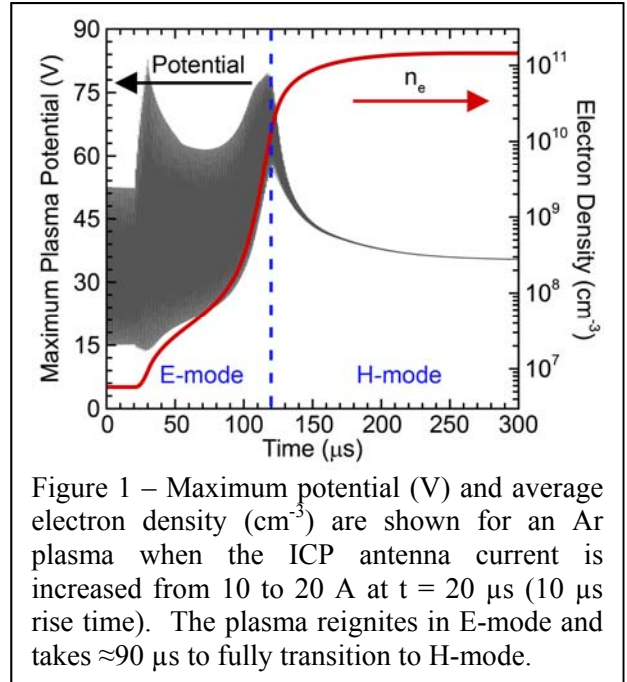
Power to form the plasma comes from an external radiofrequency antenna. When the power first turns on, the electromagnetic skin depth is much longer than the plasma chamber and essentially no power is absorbed inductively. With some small density of ions and electrons, such as in the pulse afterglow from the previous pulse, power can be delivered via electrostatic coupling of the antenna to the plasma – an E-mode discharge. In this mode, power is deposited inefficiently into ion acceleration, slowly building up charged species densities. Eventually, a critical threshold is reached where the electromagnetic skin depth is within the reactor chambers and energy from the induced electric fields is absorbed by the plasma (H-mode discharge).

Computational modeling of the transition from an E-mode to an H-mode discharge was performed using the Hybrid Plasma Equipment Model (HPEM), a 2-d hydrodynamic plasma code [2]. Results capturing the dynamics of transitioning between E- and H-modes for an Ar plasma at 15 mTorr are shown in Fig. 1 when controlling the antenna current. Even when well-controlled, initially operating in E-mode causes the electrical potential in the plasma to significantly oscillate, and fully transitioning through the E-mode takes almost 100 μ s. In other situations, such as when using electronegative gases or controlling the power, these oscillations can be more intense and cause unstable operation.

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

References

- [1] D. J. Economou, J. Phys. D. Appl. Phys. **47**, 303001 (2014).
- [2] M. J. Kushner, J. Phys. D. Appl. Phys. **42**, 194013 (2009).



Plasma Detachment in a Miniature Magnetic Nozzle Source*

Timothy A. Collard, Shadrach Hepner and Benjamin A. Jorns

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

Magnetic nozzles, which convert thermal energy within a plasma into directed kinetic energy through an externally applied diverging magnetic field, have been proposed for a number of electric propulsion devices [1, 2]. As the plasma expands in the diverging nozzle section it is initially confined to the magnetic field lines. However, in order to produce thrust the plasma must detach from the field lines. While it is believed that this detachment does occur - laboratory devices have demonstrated net thrust [2] - the mechanism by which it detaches is not well understood. The leading theory to date (by Ahedo and Merino) suggests that the detachment of electrons is driven by their finite mass while the ion detachment is dependent on their velocity and the ambipolar electric field [3]. However, the experimental evidence for this mechanism is limited. The need is apparent for a more detailed and systematic investigation into the detachment processes.

With this in mind, to investigate detachment a miniature radio frequency (RF) magnetic nozzle source is under development. For flexibility the source can operate with multiple plasma liners ranging from 1.25 cm to 2.5 cm in diameter and 1.9 cm in length. The diverging magnetic nozzle is generated by an electromagnet with 149 windings and is capable of producing a peak axial magnetic field of up to ~ 900 G within the plasma liner. Power is deposited into the plasma at 13.56 MHz via a 3-turn inductive coil antenna by an external RF source. Both the RF antenna and the electromagnet are water cooled.

A suite of electrostatic probes, including a double Langmuir probe, an emissive probe, and a Faraday probe are used to map the properties within the plume. The magnetic field is spatially mapped using a 3-axis gaussmeter. The ion velocity trajectories are directly measured using Laser Induced Fluorescence. The presence of azimuthal waves is investigated using a FASTCAM capable of up to 1.5 million frames per second.

The results from these diagnostics allow for the further development of theory describing detachment from first principles. The experiment will be repeated with different magnetic field strengths, neutral gas flow rates, input powers, and plasma liner geometries to verify the completeness of the theory over a range of plasma regimes.

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References

- [1] Sheehan, J., et al. (2015). Initial Operation of the CubeSat Ambipolar Thruster. 34th International Electric Propulsion Conference. Hyogo-Kobe, Japan.
- [2] Takahashi, K., Charles, C., Boswell, R., and Ando, A., "Performance improvement of a permanent magnet helicon plasma thruster," *Journal of Physics D: Applied Physics*, Vol. 46, No. 35, 2013, pp. 352001.
- [3] Ahedo, E. and Merino, M. (2012). "Two-dimensional plasma expansion in a magnetic nozzle: Separation due to electron inertia." *Physics of Plasmas* 19(8): 083501.



Figure 1 - A front view of the source operating on xenon with $\dot{m} = 30$ sccm and $P_{dep} < 120$ W. Note the apparent dim spot in the

Backward Wave Oscillation Thresholds In A Traveling-Wave Tube*

A. Jassem, P. Wong, F. Antoulakis, Y. Y. Lau

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

Backward wave oscillation (BWO) poses a serious threat to the stable operation of a traveling-wave tube (TWT). The threshold for the onset of BWO in a TWT was formulated by Johnson [1]. In this paper, we extend Johnson's model to include random variations of circuit phase velocity along the tube axis (Fig. 1). Such random variations may arise from the manufacturing tolerance and become increasingly important at high frequencies. Applying the 3-wave treatment [2] to Johnson's approach, we find that the BWO threshold is minimally affected by these random variations (Fig. 2).

We have also extended Johnson's theory to include finite reflections at the ends of an error-free TWT. We varied the composite reflection coefficient $R \in [0,1]$ and its associated phase $\phi \in [0,2\pi]$ to study their effects on the BWO threshold (Fig. 3). The latter theory is being compared with results from an experimental helix test circuit.

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References

- [1] H. R. Johnson, *Proc. IRE.* **43**, 684 (1955).
- [2] S. Sengele, *et al.*, *J. Appl. Phys.* **113**, 074905 (2013)



Figure 1 – Example of random variations along tube axis; b is the tuning parameter.

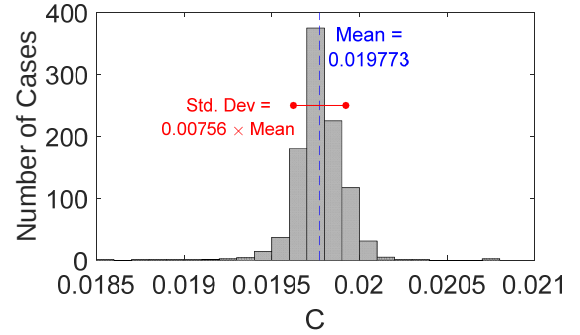


Figure 2 – Distribution in threshold gain parameter C for a standard deviation in circuit phase velocity of 3.4% in a tube with zero cold circuit loss and zero space charge

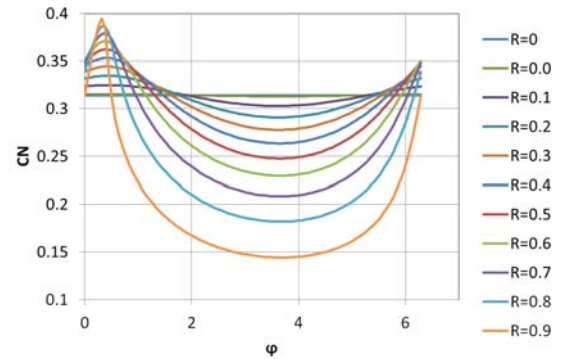


Figure 3 – Effect of end reflections on the threshold gain parameter CN

Statistical Analysis of Interchange Injection Events from Over a Decade of Cassini Data at Saturn*

Abigail Azari^a, Xianzhe Jia^a, Michael Liemohn^a, Nick Sergis^{b, c}, Michelle Thomsen^d, Donald Mitchell^e, Abigail Rymer^e, Christopher Paranicas^e

(a) University of Michigan, Climate and Space Sciences and Engineering (azari@umich.edu)

(b) Academy of Athens Office of Space Research & Institute for Astronomy

(c) Space Applications and Remote Sensing of the National Observatory of Athens

(d) Planetary Science Institute

(e) Johns Hopkins University Applied Physics Laboratory

The Cassini spacecraft has routinely observed interchange injection events with multiple instruments since arriving at Saturn in 2004. Interchange injection events are thought to initiate from a Rayleigh-Taylor like plasma instability sourced from Saturn's rapid rotation (period ~ 10.8 hours) and dense plasma population outgassing primarily from Enceladus, and are the primary source of mass transport in the inner/middle magnetosphere. This dense plasma must be transported outward, and to conserve magnetic flux, inward moving flux tubes of low density, energetic ($> \text{keV}$) plasma from the outer reaches of the Saturnian system also occur. These inward-bound flux tubes are referred to as interchange injections.

We will present a statistical evaluation of the occurrence rates of interchange injections at Saturn demonstrating seasonal dependence of interchange over the entirety of the Cassini mission's equatorial orbits between 2005 and 2016. We identify interchange events from CHarge Energy Mass Spectrometer (CHEMS) H^+ data using a trained and tested automated algorithm. Our event identification compares well with manual identification and previous surveys of injections by L-shell and local time.

We find that peak rates of interchange events occur between 7 - 9 Saturn radii, in agreement with previous surveys. We also evaluate interchange by preferred local time sector and season, splitting our events into pre-equinox, equinox, and post - equinox time periods. We determine that over all seasons, nightside occurrence dominated as compared to dayside, but the preferred dayside sector shifts from pre-noon during equinox, to post-noon during post-equinox.

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Influence of Plasma Density on the Generation of 100's MeV Electrons Via Direct Laser Acceleration

Amina Hussein^a, T. Batson^a, A.V.Arefiev^b, H. Chen^c, R.S. Craxton^c, A. Davies^c, D.H. Froula^c, D. Haberberger^c, O. Jansen^b, K. Krushelnick^a, P.M. Nilson^c, W. Theobald^c, T. Wang^b, G.J. Williams^d, L. Willingale^a

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

(b) University of California San Diego, San Diego, CA

(c) Lab for Laser Energetics, Rochester, NY

(d) Lawrence Livermore National Lab, Livermore, CA

The role of plasma density and quasi-static fields in the acceleration of electrons to many times the ponderomotive energies (exceeding 400 MeV) by high-energy, picosecond duration laser pulses via Direct Laser Acceleration (DLA) from underdense CH plasma was investigated. Experiments using the OMEGA EP laser facility and two-dimensional particle-in-cell simulations using the EPOCH code were performed. The existence of an optimal plasma density for the generation of high-energy, low-divergence electron beams is demonstrated. The role of quasi-static channel fields on electron energy enhancement, beam pointing and divergence elucidate the mechanisms and action of DLA at different plasma densities.

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The Near-Anode Region in a Hybrid-Direct Kinetic Hall Thruster Simulation*

Astrid L. Raisanen and Iain D. Boyd

University of Michigan
(astridr@umich.edu, iainboyd@umich.edu)

A two-dimensional, axisymmetric, hybrid-direct kinetic (DK) simulation is under development for use in Hall thruster analysis. To model the plasma discharge in a Hall thruster channel and near-field plume, the simulation employs a two-dimensional Vlasov solver coupled with a quasi one-dimensional electron fluid solver. Although the near-anode region falls outside of the active electron simulation domain, previous work has shown that the electron physics in the near-anode region of the thruster cannot be neglected [1]. The present study focuses on the implementation of accurate boundary conditions for the quasi one-dimensional electron model in the near-anode region of the thruster.

The electron grid is constructed of magnetic field streamlines and overlaid on the kinetic simulation domain in Figure 1. The near-anode region of the thruster is located on the left side of the channel, upstream of the first magnetic streamline. The one-dimensional thermalized potential is obtained via Ohm's Law and current conservation perpendicular to the magnetic field. This reduced description of the plasma potential can be used in conjunction with the electron temperature and plasma density to determine the two-dimensional potential and thereby the electric field which acts to accelerate ions.

Typically, electron equations are solved between the anode and cathode streamlines, which do not correspond with the left and right-hand sides of the kinetic simulation domain. In a previous study by Koo, which utilized a hybrid Particle-in-Cell (PIC) simulation, electron properties are extrapolated outside of the active domain [2]. However, due to the high fidelity and Eulerian nature of the kinetic algorithm, extrapolation of electron properties in the near-anode region of the DK simulation domain is ineffective. This study explores the relationship between the fluid electron and kinetic equations and attempts to develop boundary conditions for the potential and electron energy so that realistic electron diffusion in the near-anode portion of the simulation domain may occur.

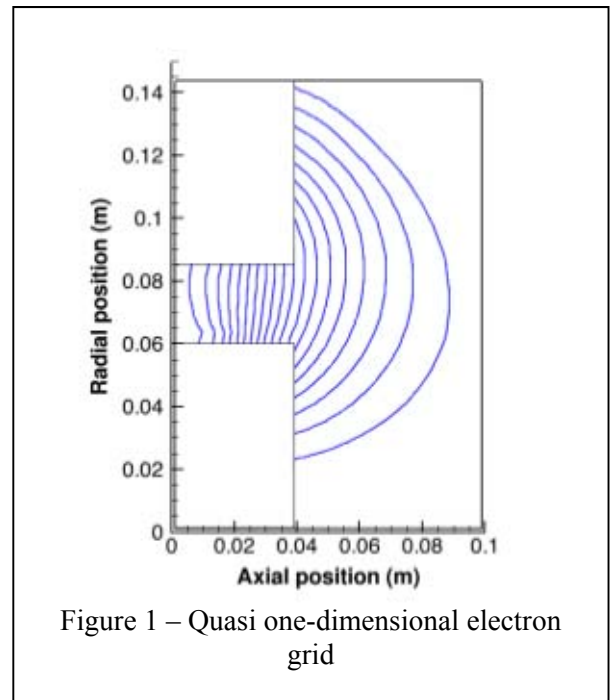


Figure 1 – Quasi one-dimensional electron grid

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

References

- [1] Raisanen, A.L, Hara, K., and Boyd, I.D., “Assessment of a two-dimensional hybrid-direct kinetic simulation of a Hall thruster,” AIAA-2017-4727, July 2017.
- [2] Koo, J.W., *Hybrid PIC-MCC Computational Modeling of Hall Thrusters*, Ph.D. Thesis, University of Michigan, 2005.

Laboratory Experiments Enabling Electron Beam use in Tenuous Space Plasmas*

Grant Miars^a, Omar Leon^b, Brian Gilchrist^a, Gian Luca Delzanno^c, and Joseph E. Borovsky^d

(a) The University of Michigan, Department of Electrical Engineering
(gmiars@umich.edu, gilchrst@umich.edu)

(b) The University of Michigan, Applied Physics Program (omarleon@umich.edu)

(c) Los Alamos National Laboratory, Applied Mathematics and Plasma Physics (delzanno@lanl.gov)

(d) Space Science Institute, (jborovsky@spacescience.org)

A mission concept is under development which involves firing a spacecraft-mounted electron beam from Earth's magnetosphere to connect distant magnetic field lines in real time. To prevent excessive spacecraft charging and consequent beam return, the spacecraft must be neutralized in the tenuous plasma environment of the magnetosphere. Particle-In-Cell (PIC) simulations suggest neutralization can be accomplished by emitting a neutral plasma with the electron beam. Interpretation of these simulations also led to an ion emission model in which ion current is emitted from a quasi-neutral plasma as defined by the space charge limit [1,2].

Experiments were performed at the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL) to help validate the ion emission model. A hollow cathode plasma contactor was used as a representative spacecraft and charged with respect to the chamber walls to examine the effect of spacecraft charging on ion emission. Retarding Potential Analyzer (RPA) measurements were performed to understand ion flow velocity as this parameter relates directly to the expected space charge limit. Emissive probe measurements of the plasma potential were made moving into the plasma sheath at the chamber wall to understand where quasi-neutrality breaks down as required to predict the space charge limit. Planar probe measurements were also made to identify where ion emission primarily occurred and to determine emission current density levels. Evidence of collisions within the plasma (particularly charge exchange collisions) and a simple model predicting emitted ion velocities are presented. While a detailed validation of the ion emission model and of the simulation tools used in [1,2] is ongoing, these measurements add to the physical understanding of ion emission as it may occur in the magnetosphere.

* 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, J. D. Moulton, and E. A. MacDonald, J. Geophys. Res. Space Physics. **120**, 3647 (2015).
- [2] G. L. Delzanno, J. E. Borovsky, M. F. Thomsen, and J. D. Moulton, J. Geophys. Res. Space Physics. **120**, 3588 (2015).

Simple Model for Cathode Coupling Voltage Versus Background Pressure in a Hall Thruster*

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

Aerospace Engineering Department, University of Michigan

Hall thrusters are a form of electric propulsion that use a crossed electric and magnetic field to ionize neutral gas and then accelerate it. They have flight history, in both the commercial and government sectors, on Earth orbiting satellites. However, the performance of the devices on orbit is known to be different than during ground testing. The source of these differences is related to the presence of conducting walls and finite pressures during ground testing. However, the exact mechanism by which these differences affect the thrusters remains an open question. Therefore, there is an apparent need to understand these trends from first-principles.

Three main parameters of the Hall thruster are known to vary with facility pressure. In general, the thrust decreases [1], the acceleration region moves axially downstream, and the cathode-coupling voltage magnitude increases with decreasing facility pressure [1]. The goal of this work is to study one of these effects: the change in cathode-coupling voltage as a function of pressure.

The central hypothesis of this work is that the cathode coupling voltage variation with background pressure is driven by anomalous resistivity in the plume of the hollow cathode. Recent work [2] has shown that by incorporating the ion acoustic turbulence (IAT), the electron resistivity in the cathode plume can be self-consistently recovered. Ion-neutral collisions act as a damping term to the IAT, and therefore, as the neutral density of the facility increases, the growth of the waves is damped and the coupling voltage decreases in magnitude.

Predictions from this model are compared to experimental data from the SPT-100 Hall thruster and it is shown, in Figure 1, that there is good agreement within uncertainty to the experimental data. This suggests that the facility effects on the cathode coupling voltage are largely driven by the ion acoustic turbulence in the plume of the hollow cathode.

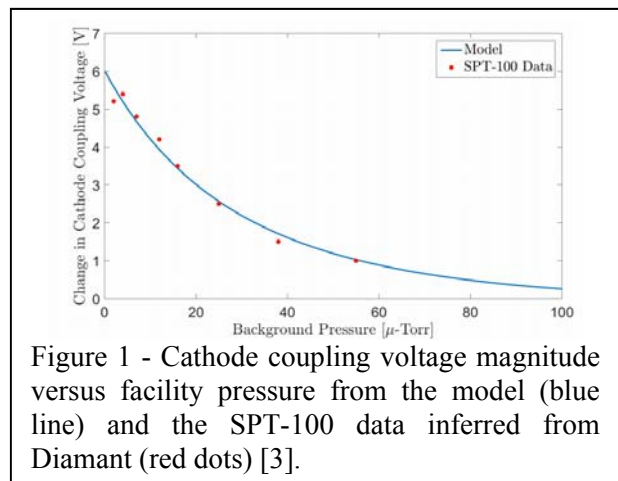


Figure 1 - Cathode coupling voltage magnitude versus facility pressure from the model (blue line) and the SPT-100 data inferred from Diamant (red dots) [3].

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References

- [1] Hofer, R. R. and Anderson, J. R., "Finite Pressure Effects in Magnetically Shielded Hall Thrusters," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2014.
- [2] Jorns, B., Lopez Ortega, A., and Mikellides, I. G., "First-principles Modelling of the IAT-driven Anomalous Resistivity in Hollow Cathode Discharges I: Theory," 52nd AIAA/SAE/ASEE Joint Propulsion Conference, 2016.
- [3] Diamant, K. D., Liang, R., and Corey, R. L., "The effect of background pressure on SPT-100 Hall thruster performance," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2014.

Evidence of Magnetized Shocks on OMEGA with Imaging Thomson Scattering

Joseph Levesque^a, Carolyn Kuranz^a, Rachel Young^a, Mario Manuel^b, Patrick Hartigan^c, Andy Liao^c, Sallee Klein^a, Matthew Trantham^a, Gennady Fiksel^a, Chikang Li^d, and Joe Katz^e

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

(b) General Atomics

(c) Rice University

(d) Massachusetts Institute of Technology

(e) Laboratory for Laser Energetics

Results from a campaign to study magnetized bow shocks using the OMEGA laser are presented. Optical imaging Thomson scattering and proton radiography diagnostics were used to make measurements of magnetized shocks in a sufficiently low β_{ram} regime. The system consisted of a slow, low-density plasma flow impinging on the azimuthal magnetic field produced by a current-carrying wire. Data collected at multiple times captured dynamical features of shock formation for two levels of the current in the wire. The proton images show regions of magnetic compression, and sharp increases in density and temperature are observed by the Thomson scattering diagnostic, all evidence of shock formation. Combining measurements from both diagnostics, some shock characteristics can be determined by comparing synthetic and experimental proton images.

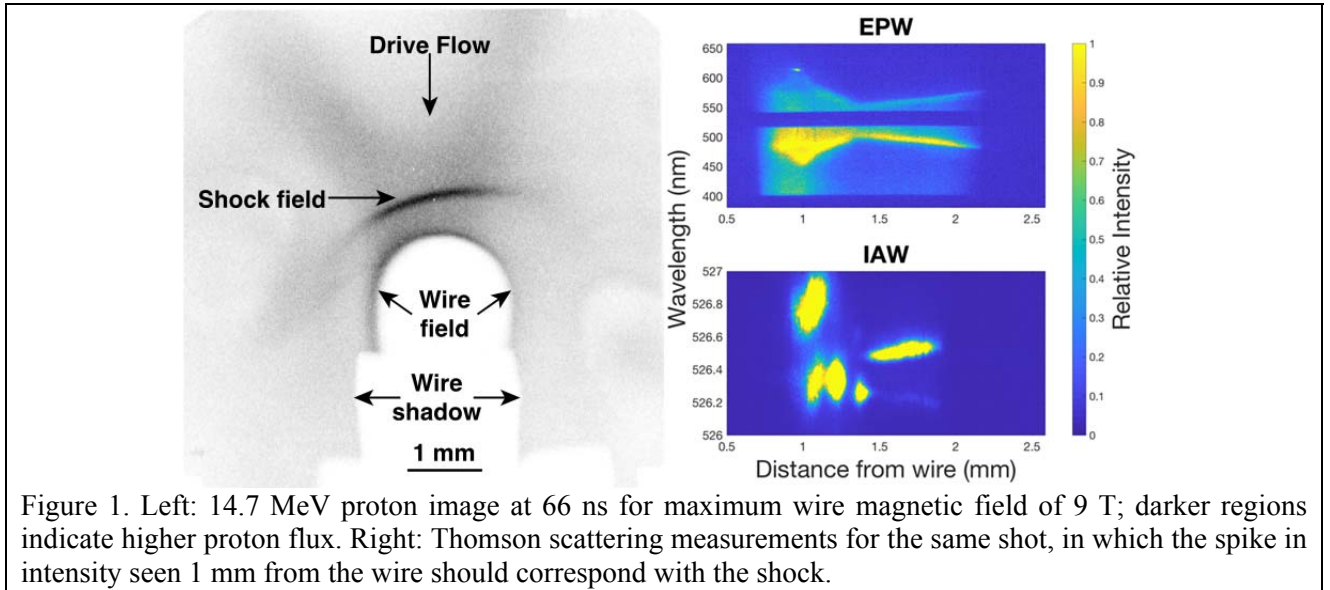


Figure 1. Left: 14.7 MeV proton image at 66 ns for maximum wire magnetic field of 9 T; darker regions indicate higher proton flux. Right: Thomson scattering measurements for the same shot, in which the spike in intensity seen 1 mm from the wire should correspond with the shock.

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Interactions Between Plasmas and Microscopic Metal Particles in Packed Bed Reactors*

Juliusz Kruszelnicki^a, Kenneth W. Engeling^a, John E. 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 plasma-catalytic packed bed reactors (PBRs) are being investigated for remediation of toxic gases. Combining plasma and metallic catalysts suspended on dielectric supports has shown synergetic increases in energy efficiency and selectivity.[1] The nature of this synergy, however, is poorly understood. We report on the results of a computational investigation of plasma evolution in a simplified 2-dimensional plasma-catalytic PBR using the multi-fluid plasma hydrodynamics simulator *nonPDPSIM*. [2]

Evolution of plasma was simulated between two dielectric rods. The mechanism of discharge formation was the same as that previously reported in full-scale 2-d reactors. Three metallic particles were imbedded in one of the dielectric rods in order to emulate the effects of the presence of catalysts. The gas mixture was humid air at atmospheric pressure with background ionization of 10^5 cm^{-3} . Negative nanosecond pulses were then applied.

We found that microdischarges form between the dielectric rods as a result of local field enhancement, which increases with the permittivity of the rods. When catalysts are present, the redistribution of charges in the conductor causes the re-strikes to be attracted to the metallic surfaces. This effect results in increased fluxes of charged species to the surface of the metal, and can contribute to its heating. As the positive re-strikes travel toward the negatively charged triple-points (dielectric/metal/gas), high electric fields lead to electric field emission. Field emission can explain reported formation of plasma on surfaces of catalyst-impregnated dielectrics.[3] Once a microdischarge formed, the presence of metal insets also prevented the formation of surface ionization waves, which are typically seen in dielectric-only PBRs.

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

References

- [1] E. Neyts, Plasma Chem. Plasma Process. **36**:185 (2016).
- [2] S. A. Norberg et al., Plasma Sources Sci. Technol. **24**, 035002 (2015).
- [3] H. Kim et al., J. Phys. D: Appl. Phys. **42** 135210 (2009).

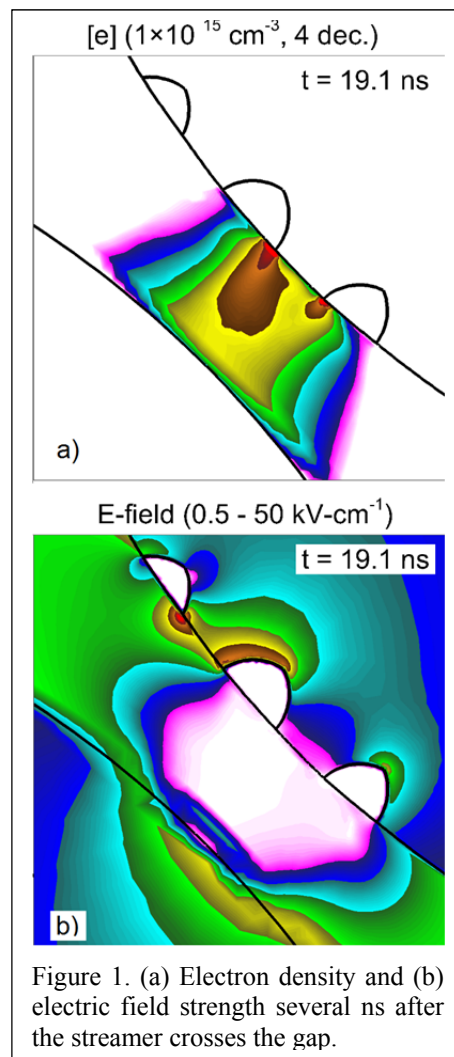


Figure 1. (a) Electron density and (b) electric field strength several ns after the streamer crosses the gap.

High-Energy-Density Physics Experiments at OMEGA 60: Evolution of the Rayleigh-Taylor Instability to the Highly Non-linear Regime*

L. Elgin^a, T. Handy^a, G. Malamud^{a,b}, C.M Huntington^c, M.R. Trantham^a, S.R. Klein^a,
C.C. Kuran^a, R.P. Drake^a, D. Shvarts^b

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

(b) Nuclear Research Center – NEGEV, Israel (gmalamud@umich.edu)

(c) Lawrence Livermore National Laboratory, Livermore, CA (huntington4@llnl.gov)

The Rayleigh-Taylor instability (RTI) occurs when two fluids of different densities are separated at a well-defined interface, where the lighter fluid pushes on the heavier fluid. An initial perturbation at the interface will grow in the form of light-fluid bubbles and heavy-fluid spikes interpenetrating across the interface, thereby mixing the two fluids. This phenomenon occurs in ordinary fluids on Earth and also in high-energy-density (HED) plasmas. HED systems exist in astrophysical environments and during the implosion of Inertial Confinement Fusion (ICF) capsules. Models for RTI growth predict time scales for fluid mixing, which affect our fundamental understanding of the universe and ability to achieve engineering feats such as ICF.

Potential flow models predict two stages of RTI growth: 1) exponential growth, 2) nonlinear growth reaching a terminal velocity (and constant Froude number) [1]. For low Atwood numbers (where the density difference between the two fluids is small), numerical simulations of single-mode systems show an additional growth phase in the late nonlinear regime, which is characterized by reacceleration (and higher Froude number) [2]. A physical interpretation of the simulation results posits that the accumulation of vorticity at the bubble and spike tips drives this reacceleration. However, there are claims that this reacceleration phase may be an artifact of the numerical simulations and not indicative of the physical evolution of classical RTI.

Prior experimental studies of RTI growth have not created the conditions necessary to observe or refute the behavior in question, which requires large aspect ratios of the spike and bubble amplitudes to the perturbation wavelength ($1 \leq h_{s,b}/\lambda \leq 3$) [2]. We are conducting a series of experiments at the OMEGA 60 laser facility to drive single-mode RTI growth to the late nonlinear regime in low Atwood number HED systems. A series of X-ray radiographs along dual orthogonal axes capture the evolution of RTI in these systems. Experimental design challenges, initial results, and future plans are discussed here.

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References

- [1] Layzer, *Astrophys. J.* **122**, 1 (1955).
- [2] P. Ramaprabhu et al., *Phys. Fluids* **24**, 074107 (2012).

Performance Characterization of a Small Low-Cost Hall Thruster*

Matthew Baird, Nagual Simmons and Kristina Lemmer

Western Michigan University (matthew.j.baird@wmich.edu, nagual.a.simmons@wmich.edu, kristina.lemmer@wmich.edu)

The Hall effect thruster (HET) is a relatively simple type of Electric Propulsion (EP) device. Using a small number of components to produce an ExB field, an HET can accelerate ions to high velocities to provide low thrust. In addition, HETs can achieve an Isp of up to 3000 seconds [1] [2]. HET efficiencies typically range between 40 and 65 percent [3]. HETs can be designed for many applications ranging from satellite orbit correction to deep space missions, and they will play an exciting role in the future of space travel.

The original project goal was to design and prototype a small HET that is accessible to any university with standard vacuum, electrical, and machining resources. The HET was a low-cost alternative that provided significant educational value to Western Michigan University (WMU) and students elsewhere. By opening this field of study to more researchers and encouraging other universities to become involved in EP research, more knowledge will be contributed to the understanding of HETs. This increased understanding will lead to better HET designs and further our knowledge of the universe. Magnetic lens, gas flow, scaling rules, thermal expansion, and machining processes represented a significant portion of the considerations made during thruster design. Many iterations of the design were conceived and simulated; however, the final design is referred to as the 44-mm-diameter Western Hall thruster (WHT-44) which is shown operating in Figure 1. The magnetic field of the WHT-44 was modeled using COMSOL Multiphysics® simulation. Non-linear B-H curves were used for high accuracy. Physical geometry and coil parameters were swept to find an ideal magnetic lens. Magnetic field mapping showed good agreement that the WHT-44 has a maximum radial magnetic fields strength of 450 G at the mid-channel near the thruster face. [4]

The next step in the development of the thruster is to verify its proper operation and perform telemetry characterization. The telemetry studies were conducted at WMU's Aerospace Laboratory for Plasma Experiments' (ALPE's) vacuum facility with a base pressure of 1E-7 Torr. These data provide significant insight into the operational behavior of the thruster and are used to make design change recommendations and gauge the utility of building such a low cost Hall thruster for university research.

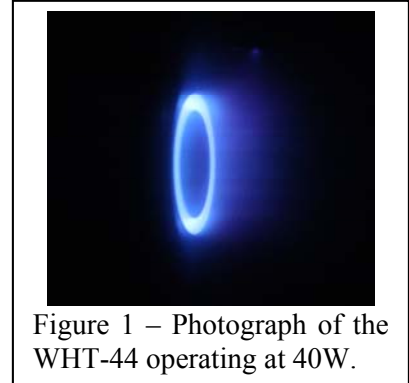


Figure 1 – Photograph of the WHT-44 operating at 40W.

* Work supported by the NASA Space Technology Research Fellowships

References

- [1] D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion, Hoboken: Wiley, 2008.
- [2] R. Hofer, H. Kamhawi, D. Herman and e. al., "Development Approach and Status of the 12.5 kW HERMeS Hall Thruster," in Joint Conference of 30th ISTS, 34th IEPC and 6th NSAT, Kobe, 2015.
- [3] NASA, "NASA Technology Area 2 Roadmap," 2015. [Online]. Available: http://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf.
- [4] M. Baird, N. Simmons and J. Thompson, "Design of a Hall Effect Thruster," Western Michigan University, Kalamazoo, 2016.

Measuring Plasma Discharge Volumes and Surface Areas of Microwave Plasma CVD Grown Single Crystal Diamond by Time-Lapse Photography

Ramón D. Díaz, Amanda Charris, Jes Asmussen and Timothy A. Grotjohn

Dept. of Electrical & Computer Engineering, Michigan State Univ., East Lansing, MI 48824, USA
(diazramo@msu.edu)

Single Crystal Diamonds (SCDs) are internally structured by a lattice which results in extraordinary mechanical, thermal, optical, and electrical properties. Before producing electrical applications based on diamond, the industry needs low defect density on large area single crystalline wafers. High quality SCDs are currently being produced by Microwave Plasma-Assisted Chemical Vapor Deposition (MPACVD). This study starts with substrates that are 3.5mm x 3.5mm x 1.4mm High Pressure High Temperature (HPHT) seeds and grows homoepitaxial diamond on top with hydrogen and methane used as the process gas. Recent advances have been obtained using this method, where linear growth rates of 30 $\mu\text{m/h}$, and normalized lateral (top surface) area gains of up to 1.92 times have been achieved.[1]

This present study begins to explore a standard photographic technique where the samples and the plasma discharges used in the previously described deposition conditions were photographed on regular intervals. Two cameras have been used, a Canon EOS 20D 8.2-megapixel, single 60-mm lens digital camera, and a 5.0-megapixel Raspberry Pi camera module. The cameras were pointed either directly at the sample, or through the pyrometer view port used to monitor sample temperature.

Scaled measurements on the sets of pictures resulted in data collected at regular intervals of the 30h+ process. The plasma discharge volume as a function of time was estimated based on pixel intensity levels as shown in Fig. 1 and 2. A video of the process was compiled where the crystal growth can be clearly appreciated. The sample area, as well as the encroaching of the Polycrystalline Diamond (PCD) growth on the surrounding molybdenum sample holder was also recorded as a function of time. Data from these measurements confirm the recent discovery of three distinct regions in time when describing lateral growth under certain conditions.[2] All observed data has been condensed in a parametrized 3D model of the growth process. Details are discussed on the poster, which will be displayed alongside a compilation of videos produced in the study.

References

- [1] A. Charris, S. Nad, and J. Asmussen, *Diam. Relat. Mater.*, **76**, pp.58–67 (2017).
- [2] A. Charris, PhD Dissertation, Michigan State University (2017).

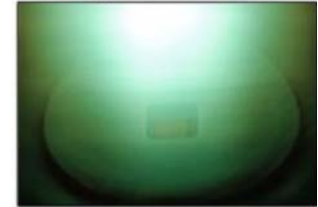


Figure 1 – SCD sample grown by MPACVD.

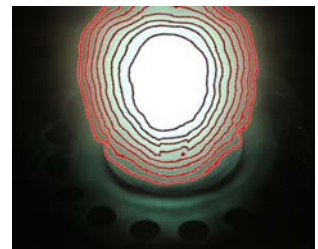


Figure 2 – Plasma discharge volume estimate based on pixel intensity levels.

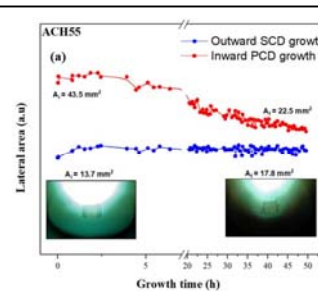


Figure 3 – Normalized SCD and PCD areas as a function of time. [2]

Simulation of Marangoni Convection Surrounding a 2-D Bubble in Liquid Induced by Plasma-driven Interfacial Forces*

Janis Lai and John E. Foster

University of Michigan (janislai@umich.edu)

Understanding the transport of plasma-derived reactive species into bulk liquid is crucial for effective plasma-based water purification and other environmental applications. Physical and chemical interactions at the plasma-liquid interface region drive flow in the bulk liquid. The mechanisms of such flow are not well-understood. A 2-D plasma-in-liquid apparatus is used to study this interface region to understand the plasma-driven fluid dynamics. [1] Previous measurements indicate shows vortices forming in bulk liquid initiated by plasma-driven forces at the interface. Simulations using commercial software are used to model the fluid flow observed, and to better understand the possible contribution of Marangoni flow.

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

References

[1] J. Foster and J. Lai, IEEE Trans. on Plasma Sci. **44**, 7 (2016).

High-Power Performance of a Nested Hall Thruster*

Scott J. Hall, Benjamin A. Jorns and Alec D. Gallimore

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

Electric propulsion systems at power levels in excess of 300 kW enable many space missions, including those to transport both cargo and crew to near-Earth asteroids and Mars [1-2]. Thrusters at power levels of 100-200 kW provide a means to optimize the propulsion system for mass and cost and to minimize system complexity [3]. Hall thrusters provide attractive performance in the specific impulse ranges required of these missions, but to date the highest power Hall thruster to fly is 4.5 kW.

One technique for scaling Hall thrusters to 100-kW class devices is to nest concentric discharge channels. These so-called Nested Hall Thrusters (NHTs) have been demonstrated at 10 kW discharge power previously [4]. Building off of that work, the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory, NASA, and the Air Force Research Laboratory have developed a 100-kW class 3-channel NHT called the X3.

Recently, the X3 was operated up to 101 kW at NASA Glenn Research Center. The thruster was tested from 300-500 V discharge voltage and at three current densities, and each of the seven channel combinations were tested at each condition. Across the operating conditions tested, the X3 demonstrated total thruster efficiencies from 0.55-0.65. In addition to the 101-kW operation, which is the highest discharge power recorded by a Hall thruster in laboratory testing to date, the X3 demonstrated 247 A discharge current operation and a maximum thrust of 5.42 N, both of which exceed previous Hall thruster operation and demonstrate the technology's capability for future high-power missions.

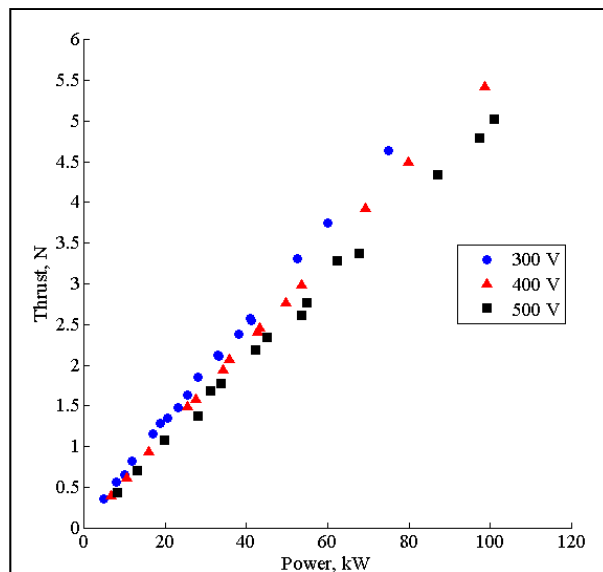


Figure 1 – Thrust versus discharge power from the X3's recent operation at NASA Glenn Research Center.

* This work supported by NASA's Next Space Technologies for Exploration Partnerships project under grant NNH16CP17C. S.J. Hall is supported by a NASA Space Technology Research Fellowship under grant number NNX14AL67H.

References

- [1] R. Myers and C. Carpenter, 32nd IEPC, IEPC-2011-261 (2011).
- [2] R.G. Merrill, et.al., 2015 IEEE Aerospace Conf., 10.1109/AERO.2015.7118956 (2015).
- [3] R.R. Hofer and T.M. Randolph, J. Propulsion and Power, **29**, 1 (2013).
- [4] R. Liang, Ph.D. Dissertation, University of Michigan (2013).

Selective Radical Production in Remote Plasma Sources with Multiple Inlets

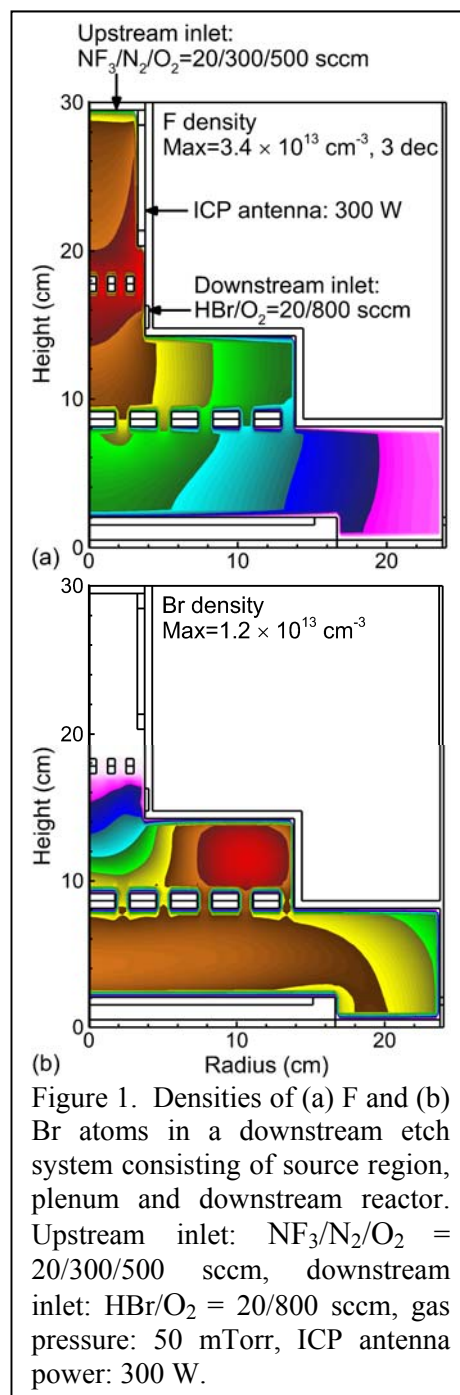
Shuo Huang and Mark J. Kushner

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

Remote plasma sources (RPS) are being used to achieve isotropic etching with high selectivity by avoiding charging, energetic ion bombardment and UV/VUV radiation using long distance and discriminating barriers between the RPS and the substrate. By using multiple plasma sources or multiple gas inlets at different locations, the reaction pathway can be optimized for producing desirable process radicals. NF_3 and HBr are frequently used sources of F and Br radicals, which are the main etchants of silicon-containing materials. NF_x ($x = 1 - 3$) and HBr can exothermically react with other neutral species to produce F, Br and OH radicals, which also enables customizing the reaction pathway by flowing gases downstream of the RPS.

In this paper, we report on results from a computational investigation of an inductively coupled RPS having multiple gas inlets with the goal of determining strategies for selectively producing reactive fluxes. The investigation was performed using the plug flow mode of 0-dimensional model, Global_Kin, and ICP operation of 2-dimensional Hybrid Plasma Equipment Model (HPEM). With $\text{NF}_3/\text{N}_2/\text{O}_2$ mixtures flowed through the RPS from an upstream inlet, the dominant radicals flowing downstream are F and O formed through dissociative excitation and attachment of NF_3 and O_2 . NO molecules were formed through endothermic reactions among N_2 , N, O_2 and O species. With HBr injected downstream of the plasma source, mixing with the plasma produced radicals enables another level of selectivity. Due to lack of electrons and low gas temperature (~ 350 K) downstream, HBr reacts with F and O through exothermic reactions ($\text{HBr} + \text{F} \rightarrow \text{HF} + \text{Br}$, $\text{HBr} + \text{O} \rightarrow \text{OH} + \text{Br}$ and $\text{HBr} + \text{OH} \rightarrow \text{H}_2\text{O} + \text{Br}$) and the dominant downstream radicals transition from F to Br as shown in Fig. 1. Vibrationally excited $\text{HF}(\text{v})$, a highly polar molecule, may be formed through reactions having a larger exothermicity than the vibrational quanta, and so may produce a significant flux of activation energy to the wafer.

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Electron Energy Distributions in Triple-Frequency Powered Capacitively Coupled Plasmas*

Chenhui Qu, Peng Tian, Shuo Huang and Mark J. Kushner

University of Michigan, Dept. Electrical Engr. & Comp. Sci.,
Ann Arbor, MI 48109-2122 USA

(chenqu@umich.edu, tianpeng@umich.edu, shuoh@umich.edu, mjkush@umich.edu)

Capacitively coupled plasmas (CCPs) are commonly used for high-technology device manufacturing in the semiconductor industry. As the feature size becomes smaller, more precise control of reactive fluxes onto the wafer surface is required. More robust control of CCPs requires a system with more independent variables so that each variable can be leveraged to customize plasma properties. Under this consideration, the dual-frequency powered CCP was designed to independently control ion fluxes and ion energy distributions.[1] A further modification is to use three separate frequencies in CCPs to add another controllable variable to the system. However, with any multiple frequency excitation scheme, there are non-linear processes that couple the frequencies through their effects on plasma properties. This impairs the independence of the variables, and particularly so in triple-frequency CCPs.

Among plasma properties, electron energy distributions (EEDs) are of greatest importance due to their fundamental role in producing ionization and excited states. In this work, the EEDs are investigated in a triple-frequency powered CCP sustained by one high frequency (10s-100 MHz, 100s W) on the top electrode and two low frequencies (1-10s MHz, 100s W) on the bottom electrode. (See Fig. 1.) The feedstock gas Ar/CF₄/O₂ (75/15/10) is injected with tens mTorr pressure through a uniformly distributed shower head located in the top electrode. A conspicuous influence of high frequency power on EEDs through sheath oscillation is observed in this work. Consequences of high energy secondary electron emission near the bottom electrodes are also observed. The effects of pressure (15-50 mTorr) and high frequency power from the top electrode (10s-1000 W) on EEDs will be discussed, highlighting the uniformity of the EEDs and consequences on excitation rates.

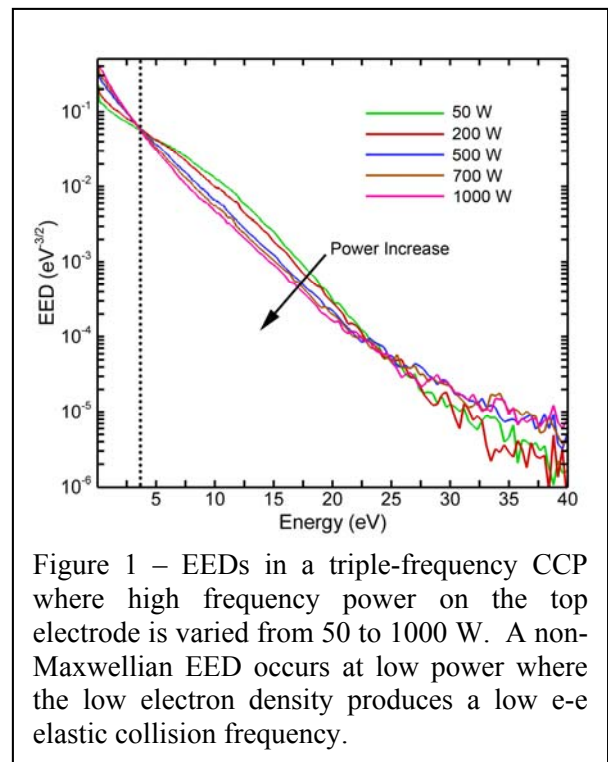


Figure 1 – EEDs in a triple-frequency CCP where high frequency power on the top electrode is varied from 50 to 1000 W. A non-Maxwellian EED occurs at low power where the low electron density produces a low e-e elastic collision frequency.

* Work supported by the NSF, DOE Fusion Energy Sciences and Samsung Electronics.

References

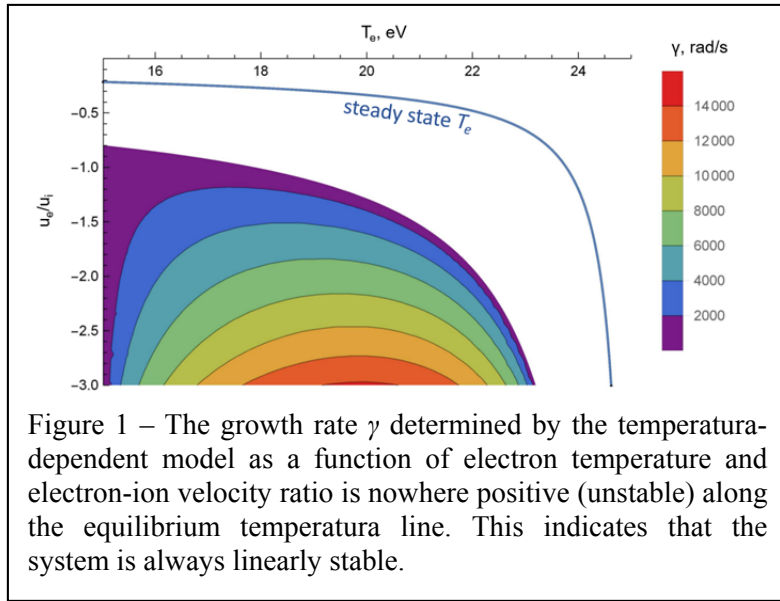
[1] S. Uhm, L. -H. Lee, H. Y. Chang, and C. W. Chung, Phys. Plasmas **11**, 4830 (2004).

Zero-dimensional Modeling Limitations for the Hall Thruster Breathing Mode*

Ethan Dale and Benjamin Jorns

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

The breathing mode is a common instability observed in Hall thrusters that is often reproduced with multi-dimensional simulations [1,2] but hard to accurately capture with a zero-dimensional (0D) model of the device. A temperature-dependent linear perturbation model proposed by Hara et al. [3] is examined by assessing the sensitivity of its predicted growth rate to several key parameters. Deficiencies in the implementation of the model are identified and the issues with determining 0D input parameters is considered by comparison with 2D simulation results. To improve the model, a



simplified Ohm's law is included to allow perturbations in electric field strength. The stability predicted by the model is investigated over a range of electron velocities and anomalous collision frequencies corresponding to a nominal discharge current. Reformulation of the model in a wave-centered frame of reference is considered. It is found through numerical experiments that temperature dependence alone leads to an unconditionally stable system, even accounting for the fact that the input parameters for the model have strong spatial dependence. Adding Ohm's law does not allow for any

unstable behavior unless an anomalous collision frequency with a non-Bohm-like functional dependence is assumed. Analysis of the wave-centered model suggests that plasma gradients are critical to describing the instability, and thus using gradient lengths in a 0D model is a major shortcoming.

* This work is support by NASA Space Technology Research Fellowship grant NNX14AL65H.

References

- [1] J. Fife, M. Martinez-Sanchez, and J. Szabo, 33rd Joint Propulsion Conference, AIAA-97-3052 (1997).
- [2] J.P. Boeuf and L. Garrigues, Journal of Applied Physics **84**, 3541 (1998).
- [3] K. Hara, M.J. Sekerak, I.D. Boyd, and A.D. Gallimore, Physics of Plasmas **21** 122103 (2014).

Absolute Instability Near Band Edges in a Traveling Wave Tube

Foivos Antoulinakis, Y. Y. Lau, Patrick Wong and Abhijit Jassem

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

We re-examine the beam mode and its interaction with the circuit mode in the immediate vicinity of the lower and upper band edges in a traveling wave tube (Fig. 1). We find that an absolute instability may arise, according to the Briggs-Bers criterion [1], if the beam current is sufficiently high, even if the beam mode intersects with the circuit mode at point Q (Fig. 1) with a positive group velocity. This threshold condition is deduced analytically and confirmed by numerical calculations. When the threshold current is exceeded, the Green's function [1], at a fixed position, exponentiates in time as t to the $1/3$ power initially, but as (wi^*t) at later time (Fig. 2), where wi is the imaginary part of the unstable pole-pinch root of w according to the Briggs-Bers criterion [1]. This finding differs from the previous works [2, 3] on absolute instabilities at the lower bandedge, and points to the vulnerability to absolute instabilities at both the upper and lower bandedges of a TWT. The upper band edge was found to be more susceptible to absolute instability than the lower band edge, however.

* Work supported by Air Force Office of Scientific Research Awards Nos. FA9550-14-1-0309, FA9550-15-1-0097, DARPA contract HR0011-16-C-0080 with Leidos, Inc., and L-3 Communications.

References

- [1] R. J. Briggs, Electron Stream Interactions with Plasmas, MIT Press (Cambridge, MA, 1964); A. Bers, Handbook of Plasma Physics, M. N. Rosenbluth and R. Z. Sagdeev, Eds., North-Holland (New York, 1983).
- [2] D. M. H. Hung et al., Phys. Rev. Lett. 115, 124801 (2015).
- [3] A. P. Kuznetsov et al., Sov. Radiophys. Electron. 27, 1575 (1984).

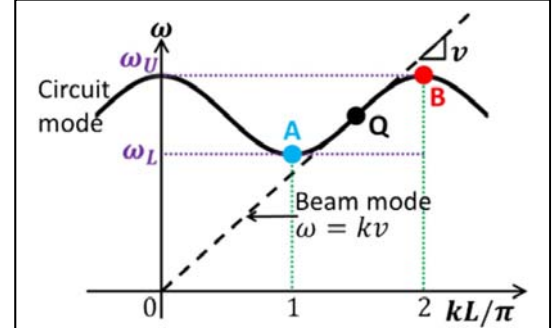


Figure 1 - The lower band edge (A), the upper band edge (B), and the operating point (Q) at which the beam mode intersects with the circuit mode in a coupled cavity TWT at $(\omega, k) = (\omega_0, k_0)$. kL is the phase shift per period.

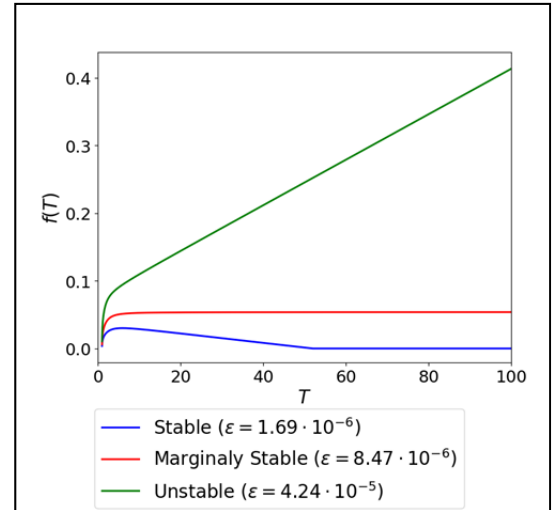


Figure 2 - Time evolution of the exponent that dominates the growth of the signal in a TWT near the lower band edge. ϵ is proportional to the electron beam current.

Self-adapting EEDF Evaluation Frequency in KGMf*

Janez Krek and John P. Verboncoeur

Michigan State University (krek@msu.edu, johnv@msu.edu)

The Kinetic Global Model framework (KGMf), simulation code, written in Python, utilizes a 0D (global) simulation model to explore complicated chemistry in multi-species systems. Due to the volume-averaged nature of the global model and short execution time compared to higher dimensional models, the KGMf is suitable for parameter scanning in systems with many species and many reactions. Along with general input parameters (input power, system geometry, species, reactions, etc.), one can define the electron energy distribution function (EEDF) to be a constant or a function of various system parameters, e.g. T_{eff} , mean electron energy, etc. Predefined EEDFs also include an EEDF defined in isotropic velocity space with shape parameter “x” [1] (where x=1 presents Maxwellian and x=2 presents Druyvesteyn distribution):

$$f(\epsilon) = \frac{x}{\left(\frac{3}{2}T_{eff}\right)^{3/2}} \frac{\left[\Gamma\left(\frac{5}{2x}\right)\right]^{3/2}}{\left[\Gamma\left(\frac{3}{2x}\right)\right]^{5/2}} \epsilon^{1/2} \exp\left\{-\left[\frac{\Gamma\left(\frac{5}{2x}\right)}{\Gamma\left(\frac{3}{2x}\right)} \frac{\epsilon}{\left(\frac{3}{2}T_{eff}\right)}\right]^x\right\}$$

Directly solving the Boltzmann equation or using a high-term approximation (e.g. six-term approximation) is a computationally demanding task and is not suitable to be incorporated into global model codes like KGMf. For modest values of reduced electric fields (E/N) when elastic collisions play a primary role, the two-term approximation of the Boltzmann equation is usually used (e.g. as in BOLOS[2] or BOLSIG+). A single computation of the EEDF with the two-term approximation takes on the order of tens of milliseconds [3], which increases the required computational time in KGMf by two orders of magnitude compared to cases with a fixed EEDF [4], if computation is performed in each step.

Reduction of the number of EEDF evaluations is necessary, and achieved in different ways. One can manually define the number of time steps between EEDF evaluations, or the EEDF can be evaluated when the reduced electric field (E/N) or electron temperature (T_e) changes more than a given threshold, all defined in advance [3]. In addition to the manual EEDF evaluation frequency, we also implemented a self-adapting EEDF evaluation frequency by splitting the EEDF into stationary (“equilibrium”) and perturbed parts [5], each with different update frequencies. The final decision of whether to evaluate the EEDF is not based on an expected change in EEDF itself (computed by the Boltzmann equation solver) but on an expected change in rate coefficients computed by KGMf. Using rate coefficients as a measure of change, we capture a more realistic influence of the EEDF on the system, and preserved fast computational speed, which is a goal of global models.

* Work supported by DOE Plasma Science Center grant DE- SC0001939.

References

- [1] S.K.Nam, J.P.Verboncoeur, App. Phy. Letters, 92, 231502 (2008)
- [2] A. Luque, <https://pypi.python.org/pypi/bolos> (2004)
- [3] G.J.M.Hagelaar, L.C.Pitchford, Plasma Sources Sci. Technol. 14, 722-733 (2005)
- [4] J.Krek, G.Parsey, J.P.Verboncoeur, ICOPS 2016
- [5] P.Kauf, <https://doi.org/10.3929/ethz-a-006706585> (2011)

High Order Harmonic Generation with Femtosecond Mid-infrared Laser

Jinpu Lin^a, John Nees^a, Karl Krushelnick^a, Franklin Dollar^b, Tam Nguyen^b

(a) Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099

(b) University of California - Irvine, Irvine, CA 92617

There has been growing interest in high order harmonic generation (HHG) from laser-solid interactions as a compact source of coherent x-rays. The ponderomotive potential in laser-plasma interactions increases with longer laser wavelength, so there may be significant differences in the physics of harmonic generation and other phenomena when experiments are conducted with mid-infrared lasers. Previous experiments, however, have been done almost exclusively with near-infrared lasers. In this work, we report the results of experiments performed with millijoule, 40 fs, 2 μm laser pulses generated by an optical parametric amplifier (OPA) which are focused onto solid targets such as silicon and glass. The HHG efficiency, polarization dependence, and x-ray emission are studied and compared to measurements with near-infrared lasers.

*Funded by AFOSR MURI.

Laser Based Neutron Source from Free-flowing D₂O Target

Jungmoo Hah, John Nees, Karl Krushelnick and Alec Thomas

Center for Ultrafast Optical Sciences, University of Michigan (jmhah@umich.edu)

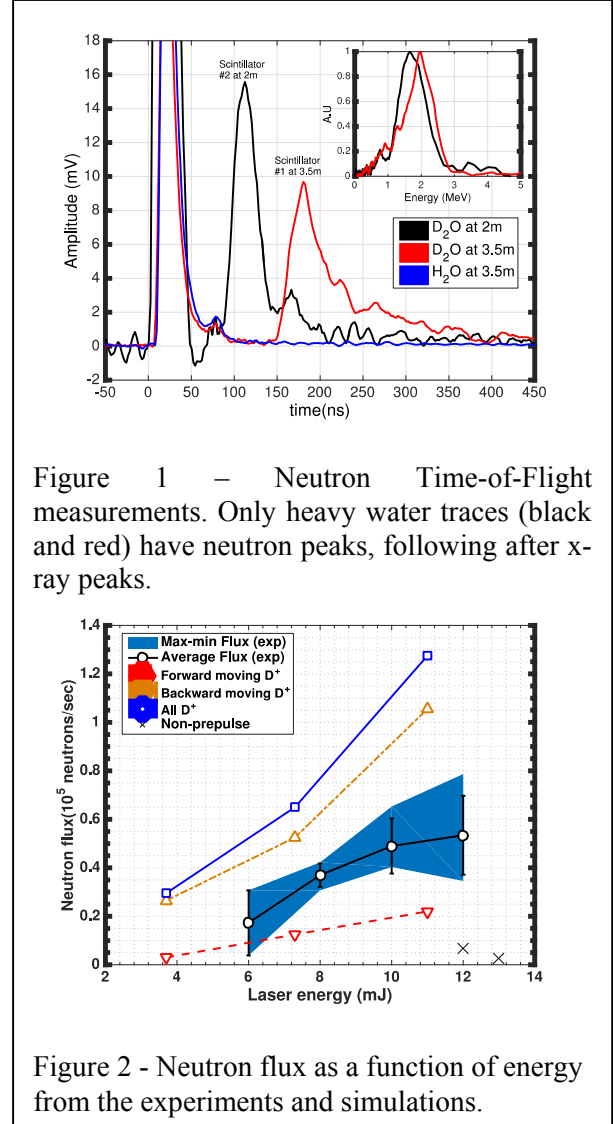
The active neutron interrogation technique has attracted significant attention in detecting special nuclear materials (SNM). Unlike x-ray, neutrons can go through typical shielding materials (e.g. lead), interact with SNMs and generate secondary neutrons and/or gamma rays, which can be detected. In order to generate fast neutrons for an active interrogation, here, we report the production of neutrons using a high repetition rate (500 Hz) laser system interacting with a heavy water stream. [1]

From a high intense laser interaction ($>10^{19}$ W/cm²) with heavy water, deuterons are accelerated up to 0.9 MeV, resulting in D-D nuclear fusion reactions. These accelerated deuterons and neutrons are detected by CR39 and a plastic scintillator with PMT, respectively. The estimated deuteron Boltzmann distribution temperature is about 0.16 MeV, and time-averaged neutron yields are measured to be up to 2×10^5 neutrons/s.

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References

[1] J. Hah et al., Appl. Phys. Lett. **109**, 144102 (2016).



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 micro-pollutants, such as pharmaceuticals, endocrine disruptors, and polyfluorinated compounds, poses challenges for conventional water treatment systems. In an effort to address these contaminants of emerging concern (CECs) and to support water reuse, new technologies must be introduced. Advanced oxidation processes (AOPs) produce hydroxyl radicals in situ and can effectively reduce most trace organics below mandatory and advisory limits. However, the primary obstacle to AOPs remains cost; AOPs are expensive due to required consumables, associated infrastructure, and an overshadowed tech adoption level relative to chlorination. An alternative source of AOPs that should address cost efficiency and degradation of conventional-AOP-immune organics is the interaction of plasma with water. Direct plasma injection eliminates conversion efficiencies and rapidly mineralizes contaminants by inducing AOPs in addition to other chemical, physical, and radiative processes, such as precipitation, shockwaves, and UV. Due to the limited transport of radicals, the primary barrier to the implementation of plasma-based water treatment is process volume scale-up.

In this work, we investigate a scalable plasma water reactor that utilizes packed bed dielectric barrier discharges to maximize the plasma water interface. Here, the water serves as the dielectric medium. The reactor is operated in a batch system for different pulser parameters and water matrices. The contaminant concentration, pH, and oxidant dose, namely the ratio of hydrogen peroxide to ozone, are mapped as functions of power and treatment time. The reactor demonstrates several log-reductions of methylene blue, methyl tert-butyl ether, and 1,4-dioxane and is compared to competing AOPs.

* National Science Foundation (CBET 1336375 and AIR-TT 1700848)

Origin of Second Harmonic Signals in Octave Bandwidth Traveling-Wave Tubes*

Patrick Y. Wong^a, Y.Y. Lau^a, David P. Chernin^b, Ronald M. Gilgenbach^a, and
Brad W. Hoff^c

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

(b) Leidos, Inc. (david.p.chernin@leidos.com)

(c) Air Force Research Laboratory (brad.hoff@us.af.mil)

In a helix traveling-wave tube (TWT) with a bandwidth exceeding one octave, the second harmonic of an input signal near the low end of the band will experience exponential growth. In such a case, we have found that the non-linear electron orbits in the beam, as opposed to the orbital bunching exhibited in the linear electron orbits [1], are the main source for second harmonic generation. This unexpected result is due to the synchronous amplification of the second harmonic. We demonstrate this phenomenon from the solution of the non-linear equations that we have formulated that govern evolution of the second harmonic field; these equations may include a sever and axial variations of the Pierce parameters. In several test cases, we compare the theory with simulation using the CHRISTINE code [2]. Good agreement between theory and simulation is found.

An example of one test case considered is shown on the right (Figure 1). We consider a realistic helix TWT with an attenuation profile and mid-stream sever (Figure 1a). The results for the RF power profile for both the fundamental (input) signal and second harmonic from simulations using the CHRISTINE code and our analytic formulation are shown on the bottom (Figure 1b). We see that there is good agreement between simulations and theory in both the pre-sever and post-sever regions.

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References

- [1] C.F. Dong, et al., *IEEE Trans. ED* **62**, 4285 (2015).
- [2] T.M. Antonsen, Jr. and B. Levush, NRL report NRL/FR/6840-97-9845 (1997).

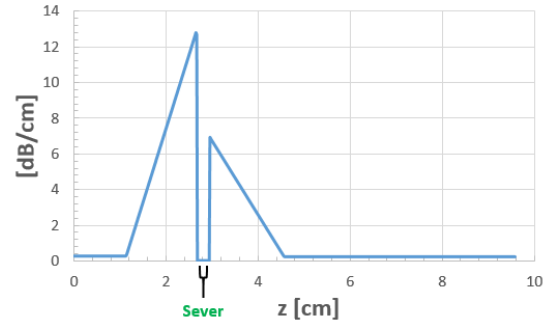


Figure 1a -The attenuation profile of a helix TWT considered in a test case example. The effects of the mid-stream sever may be seen here.

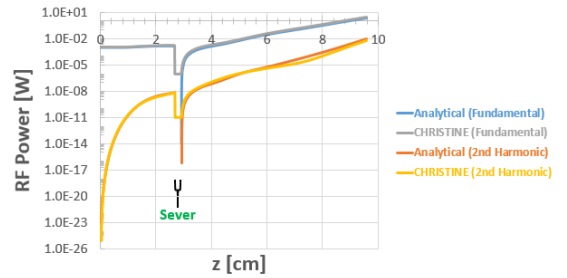


Figure 1b -The RF power profile (in semi-log scale) corresponding to the set-up of the test case considered above.

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

R. VanDervort^a, J. Davis^b, M. Trantham^a, S. Klein^a, D. Shvarts^{a,b}, P. A. Keiter^a, and R. P. Drake^a

(a) University of Michigan, USA (dervort@umich.edu)

(b) NRCN, 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 gas clumps in the interstellar media. For example, in the optically thick limit, when the radiation in the gas clump has a short mean free path, 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. 2D CRASH simulations guide our parameter selection. A stellar radiation source is mimicked by a laser-irradiated, thin, gold foil, providing a source of thermal x-rays around 100 eV. The gas clump is mimicked by low-density CRF foam. We plan to show the preliminary experimental results of this platform in the optically thick limit, from experiments scheduled in August.

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Turbulence Measurement in Magnetic Nozzle Plasma Sources

Shadrach Hepner^a, Justin Little^b, Timothy Collard^a and Benjamin Jorns^a

(a) University of Michigan

(b) University of Washington

Many radio frequency electric propulsion devices incorporate magnetic nozzles, or axially diverging magnetic fields, to facilitate conversion of thermal to directed, bulk motion. However, without a mechanism of detachment from field lines, the flowing ionized exhaust of the nozzle will follow magnetic field lines downstream of the nozzle and potentially circle back to the front of the thruster, preventing any net thrust. While detachment has been observed in magnetic nozzles before [1], the mechanism responsible is not clear. Many theories have been proposed for detachment in nozzles, including collisional diffusion, electron demagnetization, and turbulence driven transport [1]. Development of plasma turbulence is often driven by a difference in electron and ion velocities and yields an effective collision frequency that provides an FxB drift across field lines. Since turbulence is driven by differences in electron and ion velocities, it is expected to be found in the azimuthal direction to correspond with the greatest electron drift motion driven by potential and pressure gradients. While potential signals of turbulence correlating with detachment have been observed [1], a full study of the presence of turbulence and the relation to detachment has not been conducted.

We installed ion saturation probes spaced by a small distance in three dimensions, and we measured correlations in temporal and spatial fluctuations as represented through the Beall technique [2]. We also setup a FastCam downstream of the thruster to observe high frequency azimuthal oscillations in density [3].

Data from a magnetic nozzle experiment at Princeton University and from the Magnetic Detachment Experiment at the University of Michigan are analyzed and compared to turbulent fluid theory [4]. Ion saturation probe measurements from the Magnetic Detachment Experiment in the azimuthal direction are compared to FastCam data observing azimuthal density fluctuations, and dispersion results are compared to theory to determine the type of wave present.

*Work was supported by NASA Space Technology Research Fellowship grant number 80NSSC17K0156

References

- [1] Olsen, C. S., Ballenger, M. G., Carter, M. D., Diaz, F. R. C., Giambusso, M., Glover, T. W., Ilin, A. V., Squire, J. P., Longmier, B. W., Bering, E. A., et al., "Investigation of plasma detachment from a magnetic nozzle in the plume of the VX-200 magnetoplasma thruster," *IEEE Transactions on Plasma Science*, Vol. 43, No. 1, 2015, pp. 252-268.
- [2] Beall, J., Kim, Y., and Powers, E., "Estimation of wavenumber and frequency spectra using fixed probe pairs," *Journal of Applied Physics*, Vol. 53, No. 6, 1982, pp. 3933-3940.
- [3] Georgin, M. P., Byrne, M. P., Ciaston, N. E., Jorns, B. A., and Gallimore, A. D., "Passive High-speed Imaging of Ion Acoustic Turbulence in a Hollow Cathode," *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, 2017, p. 4973.
- [4] Frias, W., Smolyakov, A. I., Kaganovich, I. D., and Raitses, Y., "Long wavelength gradient drift instability in Hall plasma devices. I. Fluid theory," *Physics of Plasmas*, Vol. 19, No. 7, 2012, pp. 072112.

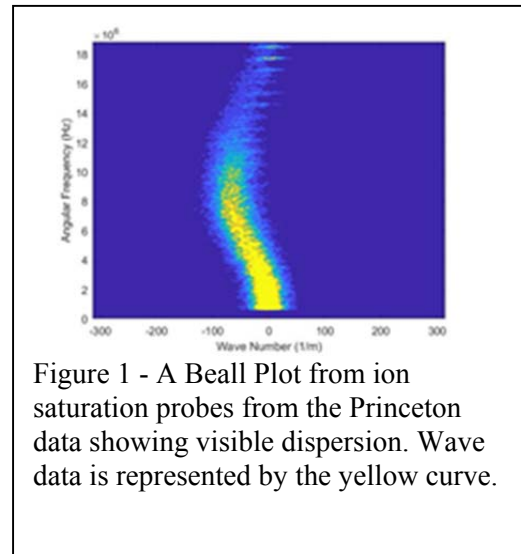


Figure 1 - A Beall Plot from ion saturation probes from the Princeton data showing visible dispersion. Wave data is represented by the yellow curve.

Energetic Electron Acceleration and Injection During Dipolarization Events in Mercury's Magnetotail

Ryan M. Dewey^a, James A. Slavin^a, Jim M. Raines^a, Daniel N. Baker^b and David J. Lawrence^c

(a) Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA (rmdewey@umich.edu)

(b) Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA.

(c) The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

MESSENGER frequently observed bursts of energetic electrons (>10 keV to ~ 300 keV) within Mercury's miniature terrestrial-like magnetosphere. These bursts are observed most often in the post-midnight sector near the magnetic equator, suggestive of the acceleration and injection of electrons from the magnetotail and their eastward drift about the planet. We use the Gamma-Ray Spectrometer's high-time resolution (10 ms) energetic electron measurements to examine the relationship between energetic electron injections and magnetospheric dynamics in Mercury's magnetotail. We find that these electron injections were observed most frequently in association with magnetic field dipolarization. Between March 2013 and April 2015, we identified 2976 electron events of which 538 were coincident with the leading edge of a dipolarization event. These dipolarization fronts were detected on the basis of their rapid (~ 2 s) increase in the northward component of the tail magnetic field ($\Delta B_z \sim 30$ nT), which typically persists for ~ 10 s. We find electrons experience brief, yet intense, betatron and Fermi acceleration during these dipolarization events, reaching energies ~ 160 keV and contributing to nightside precipitation. Dipolarization events, and subsequently, the electron acceleration associated with them, display a strong dawn-dusk asymmetry, suggestive of a post-midnight maximum in magnetotail reconnection.

Pulsed Laser Gate Experiment for Reduction of Fuel-Contaminant Mixing in Magnetized Liner Inertial Fusion (MagLIF)*

S.M. Miller^a, S.A. Slutz^b, S.R. Klein^a, P.C. Campbell^a, J.M. Woolstrum^a, M.R. Gomez^b, D.A. Yager-Elorriaga^a, N.M. Jordan^a, Y.Y. Lau^a, R.M. Gilgenbach^a, and R.D. McBride^a

(a) University of Michigan (smmil@umich.edu)

(b) Sandia National Laboratories

Fuel preheating in full scale magnetized liner inertial fusion (MagLIF) currently has low efficiency. This loss is thought to occur from laser-plasma interactions (LPI) at the laser entrance window (LEW). The gaseous fuel is held in a pressurized vessel by the thin mylar LEW that must be removed right before heating. To ensure more energy from the laser heats the fuel, the LEW could be weakened at an early time [1]. One proposed solution [1] is to use the current from a small pulse generator to break the LEW. This allows the LEW to open outward from the fuel and out of the laser's path, thus reducing LPI losses. Wire attached to a 13 kV mini-pulser will be used to remove the LEW from the laser path. We will report on the system design and the current state of the laser gate project.

* This research was funded in part by the University of Michigan, a Faculty Development Grant from the NRC, and Sandia National Laboratories for the U.S. DOE's NNSA under contract DE-NA0003525

References

[1] S. A. Slutz, C. A. Jennings, T. J. Awe, G. A. Shipley, B. T. Hutsel, and D. C. Lamppa, "Auto-magnetizing liners for magnetized inertial fusion", *Phys. Plasmas* **24**, 012704 (2017); S. A. Slutz, personal communication (2017).

Self-organization and Electrolyte Ion Mass Transport Processes with Chemistry in 1 ATM DC Glows

Yao E Kovach^a, Maria C Garcia^b and John E Foster^a

(a) PSTL, NERS, University of Michigan, USA (yaok@umich.edu, jefoster@umich.edu)

(b) Department of Applied Physics, University of Cordoba (falgamam@uco.es)

In plasma physics, self-organization is observed in phenomena ranging from plasmoid formation in low pressure. RF plasmas to large-scale, and magnetized structures observed on the surface of the sun. Of recent interests is the puzzling formation of self-organization patterns on the surface of liquid anodes in 1 ATM DC glows. While these patterns are of academic interest in regards to understanding collective phenomena, the appearance of the patterns may play an important role in the sub-surface liquid phase chemistry, driving convection and inducing thermal gradients. In this current work, a new, complex, star-shaped structure with round edges was observed with a copper sulfate electrolyte (figure 1). The pattern was not observed with sodium chloride solutions. This observation suggests that electrolyte ion mass or perhaps ionization state may play a key role in determining overall pattern shape. In order to understand the role of the transport of electrolyte ions from liquid to the gas phase on discharge maintenance, and pattern formation, spectroscopic analysis of the halo surrounds the main plasma column for multiple electrolytes are studied as a function of discharge conditions.

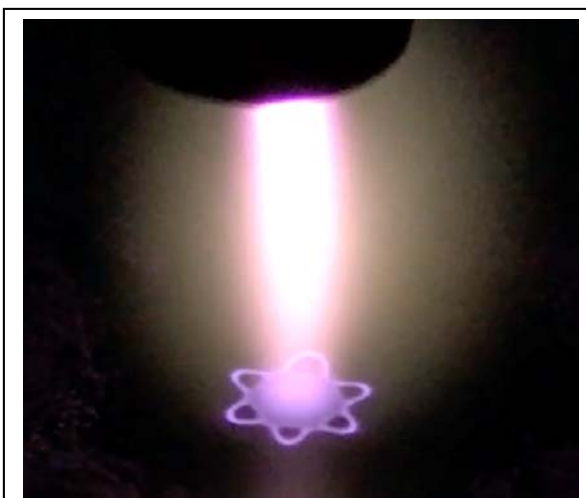


Figure 1 – A star shaped self-organization anode pattern observed at 40 mA on CuSO₄ solution with 200 sccm helium flow.

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Dispersion Relation Measurements of Ion-acoustic-like Waves in the Near-field Plume of a 9-kW Magnetically Shielded Thruster*

Zachariah A. Brown and Benjamin A. Jorns

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

Hall thrusters are a form of crossed-field plasma device commonly employed for in-space electric propulsion. In this configuration, a strong magnetic field confines the lighter species of the plasma, electrons, which ionize the injected propellant, while an applied electric field accelerates the heavier species, the ions, downstream. Ideally, the electrons would be confined by the magnetic field, serving as an efficient ionization source. However, it has been found experimentally that electrons can cross field lines in these devices at rates orders of magnitude higher than can be explained by classical effects. To date, no self-consistent model has been developed for this anomalous electron transport which greatly impedes thruster simulations.

Recent particle in cell simulations imply anomalous transport may be induced by the growth of ion-acoustic instabilities associated with high frequency (MHz) fluctuations of plasma density and electric field in the azimuthal direction [1]. Additionally, experimental measurement of the dispersion relation in the plume of a Hall thruster using collective light scattering has shown the existence of ion-acoustic-like waves in the axial and azimuthal direction [2]. Despite this result, however, a number of questions concerning the role of the acoustic-like modes for cross-field transport remain. In particular, it is not evident whether or not the amplitude of these oscillations is sufficiently large to explain the effective mobility measured in the plume. The need is thus apparent for an analytical and experimental effort to relate local measurement of the density fluctuations and associated mode dispersion to the effective mobility in the plume.

With this in mind, this work directly measures the dispersion relation in the near field of a 9-kW magnetically shielded Hall thruster using ion-saturation probes. The methodology builds on previous work that used ion-saturation probes to determine the dispersion relation of high frequency fluctuations in a hollow cathode [3]. In each direction, axial, radial and azimuthal, two ion-saturation probes are closely spaced to measure fluctuations in ion density. A Fourier analysis of the potential signals at each point yields the wave number in each direction, and using the histogram technique of Beall [4] gives the distribution of k at a particular value of ω . The strong linear dispersion relation for these acoustic-like-modes should be evident from the distribution of signal strength in the k - ω space. Quasilinear theory for turbulent-induced transport is then applied to estimate the effective mobility in the plume due to these oscillations. The measurement of these relations confirm the existence of ion-acoustic waves in the near field of Hall thrusters and demonstrate the relative contribution of these modes to cross-field transport.

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References

- [1] T. Lafleur, S. D. Baalrud, and P. Chabert. *Physics of Plasmas* 23, 053502 (2016); doi: 10.1063/1.4948495
- [2] S. Tsikata, N. Lemoine, V. Pisarev, and D. M. Grésillon. *Phys. Plasmas* 16, 033506 (2009); doi: 10.1063/1.3093261
- [3] B. Jorns, I. Mikellides, and D. Goebel *Phys. Rev. E* 90, 063106 (2014); doi: 10.1103/PhysRevE.90.063106
- [4] J. M. Beall, Y. C. Kim, and E. J. Powers, *J. Appl. Phys.* 53, 3933 (1982).