# Michigan Institute for Plasma Science and Engineering (MIPSE)

## Proceedings

# 10th ANNUAL GRADUATE STUDENT SYMPOSIUM

**November 13, 2019**
**2:00 – 7:00 pm**

**North Campus, University of Michigan**

**1301 Beal Avenue**

**Ann Arbor, MI 48109-2122**

**University of Michigan**
**Michigan State University**
**University of Notre Dame**
**Pusan National University, S. Korea**

# Schedule

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|---|---|---|
| **2:00 – 2:40** | Registration, poster set-up | EECS atrium |
| **2:40 – 3:30** | **Poster session I** | EECS atrium |
| **3:30 – 3:45** | Refreshments (box lunch + coffee, tea) | 1005 EECS |
| **3:45 – 3:50** | **Prof. Mark J. Kushner**<br>Director, MIPSE<br>***Opening remarks*** | 1005 EECS |
| | **Dr. John McLaughlin**<br>Senior Director, KLA Ann Arbor<br>***Greetings from KLA*** | 1005 EECS |
| **3:50 – 4:50** | Special MIPSE seminar<br>**Dr. Joachim Birn**<br>Space Science Institute<br>***Substorms, Dipolarization, and Particle Acceleration in the Magnetosphere*** | 1005 EECS |
| **5:00 – 6:40** | ***Hall Thruster demonstration***<br>MAISE team | EECS atrium |
| **5:00 – 5:50** | **Poster session II** | EECS atrium |
| **5:50 – 6:40** | **Poster session III** | EECS atrium |
| **6:40 – 6:55** | Poster removal | EECS atrium |
| **6:55 – 7:00** | ***Best Presentation Award* ceremony** | EECS atrium |

# Poster Session I

# Poster Session II

# Poster Session III

# Abstracts

## Modelling and Engineering of Tunneling Electrical Contacts*

Sneha Banerjee [a], John Luginsland [b] and Peng Zhang [a]

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Contact resistance and electron tunneling effects in nano scale electrical contacts, such as those based on metal-insulator-metal (MIM) thin junctions, carbon nanotube (CNT) networks, and novel two-dimensional (2D) materials, can greatly influence the device properties. Current crowding effects in these contacts can lead to localized overheating and the formation of thermal hot spots. To improve reliability and lifetime of the device, it is important to control the electrical properties in these junctions.

Here, we propose a method to design nanoscale electrical contacts with controlled current and voltage distribution via engineered spatially varying contact layer properties and geometry. A lumped circuit transmission line model (TLM) [1] is used to get a self-consistent analysis of the electrical properties across tunneling contacts formed between similar/dissimilar contacting members separated by a thin insulating gap. It is found that, the nonhomogeneous current and voltage distribution in tunneling type contacts can be controlled by varying the specific contact resistivity ($\rho_c$) along the contact length. This $\rho_c$ is either predefined (for ohmic and Schottky contacts) or calculated from the local tunneling current in case of insulating tunneling layer [2-4].

Figure 1 shows that the nonuniformity of the contact current density from thin film 1 to thin film 2 in a tunneling type contact can be reduced by parabolically varying the insulator layer along the contact length.

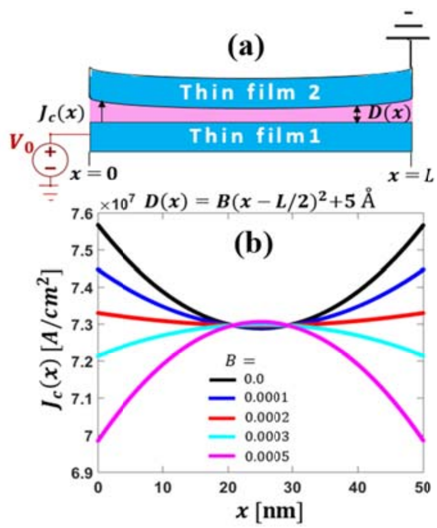


Figure 1 – (a) Electrical contact between two thin films. A thin (in nm) tunneling interface layer of permittivity $\varepsilon_r$ and thickness $D(x)$ is sandwiched between them. (b) Contact tunneling current density from thin film 1 to thin film 2 through the interfacial layer, as a function of $x$. Here, contact length $L = 50$ nm, input voltage $V_0 = 1$V, insulator layer is vacuum, with $\varepsilon_r$ = 1, electron affinity = 0, and $D(x)$ is parabolic along $x$. Work function of thin films = 4.5 eV.

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

**References**

[1] S. Banerjee, J. Luginsland, and P. Zhang, *ArXiv190609188*, 2019
[2] J. G. Simmons, J. Appl. Phys. 34, 1793–1803 (1963).
[3] P. Zhang, Sci. Rep., 5, 9826 (2015).
[4] S. Banerjee, & P. Zhang, *AIP Advances* **9**, 085302 (2019).

# Experimental Correlation between Anomalous Electron Collision Frequency and Plasma Turbulence in a Hall Effect Thruster*

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Hall thrusters are a form of crossed-field plasma device commonly employed for in-space electric propulsion. A strong magnetic field confines the lighter species of the plasma, electrons, which ionize the propellant, while an applied electric field accelerates the ions downstream. Ideally, the electrons would be confined by the magnetic field, serving as an efficient ionization source. However, it has been found experimentally that electrons can cross field lines in these devices at rates orders of magnitude higher than can be explained by classical collision effects.

To date, no self-consistent model has been developed for this anomalous electron transport. This lack of understanding about Hall thruster plasma dynamics precludes predictive modelling and forces designs to be validated with lengthy and expensive physical testing. The prevailing theory to explain anomalous electron transport supposes that a strong azimuthal plasma instability develops in the Hall thruster that can knock electrons across magnetic field lines. The instability is known as the E X B electron drift instability (EDI), due to the plasma turbulence gaining energy from the electrons' high E x B drift velocity [1].

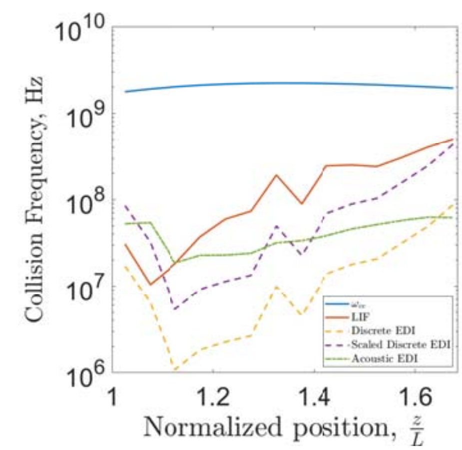


Figure 1 – Anomalous collision frequency from LIF measurements and quasi-linear theory for the EDI the discrete and acoustic limit. For the discrete EDI two results for different scaling parameters of the discrete EDI are shown. The electron cyclotron frequency is also shown as a reference.

While there has been experiment evidence for the existence of this instability in Hall thruster plumes there has not yet to be experimental validation about how significantly the instability contributes to anomalous electron transport. In our experimental we directly measure the anomalous collision frequency using Laser Induced Florescence and compare it values inferred from wave turbulence measurements and quasi-linear theory for the EDI. Our results show that there is good agreement between theory and measurements (Fig. 1), but there is consistent over-estimation of collision frequency in the acceleration. We discuss these results in regard to recent simulations that show non-Maxwellian electron distributions and non-linear instability growth.

* Work supported by National Science Foundation Program Grant No. DGE 1256260. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

**References**

[1] Ducrocq, A., Adam, J. C., and Heron, A., Physics of Plasmas, **13,** 2006

[2] Tsikata, S., Lemoine, N., Pisarev, V., and Gresillon, D. M., Physics of Plasmas, **16**, 2009

# The Effect of Ionic Strength on the Absorption Spectrum of Plasma-Injected Solvated Electrons*

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The study of plasma-liquid interactions is an emerging field with multifarious applications, which are driven by chemical species created in the plasma or at the plasma-liquid interface, such as the hydroxyl radical (OH), hydrogen peroxide ($H_2O_2$), and, in particular, solvated electrons ($e_{aq}^-$).

The solvated electron is an electron in a polar solution, loosely confined in a potential well formed by the solvent molecules, and notable for being a powerful reductant. Historically, solvated electrons have been studied by using pulse radiolysis and laser photolysis. However, recently we confirmed their presence in a direct current (DC), atmospheric pressure, liquid anode discharge using phase-locked, total internal reflection absorption spectroscopy (TIRAS). The measured absorption spectrum appeared to be blue shifted from the well-established dilute solution spectrum, and one possible explanation is that the local ionic strength in the double layer at the plasma-liquid interface alters the solvation potential well via increased Coulombic interactions.

In this work, we use TIRAS to measure the absorption spectrum as a function of the solution ionic strength and compare the results to measurements produced using pulse radiolysis in order to resolve any differences in the spectra of plasma-injected and bulk-produced solvated electrons.

* Work supported by the Army Research Office and Rickover Fellowship Program

# Computational Investigation of Early-time Kelvin-Helmholtz Instability Growth Driven by Radiative Shockwaves*

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Although the Kelvin-Helmholtz (shear) instability has received significant interest in the classical fluid dynamics community, its phenomenology under high-energy-density conditions remains poorly understood, in particular as the mixing region evolves to turbulence. Recent experiments on the National Ignition Facility (NIF) [1,2] investigated the mixing region produced by counter-propagating shockwaves in the high-energy density (HED) regime. However, these past studies have yet to consider the role of a radiative environment, which can be a substantial effect in HED systems. Our objective is to simulate the Kelvin-Helmholtz instability produced by counter propagating radiative shocks, in which the radiative precursor moves ahead of the shockwave. We hypothesize that the radiative precursor will alter the viscosity of the plasma before the shear flow is established, affecting the instability growth and the resulting turbulent flow.

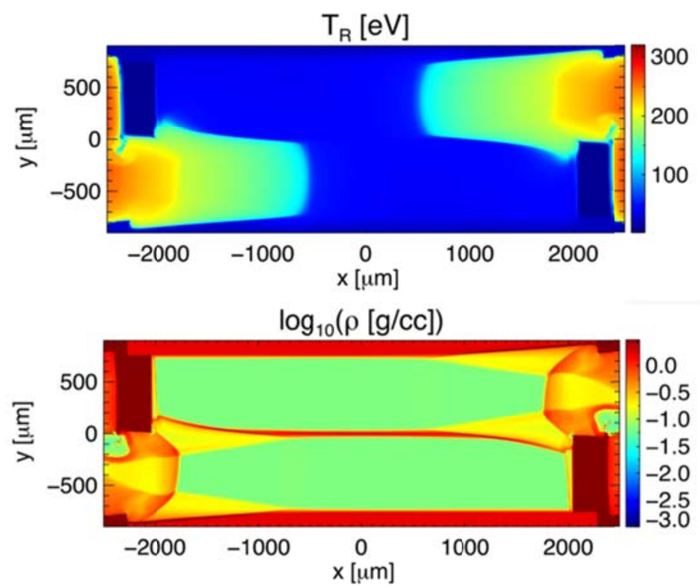


Figure 1 - Radiation temperature and mass density contours demonstrating a radiative shock

We use the CRASH radiation-hydrodynamics code [3] to simulate this problem for a range of radiative energy fluxes. Preliminary CRASH simulations show that a radiative shock can be obtained on a variation of the Shock Shear platform using higher drive fluxes still attainable on NIF (Figure 1). Additionally, an analysis of these results compares the early-time growth of the instability to existing theory and to the low-drive, purely hydrodynamic HED case, revealing the effect of a radiative precursor in systems with shock-driven shear instabilities.

*This work is supported by the Lawrence Livermore National Laboratory under subcontract B632749, and the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

**References**

[1] F. Doss et al., Phys. Rev. E **94**, 023101 (2016).
[2] K. Flippo et al. Phys. Plasmas **25**, 056315 (2018).
[3] B. Van Der Holst et al., Astrophys. J. Supp. Series **109** 2 (2011).

# Investigating a Plasma Source for Generating Ultrasonic and Ultraviolet Radiation in Water*

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Ultrasonic and ultraviolet (UV) radiation in water can lead to the production of hydroxyl radicals, and are thus considered oxidation processes capable of removing organic contaminants from waters and wastewaters. Combining both ultrasonic and UV irradiation in water can increase contaminant removal efficiencies beyond those of the individual techniques, and traditionally involves both high-power ultrasonic transducers and UV lamps.[1] Here, a plasma source is investigated for generating ultrasound and UV light simultaneously in water. Ultrasound transmitted to water is measured using a hydrophone, while the UV intensity is assessed using a radiometer and by chemical actinometry. Hydrogen peroxide concentrations are measured as a function of treatment time, suggesting hydroxyl radical production in the liquid.

* Work supported by the National Science Foundation

**References**

[1] V. Naddeo, M. Landi, V. Belgiorno, and R.M.A. Napoli, J. Hazard. Mater. **168**, 925 (2009).

# An Analytical Model for Two-color Photoemission from Biased Metal Surface*

Yi Luo and Peng Zhang

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Photoelectron emission from solids driven by strong-field lasers provides a platform to coherently control the electron motion in ultrashort spatiotemporal scales. It is fundamentally important to time-resolved electron microscopy, electron sources, and novel quantum nanocircuits [1, 2]. Recently, there has been strong interest in photoemission from nanostructures driven by two-color lasers [3-5], due to the relative straightforward waveform control of the two-color lasers and the substantial emission current modulation.

Here, we present an exact analytical model for the nonlinear photoemission from a dc biased metal surface illuminated by two-color laser fields (Fig. 1), by solving the time-dependent Schrödinger equation [5, 6]. Our calcuations reveal various emisison processes, including photo-induced over-barrier emission and tunneling emisison, for different dc and laser fields. Our study demonstrates adding a strong dc electric field on the metal surface could provide great tunability on the emisison current modulation depth, and suggests a practical way to maintain a strong modulation to high current photoemission, by simply using a strong dc bias and a weak harmonic laser (Fig. 2).

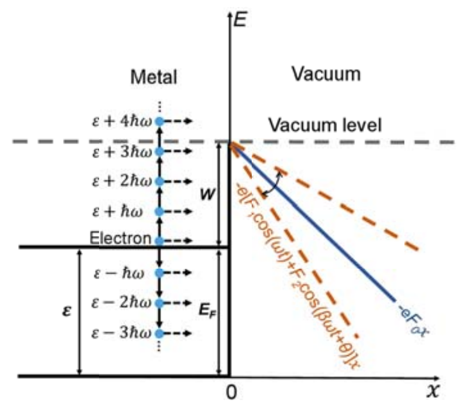


Figure 1 – Energy diagram for electron emission under two-color laser fields and a dc bias. Electrons with initial energy $\varepsilon$ are emitted from a dc biased metal-vacuum interface at $x$=0, due to the $n$-photon contribution. The fundamental and harmonic laser fields are $F_1\cos(\omega t)$ and $F_2\cos(\beta\omega t + \theta)$, respectively. The dc field is $F_0$. $E_F$ and $W$ are the Fermi energy and work function of the metal, respectively.

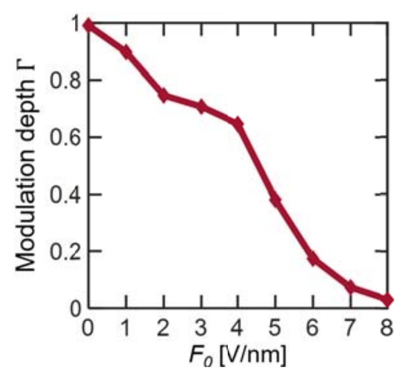


Figure 2 – Current modulation depth Γ as a function of the dc field $F_0$, with $\omega$-laser-field $F_1$ and $2\omega$-laser-field $F_2$ fixed at 1.6 V/nm and 0.22 V/nm respectively (experimental laser fields in Ref. [3]). The wavelength of the fundamental laser is 800nm ($\hbar\omega$ = 1.55 eV). The metal is assumed to be gold with Fermi energy $E_F$=5.53 eV and the work function $W$ =5.1 eV.

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

**References**

[1] P. G. O'Shea and H. P. Freund, Science **292**, 1853-1858 (2011).
[2] P. Zhang, et al., Appl. Phys. Rev. **4**, 011304 (2017).
[3] M. Förster, et al., Phys. Rev. Lett. **117**, 217601 (2016).
[4] W. C.-W. Huang, et al., New J. Phys. **19**, 023011 (2017).
[5] Y. Luo, and P. Zhang, Phys. Rev. B, **98**, 165442 (2018).
[6] P. Zhang and Y. Y. Lau, Sci. Rep. **6**, 19894 (2016).

# Inclusion of Circuit Loss in an Exact Theory of Helix Traveling Wave Tubes*

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Traveling wave tubes (TWTs), because of their wide bandwidth and high power capabilities, are widely used in communication satellites. Modern tight design criteria prompted a recent exact treatment of the small signal gain that results from the interaction of an electron beam with a thin tape helix circuit structure [1]. This study revealed that Pierce's classical theory of TWTs [2] needs to be modified. Specifically, at a high beam current, the circuit phase velocity is modified, by as much as 2 percent in a realistic example. This is a very significant effect of circuit detune, not only unaccounted for in Pierce's classical theory, but is also absent in virtually all modern numerical simulation codes of helix TWTs. This effect is quantified by a new parameter $q$ [1]. However, this exact theory requires the assumption that the entire circuit structure is lossless, whereas in practice, resistive loss is always introduced to stabilize the amplifier against oscillations. In this paper, we propose a method to include the effects of these resistive losses through a complex permittivity of the dielectric support structure. A new dispersion relation that includes the new effects of $q$ is next obtained. Its validity is demonstrated by test cases with both uniform and non-uniform resistivity over the tube length. An example is shown in Fig. 1 where it is shown that Pierce's classical theory is valid only over a restricted range of frequency.

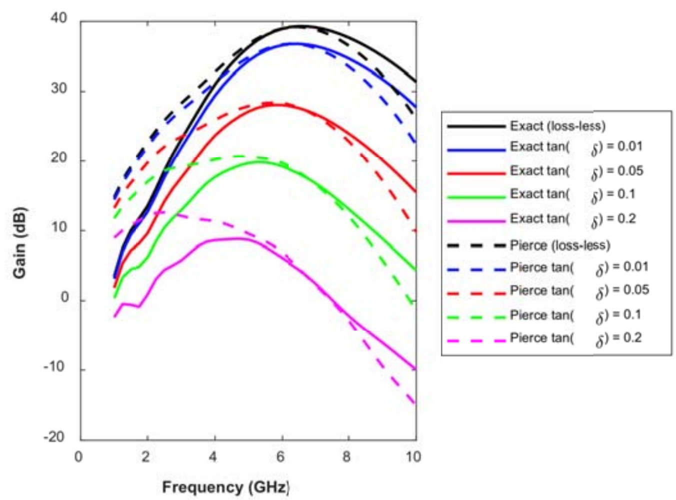


Figure 1 – Comparison of small signal gain for a tape helix TWT from exact and Pierce theory. Circuit loss is represented by the loss tangent, tan ($\delta$), in the dielectric support.

*Work supported by DARPA, contract HR0011-16-C-0080 with Leidos, Inc, Air Force Office of Scientific Research Awards Nos. FA9550-18-1-0153, and L3 Technologies Electron Device Division.

**References**

[1] P. Wong, D. Chernin, and Y. Y. Lau, IEEE Electron Device Lett. **39**, 1238 (2018).

[2] J. R. Pierce, Traveling-Wave Tubes. Van Nostrand, 1950.

Production of Reactive Species in 2-D Packed Bed Reactors – Impact of System Parameters*

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Control of chemical conversion using plasma-based Packed Bed Reactors (PBRs) is a complex function of system parameters, including gas flow rate, repetition rate and properties of the packing material. Impacts of these parameters were computationally investigated in a 2-dimensional PBR using the nonPDPSIM modeling platform. The system consisted of seven, 700-µm dielectric rods (εr = 9.0) inserted between two, coplanar electrodes with 10-ns DC pulses applied at frequencies between 100 Hz and 1 kHz. Humid air ($N_2/O_2/H_2O$ 78/21/1) was flowed through the system. Periodic boundary condition was applied to simulate the flow of gas through a longer PBR.

We found that primary dissociation products (O, N, H, OH) formed at high rates near surfaces of the rods which then reacted with background gases, forming secondary species ($O_3$, $H_2O_2$, $HO_2$). Increasing the permittivity of the rods led to higher plasma densities which favored production of reactive nitrogen species. Decreasing the separation between the rods led to similar effects while also producing gas-flow stagnation, which favored production of tertiary species ($N_2O_x$, $HNO_4$). Decreased pulse frequency and increased gas flow were both found to mitigate this stagnation.

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

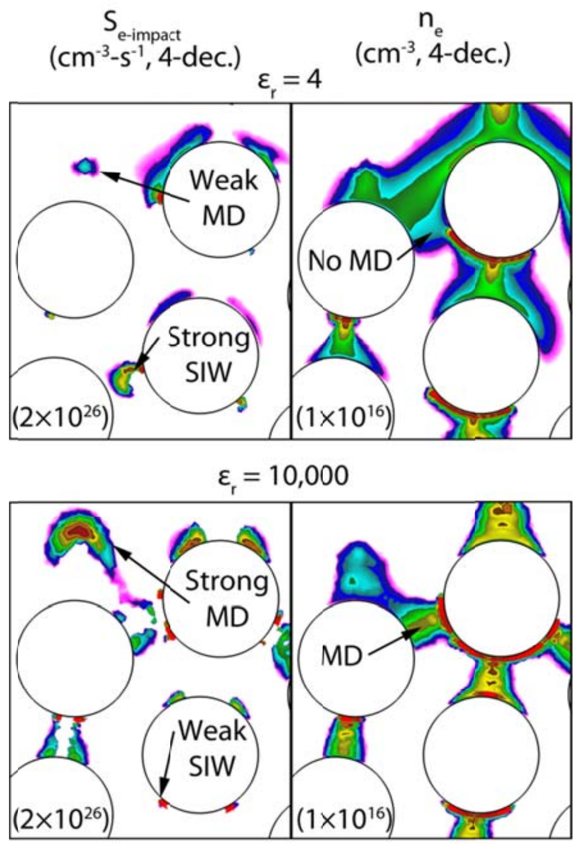


Figure 1 - Types of discharges present in PBRs with quartz ($\varepsilon_r$ = 4) and barium titanate ($\varepsilon_r$ = 10,000). Stronger inter-bead discharges, but less intense SIWs are observed with higher dielectric content packing materials.

# Scaling Relativistic Laser-solid Interaction Using Ultrashort Laser Pulses

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There has been growing interest in relativistic laser-solid interaction as a compact source of relativistic electron beams and hard x-rays. Femtosecond hard x-ray pulses have important applications such as probing time-resolved x-ray absorption and diffraction. Relativistic electrons from solid targets have superior properties in beam charge and divergence than those from wakefield acceleration in underdense plasmas, and can find applications in warm dense matter creation, electron radiography, seed of wakefield accelerators and fast ignition researches. In this work, the 30fs laser pulses are focused down to near diffraction-limit spot size to achieve relativistic intensity ($a_0 > 1$) and ablate into a thick (~mm) glass target. We investigate the scaling laws of this interaction in terms of laser wavelength (0.8μm, 1.3μm and 2μm), laser energy (millijoule to joule level), angle of incidence (grazing, 45° and normal) and preplasma scale length ($0.1\lambda\ to\ 5\lambda$). Particle-In-Cell simulation (PIC) and particle tracking shows that the incident half and reflected half of the laser pulse form a standing wave to accelerate electrons to relativistic (MeV) energy.

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Comparative Study of an Atmospheric Pressure Helium Plasma Jet Driven by Unipolar Nanosecond-pulses

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Dielectric barrier discharge (DBD) is a classical construction to produce non-thermal plasma at atmospheric pressure [1]. A nanosecond-pulse power source transfers energy to electrons of atmospheric pressure discharges in a nanosecond scale and shows different plasma chemistry from slow sinusoidal discharges. It is important to understand how the pulse parameters affect the discharge such as pulse height, pulse width, and repetition frequency. In this experiment, a dielectric barrier discharge plasma jet developed by Pusan National University lab was instigated. Optical emission spectrometry (OES) shows that the pulse repetition frequency dominantly affects the plasma density more than the other pentameters do. With the widely-used equivalent circuit model and measure data of the DBD, electrical parameters including discharge current, discharge voltage and discharge energy per cycle are calculated [2,3]. We found that the pulse voltage plays a dominant role in the discharge energy in a single pulse cycle, but the repetition rate plays a dominant role in the formation of the overall radical generation. The water contact angles on the PDMS with the variation of the control parameters are also presented.

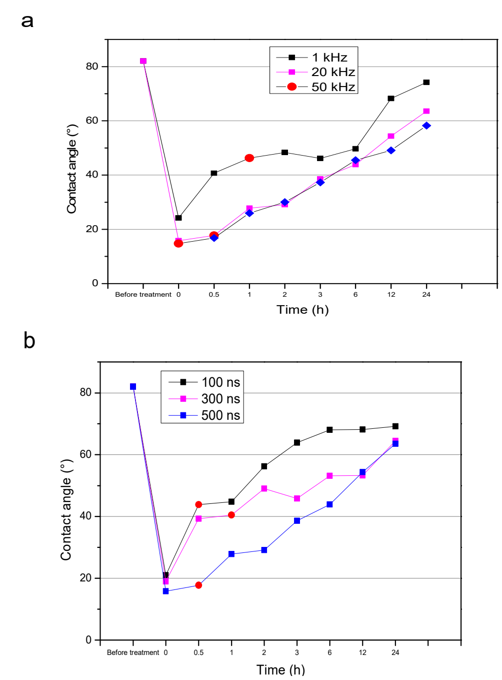


Figure 1 – The change of the water-drop contact angle over time on the PDMS film treated by a He plasma jet for the variation of (a) frequency and (b) pulse width. Red dots represent the AFM measurement time.

**References**

[1] A. Fridman, A. Chirokov, and A. Gutsol, J. Phys. D: Appl. Phys. **38**, R1(2005).
[2] S. Tao *et al.*, J. Phys. D: Appl. Phys. **41**, 215203 (2008).
[3] S. Liu and M. Neiger, J. Phys. D: Appl. Phys. **36**, 3144 (2003).

# Modeling the Erosion of a Wire in the Plume of a Hall Thruster

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(b) University of Colorado Boulder

Integration of electric propulsion devices such as Hall thrusters onto spacecraft needs to be well understood, as Hall thrusters are commonly used on Earth-orbiting satellites and for deep-space missions. One consideration when placing a Hall thruster on a spacecraft is erosion by ion impact sputtering of spacecraft components, as erosion can affect the performance of those components. This work aims to understand the erosion of one such component: the meshed reflector. Meshed reflectors are parts of antenna on spacecraft and are typically composed of a mesh of small molybdenum wires coated with gold. Despite the erosion of flat surfaces being well characterized in the literature[1], the erosion of cylindrical wires in the plume of a Hall thruster has not been studied previously, as the angle of incidence varies around the wire. There are two main challenges in determining the erosion of a wire in the meshed reflector: the distribution of ion energies in a Hall thruster plume and the cylindrical geometry of a wire. Because of these challenges, the erosion is calculated by discretizing the cross-section of the wire into small, flat surfaces and tracking the erosion of each of those surfaces through time.

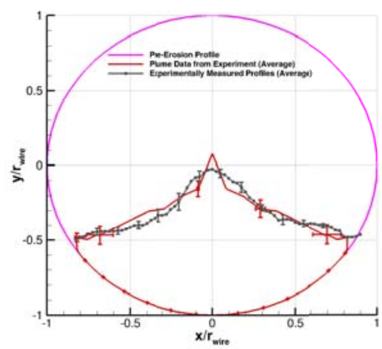


Figure 1 – Predicted eroded wire profile compared to experimentally measured wire profile at 18° from the thruster centerline and 1 m from the thruster exit.

The erosion of a flat surface depends on the local plasma properties, material properties, and the angular incidence sputter yield. The local plasma properties required are the ion current density and ion energy distribution function (IEDF). Material properties such as the mass and density of the surface are required. The angular incidence sputter yield represents the number of atoms removed from the surface per incident ion and depends on the incident ion energy and incident angle. Assuming singly-charged ions incident on the wire from a uniform direction, the cross-sectional profile of the eroded wire can be predicted.

Experiments performed at the Plasmadynamics and Electric Propulsion Laboratory measured the plasma properties of the H6US thruster at various locations in the plume. The experiments also placed small samples of the meshed reflector in the plume, and the eroded wire profiles were measured to compare to the predictions of the model[2]. As the model predictions varied for the different sputter yield models, an average of the final profiles was compared to the experimentally measured profiles, as seen in Figure 1.

**References**

[1] I. D. Boyd and M. L. Falk, in *AIAA-2001-3353* (2001).
[2] M. P. Byrne, M. E. Meyer, I. D. Boyd, and B. A. Jorns, in *AIAA-2019-3988* (2019).

# Impact of Magnetic Shielding on Efficiency of Krypton Operation*

Leanne L. Su and Benjamin Jorns

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Krypton operation on Hall thrusters has the advantage of higher specific impulse and lower prices at the cost of lower thrust compared to xenon. This results in a device that fills a different mission space than xenon-powered Hall thrusters. On high-power Hall thrusters, krypton-operated Hall thrusters could fly space science missions to the outer planets and beyond [1]. We expect krypton efficiency to be lower than xenon efficiency due to its lower atomic mass and higher ionization energy threshold. However, experimental results have shown that xenon Hall thruster anode efficiencies are 5-15% higher than those of krypton operation; these experimental krypton efficiencies fall further below theoretical values than xenon efficiencies [2,3,4].

This phenomenon is thought to be mitigated by the side effects of magnetic shielding. Magnetic shielding is a recently-developed technique that takes advantage of the isothermal nature of magnetic field lines, shaping them in a Hall thruster channel such that energetic ions do not impact the channel walls [5]. This field topology has been shown to extend Hall thruster lifetimes by multiple orders of magnitude [5,6]. Magnetic shielding also causes electron temperatures along centerline to reach higher values [6]. Comparing krypton and xenon ionization curves show that for a given change in electron temperature, the ionization cross-section of krypton increases by a larger factor than the ionization cross-section of xenon [7]. Consequently, we expect increased electron temperatures to cause a larger increase in the efficiency of krypton operation than the efficiency of xenon operation; the ratio between xenon and krypton efficiencies on a magnetically-shielded Hall thruster should be closer than it would be on an unshielded thruster. Additionally, high-voltage operation has been shown to improve krypton efficiency [3,4]. We can explore the magnitude of this effect at high voltages compared to lower voltages. Therefore, there is an apparent need for an experimental investigation of krypton efficiency on a magnetically-shielded, high-power Hall thruster and a comparison of results to xenon efficiency.

To evaluate this potential increase in efficiency, we operate the H9, a 9-kW magnetically-shielded thruster, on krypton and compare its efficiency to previous measurements on xenon at five different operating conditions. An experiment was conducted in the Large Vacuum Test Facility (LVTF) at the University of Michigan wherein the H9 was mounted to a thrust stand and run at five different operating conditions up to 9 kW. A null-type inverted pendulum thrust stand was used to take thrust measurements and calibrated mass flow controllers used to take mass flow measurements. We then compare the difference between krypton and xenon efficiencies to the difference typically seen on unshielded Hall thrusters.

* Work supported by the National Science Foundation

**References**

[1] Jacobson, D. T., & Manzella, D. H. (2003). *50 kW Class Krypton Hall Thruster Performance*. Cleveland, OH.

[2] Linnell, J. A., & Gallimore, A. D. (2006). Efficiency Analysis of a Hall Thruster Operating with Krypton and Xenon. *Journal of Propulsion and Power*, *22*(6), 1402–1418.

[3] Nakles, M., Hargus, W., Delgado, J., & Corey, R. (2011). A Performance and Plume Comparison of Xenon and Krypton Propellant on the SPT-100. *32nd International Electric Propulsion Conference*.

[4] Hofer, R. R., Peterson, P. Y., Jacobson, D. T., & Manzella, D. M. (2004). Factors Affecting the Efficiency of Krypton Hall Thrusters. *46th Meeting of the APS Division of Plasma Physics*.

[5] Mikellides, I. G., Katz, I., Hofer, R. R., & Goebel, D. M. (2014). Magnetic shielding of a laboratory Hall thruster. I. Theory and validation. *Journal of Applied Physics*, *115*(4).

[6] Hofer, R. R., Goebel, D. M., Mikellides, I. G., & Katz, I. (2014). Magnetic shielding of a laboratory Hall thruster. II. Experiments. *Journal of Applied Physics*, *115*(4).

[7] Bordage, M. C., Biagi, S. F., Alves, L. L., Bartschat, K., Chowdhury, S., Pitchford, L. C., … Zatsarinny, O. (2013). Comparisons of sets of electron-neutral scattering cross sections and swarm parameters in noble gases: III. Krypton and xenon. *Journal of Physics D: Applied Physics*, *46*(33).

# Interaction of Relativistic Magnetized Electrons with Obstacles*

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Using a laser pulse from the OMEGA EP laser system focused to an intensity of ~$10^{19}$W/cm$^2$ we generate hot electron plumes on the surface of 25μm thick Al targets with high magnetization due to self-generated fields, given by $\sigma_{cold} = B^2/\mu_0 n_e m_e c^2 > 1$. These plumes expand at ~c and interact with obstacles in the form of holes, or "blobs" of glue on the target. This interaction is probed using time-resolved proton radiography which allows for the measurement of fields in the plane of the target. The proton radiographs are analyzed using standard radiograph inversion codes and are compared to 2D and 3D particle-in-cell simulations.

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# Time-Dependent Physics of Single-Surface Multipactor with Dual-Tone RF Carriers*

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This work investigates the time-dependent physics of single-surface multipactor with dual-tone carriers by Monte Carlo (MC) simulations [1-3]. We employ a multiparticle MC simulation scheme [4] in one dimension with exact adaptive time steps to examine the effects of the relative strength ($\beta$), relative phase ($\gamma$), and the frequency ratio ($n$) of the two carriers on the multipactor electron trajectories, the temporal profiles of the normal electric field due to surface charging, and the secondary electron yield (SEY).

We find that dual tone operation can result in weaker single surface multipactor strength than single tone operation at the same total power. We observe the migration of multipactor electron trajectories with appropriate configuration of the second carrier frequency (Figure 1) and propose the steerability-to-zero criterion [5] to determine the conditions under which multipactor electron trajectories can be controlled for dual-tone operation.

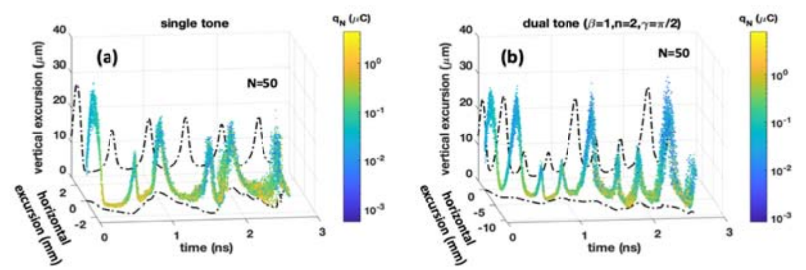


Figure 1 – Horizontal (along the dielectric surface) and vertical (normal to surface) excursions of $N = 50$ multipacting macroparticles with respect to time, (a) for single-tone rf electric field, and (b) for dual-tone rf electric field with $\beta = 1, n = 2,$ and $\gamma = \pi/2$ . Charge contained in the macroparticles is shown in the color bar. Mean displacements of the macroparticles with respect to time are shown as projections on the horizontal and vertical planes.

It is found that the non-integer frequency ratio between the two carrier modes results in the formation of beat waves in the temporal profiles of the normal electric field due to surface charging. We have examined the frequency components of these beat waves and their relationship with the two driving frequencies of the rf carrier by frequency domain analysis of the temporal profiles.

*Work supported by AFOSR MURI Grant No. FA9550-18-1-0062, and MIPSE Graduate Fellowship.

**References**

[1] R. A. Kishek and Y. Y. Lau, Phys. Rev. Lett. **80**, 193 (1998).
[2] H. C. Kim and J. P. Verboncoeur, Phys. Plasmas **12**, 123504 (2005).
[3] A. Iqbal, J. Verboncoeur, and P. Zhang, Phys. Plasmas **25**, 043501 (2018).
[4] A. Iqbal, J. Verboncoeur, and P. Zhang, Phys. Plasmas **26**, 024503 (2019).
[5] S. A. Rice and J. P. Verboncoeur, IEEE Trans. Plasma Sci. **45**, 1739 (2017).

# Vacuum Ultraviolet and Visible Spectroscopy for Power Flow Studies on the 1 MA, 100 ns MAIZE LTD*

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Power flow studies on the 25-MA Z machine at Sandia National Laboratories have shown that plasmas present in the Z machine's magnetically insulated transmission lines (MITLs) can result in a loss of current delivered to the load. This presentation reports on efforts to develop spectroscopic diagnostics for power flow experiments on the University of Michigan's 1-MA MAIZE facility to validate ongoing simulation studies.

A vacuum ultraviolet (VUV) spectrometer will be used to measure the rate at which various constituents desorb out of the MITLs on MAIZE. These experiments will be run with scaled anode-cathode dimensions to obtain electric field intensities or current densities comparable to those found in certain regions of the Z machine. The VUV range (100-200 nm) was chosen due to the expectation of low levels of black-body emission, supported by preliminary simulations with PrismSPECT. Visible spectroscopy on MAIZE will allow comparison with VUV data on MAIZE and with published visible spectroscopic data from the Z machine. These comparisons will help inform efforts to implement VUV spectroscopy on the Z facility.

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# Reactor Scale Modeling of Nanoparticle Growth in Low Temperature Plasmas*

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In recent years, low temperature "dusty" plasmas have emerged as a viable alternative to gas and liquid phase technologies for nanoparticle synthesis. Nanoparticles grown in plasmas have demonstrated a wide variety of novel properties such as exceptional hardness, increased melting temperatures, and superior luminescence. Properties can be tuned by changing plasma parameters such as gas flow rate, gas composition, and power deposition [1,2].

In this work we computationally investigated silicon nanoparticle (NP) growth in plasmas at the reactor scale. The Hybrid Plasma Equipment Model (HPEM) [3], a two-dimensional reactor scale multi-physics model was used to track particle mass and diameter as NP grow. Silicon NP growth in an argon inductively coupled plasma (ICP) using silane ($SiH_4$) as a precursor gas was modeled. Typical plasma conditions at 1-1.5 Torr pressures with 10-100s sccm flowrates of Ar/$SiH_4$ 0.99/0.01 mixture are electron densities on the order of $10^{10}$ $cm^{-3}$ and electron temperatures on the order of 3-4 eV. Results for trends in silicon NP growth as a function of plasma parameters such as pressure, gas flow rate, and power deposition will be discussed (See Fig. 1.). Computational results will be compared with experimental results for validation.

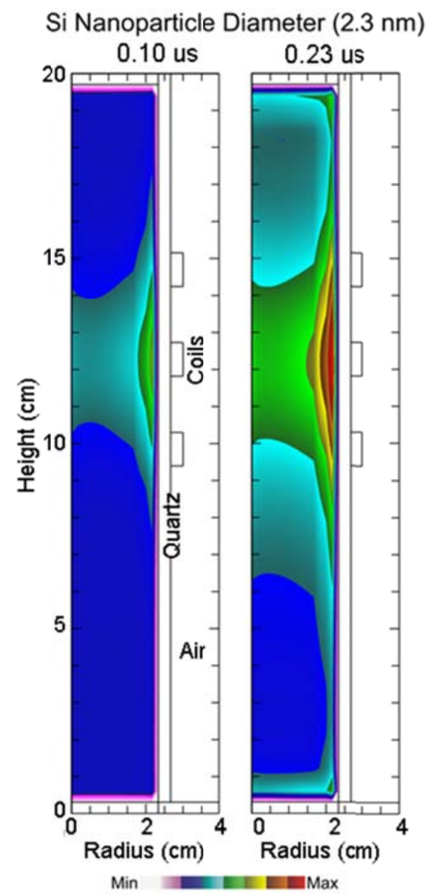


Figure 1 – Silicon nanoparticle diameter as a function of time. (1 Torr, 10 W power deposited, 250 sccm 0.99Ar/0.01$SiH_4$)

* Work supported by the Army Research Office MURI Program and the Department of Energy Office of Fusion Energy Science.

**References**

[1] L. Mongolini, E. Thimsen, and U.R. Kortshagen. Nano Lett. **5**, (2005).
[2] U. R. Kortshagen. Plasma Chem. Plasma Process. **36**, (2016).
[3] M. J. Kushner, J. Phys. D Appl. Phys. **42**, 194013 (2009).

# Vlasov-Poisson Simulations of Ion-Acoustic Turbulence*

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Hollow cathodes are electron sources which are ubiquitous in the field of electric propulsion. These devices utilize thermionic emission to create an electron current which both i) ionizes propellent and ii) neutralizes the resulting ion beam that generates thrust in Hall and ion thrusters. As these thrusters are candidates for future long duration deep space missions, life-limiting processes such as erosion must be kept to a minimum. However, hollow cathodes have demonstrated levels of erosion in excess of those predicted by classical expansion of the plume plasma; energetic ions have been identified as the source of this erosion. Recent experimental and theoretical work has determined that a plasma instability, namely ion-acoustic turbulence (IAT) is prevalent in the plume region of hollow cathodes. [1] Indeed, this instability is capable of generating high energy ions which may lead to increased erosion.

This work aims to simulate IAT using a high-fidelity Vlasov-Poisson solver in 1D1V. Simulations of ‘triggered’ IAT will be carried out to benchmark against those in the literature [2], where the boundary conditions are periodic and electrons are assigned a drift velocity at startup. These simulations will be followed by more realistic simulations of ‘spontaneous’ IAT, where both ions and electrons are resting and a potential difference is applied across the domain.

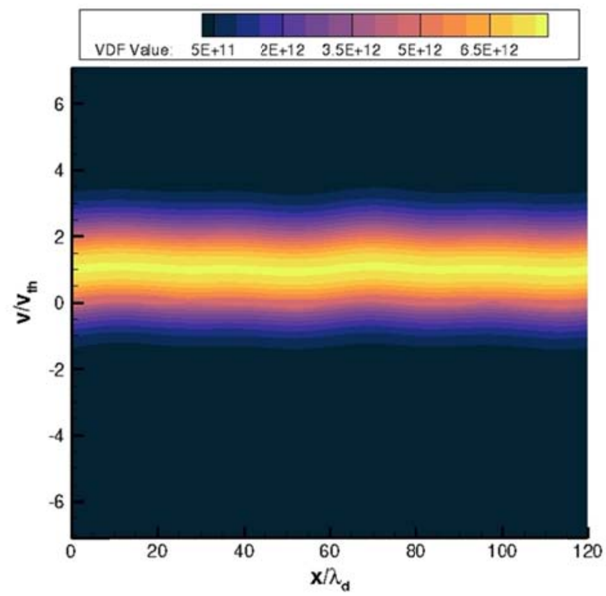


Figure 1 – Example electron phase space plot demonstrating trapping at the ion acoustic velocity.

A variety of useful information can be obtained from these high-fidelity simulations. For example, erosion rates of the cathode can be estimated by the energies of ions which back-stream in the domain. Additionally, the resistivity of the plasma due to the instability can be quantified to provide inputs to reduced order fluid models. [3] Future work will involve the use of a fluid model to compare to the Vlasov results to study the accuracy of reduced order simulations by varying tuning parameters for anomalous mobility, and to investigate what these parameters indicate about the state of the turbulence.

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

**References**

[1] B. A. Jorns, I. G. Mikellides, and D. M. Goebel, “Ion acoustic turbulence in a 100-A LaB6 hollow cathode,” *Phys. Rev. E - Stat. Nonlinear, Soft Matter Phys.*, vol. 90, no. 6, pp. 1–10, 2014.

[2] K. Hara and C. Treece, “Ion kinetics and nonlinear saturation of current-driven instabilities relevant to hollow cathode plasmas,” *Plasma Sources Sci. Technol.*, vol. 28, no. 5, p. 055013, 2019.

[3] P. Petkaki and M. P. Freeman, “Nonlinear Dependence of Anomalous Ion-Acoustic Resistivity on Electron Drift Velocity,” *Astrophys. J.*, vol. 686, no. 1, pp. 686–693, 2008.

# Line Integrated Barium Absorption Spectroscopy Along Cathode Axis*

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The lifetime of the HCA in many cases determines the overall lifetime of the thruster. The lifetime of both LaB6 and barium impregnated tungsten based cathodes is dependent upon the state of the emitting surface, which is characterized by a mean work function. Due to various processes, the work function of the emitter tends to increase over time ultimately ending in emitter failure at practical emission temperatures. Future high power gridded ion and Hall thrusters will require higher emission currents than the current state of the art while maintaining lifetime. Qualifying an EP device for missions is currently accomplished through expensive, long duration life tests wherein the device operational parameters are set to those expected during the proposed mission. Such testing offers limited application to varying designs and broader operating envelopes. One approach to determining lifetime is to utilize predictive models to predict the evolution of the cathode over its projected operating lifetime. Practical implimentation requires that the model be sufficiently mature. The physics within the model must be verified and then the model bench-marked against simple cases. Next, the model must be tested against experiment for predictive validation. This work focuses on gaining insight into the evolution of the barium supply within the insert region of a oxide emitter HCA. Through the use of absorption spectroscopy, we obtain a line-integrated measure of the barium density during cathode operation as a first step towards quantifying barium transport in the insert region. Here we present the progress of this work. In this work, a Xenon Arc Lamp is used to excite barium neutrals circulating in the insert region in a classic setup [1][2]. Using Beer's law and the equivalent width method, we measure the line integrated barium density as a function of cathode operating conditions[3].

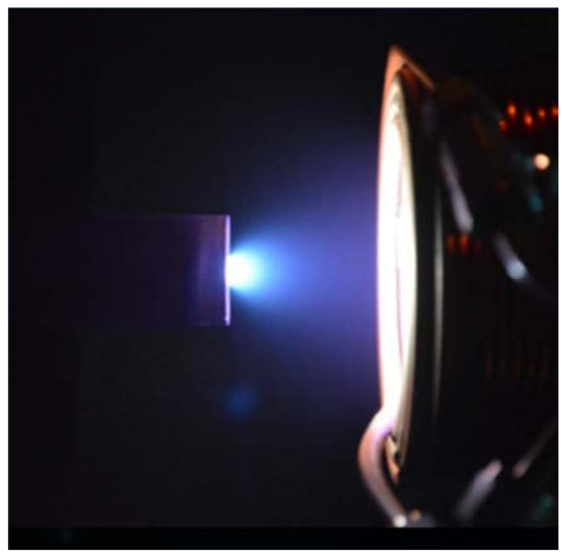

Figure 1 – Hollow Cathode Assembly in operation with cylindrical anode.

* Work supported by the NASA through NSTRF Grant 80NSSC18K1151

**References**

[1] Y. Andrew *et al,* Journal of Applied Physics **88**, 3208 (2000); https://doi.org/10.1063/1.1289219
[2]R.C Wamsley, K. Mitsuhashi, and J.E. Lawler, Rev. Sci. Instrum. **64,** 45 ~1993
[3]S. S. Penner, *Quantitative Molecular Spectroscopy and Gas Emissivities* (Addison-Wesley, Reading, MA, 1959).

# Numerical Optimization of a Rotating Magnetic Field Field-reversed Configuration Thruster

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The 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 remain poorly understood.

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, rotating magnetic fields (RMFs) form the azimutha currents. 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]. However, there are still open questions about how the thrust and efficiencies depend on the thruster operating conditions. This study uses the dimensionless form of a circuit model previously derived by Woods et al to determine optimal operating parameters for an RMF-FRC [2]. Following the method of optimizing an FRC thruster, the various operating parameters are folded into a set of dimensionless terms [3]. Using a genetic algorithm, the circuit is optimized to produce the highest efficiency operating conditions. The ramifications of the optimal condition are discussed in the context of thruster performance and design.

**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] Woods, J. M., Jorns, B. A., and Gallimore, A.D., "Circuit Modeling of Rotating Magnetic Field Field-reversed Configuration Thrusters", 54th AIAA/SAE/ASEE Joint Propulsion Conference, Cincinnati, OH, AIAA-2018-4911, July 9-11, 2018

[3] Niemela, C. S. and King, L. B., "Numerical Optimization of an Annular Field Reversed Configuration Translation Experiment," 31st International Electric Propulsion Conference, Ann Arbor, Michigan, September 2009.

# Data-Driven Modeling of the Effect of Background Pressure on the Operation of a Hall Effect Thruster

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Hall effect thrusters (HET) are increasingly becoming one of the most widely used electric propulsion technologies. Yet, one of the major unanswered question about the operation of HETs is the validity of using ground measurements to predict the behavior of the thruster on-orbit. It is not yet possible to recreate true space conditions in the laboratory. Facility backpressure can have a significant effect on the operation of HETs, influencing key thruster properties such as thrust, plume divergence, cathode operation, discharge current oscillations, and plume plasma parameters like ion current density [1]. There is then a strong motive to develop a method to map ground-based measurements to on-orbit behavior. One way others have attempted to address this problem is through parametric studies, systematically lowering the facility pressure to map the dependence of key thruster properties on backpressure [1]. Extrapolation can be used to then map these trends to space-like pressures, however, it is not clear what type of extrapolation should be used or if there is even a valid way to extrapolate over such a large range. Additionally, the only way to truly validate the extrapolation is with orbital tests which are prohibitively expensive. The goal of this study is to develop methods which can predict with uncertainty how thruster properties will transition from ground to flight conditions based solely on ground measurements. Multiple models with various functional forms are tested and their most probable fitting parameters are estimated using a Bayesian parameter estimation method with a nested Markov Chain Monte Carlo sampling approach [2]. Finally, the trained models are used to estimate the properties of an SPT-100 thruster under orbital conditions with a well-defined uncertainty envelope. These predictions are compared to orbital measurements from the Russian express missions [3] to quantify the accuracy of the model.

**References**

[1] Kevin D. Diamant, Raymond Liang, and Ron L. Corey., AIAA Propulsion and Energy Forum, (AIAA-2014-3710)

[2] Sivia, D. S., and Skilling, J., Data Analysis: A Bayesian Tutorial, 2nd edition, Oxford University Press, 2006

[3] D. Manzella, R. Jankovsky, F. Elliott, I. Mikellides, G. Jongeward, and D. Allen, 27th International Electric Propulsion Conference, Pasadena, California, 2001

# Modeling Collisional Ionization Using a Modified Binary-Encounter-Bethe Model in the Particle-in-Cell Code OSIRIS*

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Collisions, and subsequently collisional ionization, have become necessary to a proper understanding of plasma dynamics in a variety of situations. For example, collisional ionization must be used to properly model electron bunch propagation over long distances (up to several meters or more) outside vacuum. To correctly simulate these problems, it is important to develop and implement computational models that accurately depict the complex atomic physics of these interactions. However, difficulties can arise when the atomic structure and electron configuration of an atom greatly alters the binding energy and cross sections to be used in these formulations. We have implemented a collisional ionization routine in the particle-in-cell code OSIRIS that draws on examples and advancements from other particle-in-cell codes. We use a modified binary-encounter-Bethe model to calculate atomic cross-sections along with the Monte Carlo collisional scheme in order to model inter- and intra-species collisional ionization in both relativistic and non-relativistic regimes. We present details of the implementation and results from running OSIRIS using this new collisional ionization module.

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# Azimuthal Current Measurement in an Expanding Magnetic Field

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Magnetic nozzles consist of expanding magnetic fields applied to a plasma exhaust to convert thermal energy into thrust. Since they often implement an externally-mounted radio frequency or microwave antenna for ionization, they can operate for extended durations without eroding any current-carrying components. A potential shortcoming of these devices is that a plasma that remains too strongly attached to the magnetic field will return to the thruster, negating thrust. While ions are often unaffected by the magnetic field in low-power versions of these devices due to their inertia, electrons may follow the fields more strictly, generating electric fields that will cause the ions to diverge or return to the thruster as well. Thus, some mechanism for electron cross-field transport is necessary for thrust generation.

In this work, we measured directly for the first time the magnitude and extent of this anomalous electron resistivity in a magnetic nozzle plume. This was done on a 30 W magnetic nozzle test article located at the University of Michigan (Ref. [1]). We employed plasma probes to characterize the background plasma properties and resulting gradients in potential and pressure. We in turn measured the electron drifts in the plume directly by employing a translating B-dot probe following the techniques outlined Refs. [2, 3]. Combing these measurements of plasma properties and current with a generalized Ohm's law allowed us to determine the effective resistivity in the plume. In parallel, we determined the classical resistivity from Spitzer collisions with the plasma properties found by the Langmuir probe. Assuming that electron-neutral collisions are negligible, we subtracted this value from the total resistivity to yield an anomalous resistivity term. In keeping with our previous work [4], we have found that the anomalous resistivity is orders of magnitude higher than classical. We discuss that this discrepancy may be a result of the presence of drift-driven instabilities in the plume.

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

**References**

[1] Wachs, Benjamin, and Benjamin Jorns. "Effect of Background Pressure on Ion Dynamics in an Electron Cyclotron Resonance Thruster." In 2018 Joint Propulsion Conference. Cincinnati, 2018. doi:10.2514/6.2018-4585.

[2] Takahashi, Kazunori, and Akira Ando. "Laboratory Observation of a Plasma-Flow-State Transition from Diverging to Stretching a Magnetic Nozzle." Phys. Rev. Letters 118, no. 225002 (2017). https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.118.225002.

[3] Roberson, B Race, Robert Winglee, and James Prager. "Enhanced diamagnetic perturbations and electric currents observed downstream of the high power helicon." Phys. Plasmas 18, no. 053505 (2011). doi:10.1063/1.3574753.

[4] Hepner, Shadrach T, Benjamin N Wachs, Timothy T Collard, and Benjamin A Jorns. "Observation of low frequency plasma oscillations in the plume of a partially magnetized magnetic nozzle." In 2018 Joint Propulsion Conference. Cincinnati, OH, 2018. doi:10.2514/6.2018-4730.

# Simulations of Magnetized Turbulence in the Taylor-Green Vortex*

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Magnetized turbulence in the compressible magneto-hydrodynamic (MHD) regime is important in the evolution of terrestrial and astrophysical plasmas as it mediates an exchange of magnetic, kinetic, and thermal energies between different length scales. Large scale kinetic flows break down into smaller kinetic eddies that build up magnetic energy through the small scale dynamo. These kinetic eddies in turn dissipate energy down to smaller scales and eventually into thermal heating. Modeling these energy changes is essential for high fidelity numerical plasma simulations. However, fully capturing magnetic turbulence in a simulation can require high temporal and spatial resolutions that cannot be feasibly simulated in large systems. Instead, we can develop and incorporate models of the turbulence below the grid resolution of low resolution simulations. Fine tuning such sub-grid models requires first understanding the behavior of turbulence in a variety of regimes in high resolution simulations of idealized systems.

To help develop sub-grid models of turbulence for decaying magnetized turbulent flows, we simulated the magnetized Taylor-Green vortex over a range of flow velocities and magnetic field strengths. The magnetized Taylor-Green vortex is a periodic flow with imposed magnetic field that decays into a chaotic, magnetized turbulent flow.[1] The model is free from external drivers of turbulence, mimicking intermittently driven flows that are common in nature. Simulations were done using K-Athena, a performance portable conversion of the plasma simulation code Athena++, which facilitated high resolution simulations on several computing platforms.[2,3]

We present the kinetic and magnetic energy spectra of the resulting turbulent flow under a range of different parameters. Additionally, we show analysis of the kinetic and magnetic energy budgets of the plasma and of how energy is transferred between different energy reservoirs.[4] By simulating the Taylor-Green vortex at sufficiently high resolution with compressible MHD, broad properties of decaying magnetized turbulence can be better quantified.

* Work supported by Blue Waters at the National Center for Scientific Computing and the Michigan Institute for Plasma Science and Engineering

**References**

[1] M. E. Brachet, M. D. Bustamante, G. Krstulovic, P.D. Mininni, A. Pouquet and D. Rosenberg, Phys. Rev. E. **87**, 013110 (2013)
[2] P. Grete, F. W. Glines and B. W. O'Shea, *in prep.* (2019)
[3] C. J. White, J. M. Stone and C. F. Ammie, ApJS **225:2**, 22 (2016)
[4] P. Grete, B. W. O'Shea, K. Beckwith, W. Schmidt and A. Christlieb, Phys. Plasmas **24**, 092311 (2017).

# Development and Characterization of a Small-Scale Helical Dielectric Barrier Discharge for Studying Plasma-Surface Interactions

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The study of plasma-surface interactions is an emerging field for a wide variety applications, including sustainable energy (catalytic $H_2$ production), environmental remediation (water purification), medicine (sterilization), and high-value manufacturing (nanomaterial synthesis). These applications are driven by species created in the plasma or at a plasma-surface interface, such as free electrons, gaseous ions, excited molecules and radicals, driving chemistry at a surface. Here, we develop a new dielectric barrier discharge (DBD) configuration to produce surface DBDs over a three-dimensional geometry. The motivation for this geometry was to embed the plasma source inside a packed bed (*e.g.*, catalyst) reactor that had tight spatial restrictions so that it could be implemented in a commercial Fourier transform infrared (FTIR) spectrometer instrument.

The design, which we term a helical DBD, was inspired by surface DBD configurations often employed in plasma actuators for fluid dynamics applications. However, rather than using a 2D surface common in plasma actuators, the helical DBD uses the 3D surface of a cylinder as its dielectric, allowing for greater plasma coverage and in this case, greater interaction with a packed bed. This study characterizes the electrical properties of the helical DBD in both free space and within a packed bed reactor. Various electrical parameters, including deposited power and plasma current are measured in air and argon environments. Visual properties are presented to show how the DBD spreads along the dielectric surface or into the packed bed. The effect of being immerged in a packed bed is quantified and the potential future prospects of this type of DBD geometry are discussed.

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## Uncertainty in Curlometer Technique: Cluster Ring Current Observations*

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During its ongoing mission, the Cluster II constellation has provided the first small-scale multipoint measurements of the space environment, and dramatically advanced scientific understanding in numerous regimes. One such region is the Earth's ring current, which could now be computed using the curl of the magnetic field over a spacecraft tetrahedron instead of plasma moments. While this produced the first 3D ring current estimates [1], it also dramatically contradicted prior ring current studies through enhanced magnitudes and differing correlations with storm indices/local times [2]. In this analysis, we revisit Cluster ring current data via curlometry, and conduct additional sensitivity simulations for the first time using actual spacecraft position data. During the orbits observing ring current structure, tetrahedron shape and linearity assumptions can create large errors in curlometer output that contradict accepted estimated quality parameters. Furthermore, the plasma gradients computed from JxB are distinctly different from those measured via plasma spectroscopy, and are also contrary to theorized plasma structure. Nevertheless, previous studies use these curlometer outputs to draw conclusions about ring current distributions and structure [3][4]. A new climatology of the ring current is then presented, but with severe limitations that are explicitly defined. Thus, the discrepancies are addressed by improved curlometer uncertainty estimates.

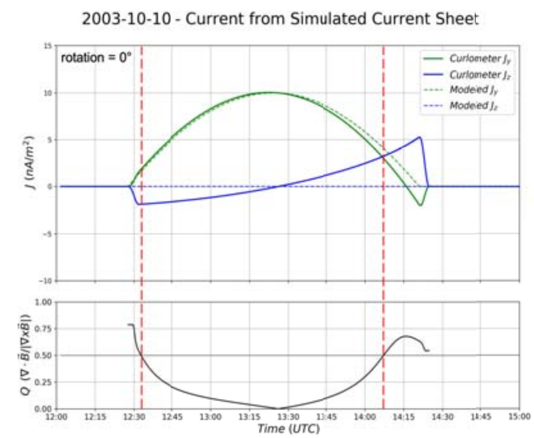


Figure 1 – Simulated current sheet using actual spacecraft position data without modified orientation. The top panel shows the curlometer results capturing the simulated current and producing a false current as well. The bottom panel shows the accepted quality parameter. Red dashed lines denote standard quality thresholds, which demonstratably can still include large uncertainty.

* Work funded in part through a grant from the National Science Foundation's Research Experience for Undergraduates Program (Grant Number 1659248)

**References**

[1] Vallat et al., Annales Geophysicae. **23**, 1849–1865 (2005).
[2] Liemohn et al., Journal of Geophysical Research: Space Physics. **121**, 6763-6768 (2016).
[3] Zhang et al., Annales Geophysicae. **29**, 1655-1662 (2011).
[4] Shen et al., Journal of Geophysical Research: Space Physics. **119**, 2458-2465 (2014).

# Kinetic Modeling of Nanoparticle Growth in Low Pressure Plasmas*

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Dusty low pressure plasmas can be used to synthesize high quality nanoparticles (NPs). Properties of NPs can be tuned based on the operating conditions for the plasma. Modeling this complicated growth process can give valuable insight about the physics of growing NPs in a plasma chamber. Particles have variable charges based on size and local plasma properties. Small nanoparticles (< 1 nm) may have either a negative or positive charge depending on discrete collisions with charged particles, while larger particles generally negatively charge. Many forces acting on the NPs scale with particle size and charge, such as the fluid drag force, the electrostatic forces between particles, and drag forces by ions. Negative particles can become trapped by the positive plasma potential, leading to growth through collisions of precursor molecules. The coupled growth and charging mechanisms of NPs in plasma naturally make a kinetic approach to modeling appealing.

In this work, we discuss efforts to model silicon NP growth for comparison with experimental results. The Hybrid Plasma Equipment Model (HPEM), a plasma multi-fluid model, was used in this work. Kinetic methods and algorithms for nanoparticle growth were implemented in the Dust Transport Simulator (DTS), a 3D supplement to HPEM for modeling dust particles. Trends of NP growth under various operating conditions (base case ≈ 1.5 mTorr, 5 W, 15 sccm of 99/1 $Ar/SiH_4$) in an inductively coupled plasma tube will be discussed.

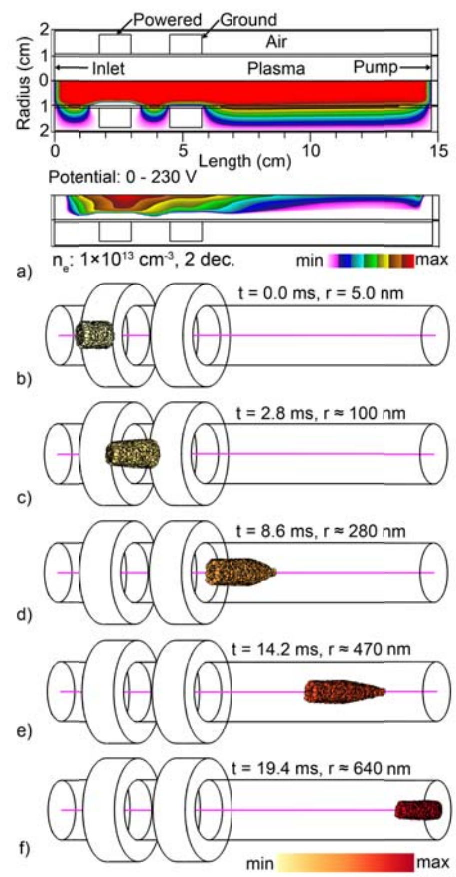


Figure 1 – An example simulation of a capactiviely coupled plasma used to grow nanoparticles. a) Plasma potential and electron density, b-f) average particle sizes and positions over time.

* Work supported by Army Research Office MURI Program and Department of Energy Office of Fusion Energy Science

**References**

[1] U. Kortshagen et al. Chem. Rev. 116, 11061 (2016).

# Numerical Investigation of Current Closure in the Plume of a Magnetic Nozzle

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Propulsive magnetic nozzles are spacecraft propulsion devices in which a plasma expands along diverging magnetic field lines, accelerating to produce thrust. Due to their largely wall-less mode of operation and the lack of any electrodes, devices using magnetic nozzles should erode at a much lower rate than comparable devices. This makes them attractive for a wide variety of mission architectures that require long lifetimes or make use of less inert propellants than the noble gases typically used in electric propulsion devices. These properties mean that magnetic nozzles are potentially ideal for deep space propulsion architectures that incorporate in-situ resource utilization. However, current magnetic nozzle designs suffer from abysmal efficiency, typically on the order of 10% or less. While most of this inefficiency stems from losses during the generation of the plasma (low "source efficiency"), a significant amount comes from inefficient expansion of the plasma (low "nozzle efficiency) [1]. In order to optimize nozzle design and maximize nozzle efficiency, it is critical to analyze the plasma's behavior during the expansion. Central to this problem is a good understanding of plasma detachment.

Plasma detachment is the process by which the plasma streamlines diverge from the magnetic field lines. Were the plasma to stay attached, it would follow the closed field lines of the nozzle and impact the spacecraft, nullifying thrust and eroding the device. While it experimentally appears that detachment occurs in real devices [3][4], parts of this process remain poorly understood. For example, while it has been established that the heavier ions detach convergently (inward from the field lines), models predict the lighter electrons should detach divergently [1]. This creates a current ambipolarity (CA) violation as electron and ions move in opposite directions at different velocities. This leads to current contour lines remaining unclosed at the simulation far-field boundary [2]. To explore if and how downstream current closure occurs and how it impacts thrust, there is a need to develop models with a large experimental domain and which can incorporate a wide range of plasma phenomena. To this end, the open source CFD code SU2 was modified to simulate a magnetic nozzle. For the initial treatment, ions were treated as a collisionless fluid, and electrons were considered fully magnetized, isothermal, and massless. The results provide more evidence of the current closure problem in the magnetic nozzle plume and demonstrate its detrimental effect on thrust efficiency. Estimates of the impact of other effects, including collisions and electron cooling, on the plasma expansion are also provided.

**References**

[1] E. Ahedo and M. Merino, Physics of Plasmas **18**, 153504 (2011).
[2] E. Ahedo and M. Merino, Physics of Plasmas **17**, 073501 (2010).
[3] C. Deline et al, Physics of Plasmas **16**, 033502 (2009).
[4] C. Olsen et al, IEEE Transactions on Plasma Science **43**, 14864083 (2015).

# Gas Phase Plasma-Based Approach for Synthesis of Gold Nanoparticles*

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There are different class of applications for gold nanoparticles (AuNPs) due to their interesting optoelectronic properties such as tunable optical absorption and surface plasmonic resonance behavior (LSPR). However, modern fabrication and stabilization of colloidal AuNPs are well established, especially in liquid phase, new synthesis routes can lead to enhanced versatility of applications for AuNPs, particularly if the perspective methods allow avoidance of wet chemistry processes and surface-ligands. Here, we introduce a non-thermal radio frequency plasma- based synthesis of AuNPs, using a consumable gold wire as grounded electrode[1]. The AuNPs are monodisperse, with an average diameter of 4 nm. Although production yield is low compare to pre-existing methods, including atmospheric hotwire method, the narrow size distribution of the AuNPs (regardless of background gas flowrate) and the avoidance of solution processing in this method are promising for future syntheses of metal NPs based on plasmas. Here, we compared reduced pressure Hotwire method as studied with *Boies et al.* [2]with our new plasma-based approach. Moreover, we try to investigate AuNP formation with other frequency power supply and another range of pressure including atmospheric pressure.

* Work supported by the National Science Foundation (NSF) CAREER Grant number (CMMI-1651674)

**References**

[1] A.Izadi and R.J. Anthony, J. Plasma Processes and Polymers **16**, e1800212. (2019).
[2] A.M. Boies et al., J. Aerosol Science and Technology. **45(5)**, 654-663(2011).

# Chemical Analysis of the Secondary Emission in a Non-thermal Plasma with a Liquid Cathode*

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A common configuration used in plasma-liquid interactions is that in which a direct current (DC) gas discharge is generated between a liquid and a metal. Under this configuration, known as plasma electrolysis or glow-discharge electrolysis, the liquid itself functions as a plasma cathode or anode, for a positive or negative DC bias, respectively. However, it is not clear exactly how the liquid participates in the formation and sustaining of the plasma, including charge transfer at the plasma-liquid interface. This is especially true when the liquid is acting as a cathode, and secondary emission from the liquid is ostensibly required to sustain the plasma. In this work, we use measurements of discharge voltages to understand this process. Voltage measurements for an argon plasma in contact with an aqueous solution are conducted in an electrochemical H-cell reactor to test for conditions that would facilitate secondary emission from the liquid. We tested the effects of the interfacial chemistry in the secondary emission from an aqueous cathode, including pH (from pH = 0 to 14), the hydroxyl radical, the hydrogen atom, the solvated electron, and the pre-solvated electron. These experiments had no significant effect on the plasma voltage, suggesting that the solvated electron, the pre-solvated electron, and the hydrogen atom do not play a crucial role in secondary emission as previously proposed.

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# The Impact of a Magnetic Field on Ion Emission from a Hollow Cathode Plasma Contactor*

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Recent experimental validation of the novel "ion emission model" has paved the way for a new class of space missions [1,2]. Specifically, missions which require significant electron beam emission in regions with a tenuous (low density) ambient plasma were previously not possible. This is because the electron beam emission current could not be realistically compensated by electron collection from the tenuous ambient plasma. This current imbalance led to significant increases in the spacecraft potential until ultimately the electron beam was electrostatically pulled back to the spacecraft. According to the ion emission model, the electron beam current can be compensated by equivalent ion emission from the surface of a quasi-neutral plasma contactor according to the space-charge limit. While the fundamentals of the ion emission model have been validated, there remain physical effects which require further study.

One major concern is the geomagnetic field's effect on the ion emission process, as it defines the expansion and geometry of the quasi-neutral plasma contactor. Experiments were performed to better understand this process and how the ion emission current scales with ambient magnetic field strength. Plasma parameters were scaled to study this effect in an Earth-based vacuum chamber using a hollow cathode plasma contactor enclosed in a custom solenoid capable of producing a uniform magnetic field of 10mT. Ion emission current was recorded as the magnetic field strength and hollow cathode potential were varied parametrically. A magnetic field mapping of the custom solenoid, plots of ion emission current versus magnetic field strength and hollow cathode potential, new physical insights, and implications for future space missions are discussed.

* Work supported by the Directed Research and Development program at 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).

# Effect of Quantum Synchrotron Emission in High-Energy Wakefield Stages

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An electron beam passing through an undulator will experience radiation emission such that the high energy part of the beam will radiate more energy than the low energy part, decreasing its energy spread[1]. In plasma accelerator stages[2] with an injected electron beam at above one hundred GeV, stochastic radiation emission can cause a broadening of the energy spread as well[3]. We use Particle-in-Cell simulations[4][5] to study how quantum radiation emission would influence the energy spread and emittance of external injected beams inside laser wakefields. The effect of nonlinear focusing forces, beam energy spread and laser beam mismatch, however, can distort the phase space distribution and cause significant emittance growth[6]. Theoretical analysis and numerical simulation were performed to find optimal conditions to minimize phase space distortions.

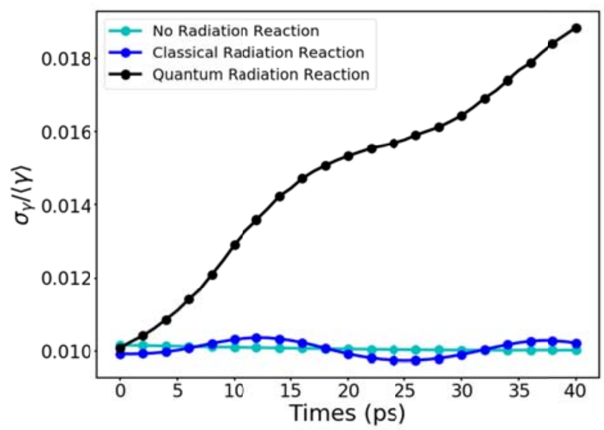


Figure 1 – Change of energy spread under different radiation reaction models for an 100GeV electron beam with a ring shape distribution in phase space inside laser wakefield. (a) No radation reaction (b) Classical radiation reaction (c) Quantum radiation reaction.

* The authors would like to acknowledge the OSIRIS Consortium, consisting of UCLA and IST (Lisbon, Portugal) for providing access to the OSIRIS 4.0 framework. Work supported by NSF ACI-1339893.

**References**

[1] P. Michel et al, Phys. Rev. E 74, 026501 (2006).
[2] S. Steinke, Nature 530, 190 (2016).
[3] C. P. Ridgers et al, J. Plasma Phys. 83, 715830502 (2017).
[4] R. G. Hemker 'Particle-in-Cell Modeling of Plasma-Based Accelerators in Two and Three Dimensions', PhD Dissertation UCLA (1999).
[5] R. A. Fonseca et al., Lect. Notes Comp. Sci. 2331 342 (2002).
[6] E. Esarey et al, Phys. Rev. E 65, 056505 (2002).

# Design and Construction of a 30 kW FRC Thruster

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Advancements in solar panel technology and desire for thrusters to be able to be In-Situ Resource Utilization (ISRU) compatible, is opening up the need for a >100 kW electrodeless thruster. A promising candidate to fill this role is the Field-Reversed Configuration (FRC) thruster. An FRC plasmoid is characterized by an axial magnetic field whose sign is reversed near the axis by azimuthal currents induced in the plasma by one of several techniques, such as a rotating radial magnetic field (RMF) [1]. The plasma forms a toroid with closed magnetic field lines. Thrust is produced by introducing a radial component to the magnetic field which interacts with the azimuthal current in the plasma via the Lorentz force. The thruster is operated in a pulsed mode, repetitively forming and accelerating plasmoids [2].

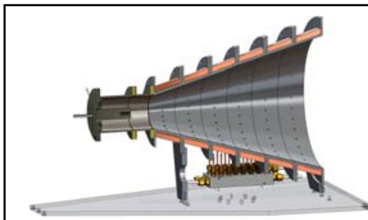

Figure 1 - A cross section cutout of the thruster design, from cathode plasma source on the left to the RMF cone to the right.

The FRC's unique method for generating thrust provides many advantages compared to state-of-the-art high-power concepts. Plasmoid confinement makes the device agnostic to propellant species, and potential power scaling is up to 20 kW/kg, compared to Hall thrusters at about .5 kW/kg [3]. B-field detachment in the plume is unnecessary because magnetic field lines in the plasmoid are closed. Although these devices have been successfully built and operated [2][4], many basic performance tests like direct thrust measurements have not been done, and fundamental questions regarding the physics of plasmoid acceleration are unanswered. There are ongoing efforts to address these questions by deriving scaling laws using circuit models [5], but we ultimately need a highly configurable experimental setup to validate those analyses.

We have designed and constructed an RMF-FRC thruster to fill the need for a test article. We have demonstrated acceleration of the intact plasmoid using a conical coil to generate an external magnetic field with axial and radial components. We similarly have performed preliminary thruster characterization by establishing plasmoid shape, temperature, density, and velocity. These initial measurements in turn have guided a preliminary validation of our proposed RMF-FRC scaling laws.

* Work supported by the NASA Space Technology Research Fellowship, under Grant 80NSSC18K1190

**References:**

[1] Blevin, H.A., and Thoneman, P.C. Plasma Confinement Using and Alternating Magnetic Field. (1962). Nuclear Fusion: 1962 Supplement, Part 1.
[2] Weber, T.E., Slough, J.T., and Kirtley, D. (2012). The Electrodeless Lorentz Force (ELF) Thruster Experimental Facility. Review of Scientific Instruments 83, 113509.
[3] Weber, T. E., "The Electrodeless Lorentz Force Thruster Experiment," Ph.D. thesis, University of Washington, 2010.
[4] Eskridge, R. H., Fimognary, P. J., Martin, A. K., and Lee, M. H., "Design and Construction of the PT-1 Prototype Plasmoid Thruster," AIP Conference Proceedings, 2006, pp. 813, 474.
[5] Woods, J. M., Jorns, B. A., , and Gallimore, A. D., "Circuit Modeling of Rotating Magnetic Field Field-reversed Configuration Thrusters," AIAA-2018-4911, 2018.

# Accelerating Warm Dense Matter Simulations to Elucidate Diffusive Mixing Processes Using Machine Learning*

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Inertial confinement fusion (ICF) compresses fuel to potentially generate unlimited, clean energy. In the presence of energy loss mechanisms such as ablator-fuel mixing, a net gain in energy remains to be achieved [1]. A detailed microscopic model of interfacial mixing is computationally intractable because of the expense of computing on-the-fly force fields. Pair potential molecular dynamics (PP-MD) offers a computationally efficient approach but with questionable accuracy [2,3]. We explore learning accurate pair potentials by using the forces produced by Kohn Sham density functional theory. These potentials are obtained by optimizing, using simulated annealing and a genetic algorithm, a least squares loss function for the forces and the results are compared to existing pair potentials. We find that many extant pair potentials lack certain features apparent in our learned potentials, such as oscillatory behavior. Current efforts are exploring the implications of these potentials on transport phenomena.

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**References**

[1] LLNL Report, LLNL-TR-570412 (2012)
[2] T. G. White, S. Richardson, B. J. B. Crowley, L. K. Pattison, J. W. O. Harris, and G. Gregori, Phys. Rev. Lett. 111, 175002
[3] K. Wünsch, J. Vorberger, and D. O. Gericke, Phys. Rev. E 79, 010201(R)

## Customization of a Plasma Source for LIF Dip Measurements

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Understanding gas phase chemistry is necessary in several applications, but it also offers significant challenges. We have developed an experiment to use laser-induced fluorescence (LIF) dip spectroscopy to obtain insight into the changing gas composition in an Argon plasma, to later be applied to an air plasma. Two lasers are used, one to populate the fluorescing state and one to depopulate the plasma to the Rydberg states, and both are directed into the plasma through a laser access flange. The electric field is measured by analyzing the "dip" in the fluorescence signal [1]. This technique can detect a low electric field magnitude because Rydberg states are highly sensitive to the Stark effect. The plasma source in this experiment was designed to ensure different species concentrations are captured. The plasma source used in this experiment will combine a DC discharge with a hollow cathode plasma source to supply metastable species.

* Work supported by Naval Research Laboratories

**References**

[1] K. Takizawa, K. Sasaki, and K. Kadota, Jpn. J. Appl. Phys. Vol. 41 (2002) pp. L 1285–L 1287

## Characterizing the Spatial Resolution of Scintillators for Imaging Applications of Laser-Driven Proton Beams *

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Laser driven proton beams are widely used in visualizing the electromagnetic fields in high-energy-density physics experiments. However, typical detectors for proton imaging, i.e. radiochromic film (RCF) and plastic-track (CR39) detectors, are single-use and unable to meet the needs of higher repetition-rate facilities. Scintillators are a viable substitute their reusability and prompt, easy data acquisition by imaging the emitted optical signal onto a CCD camera are both advantageous features for a rep-rated experiment. We perform experiments using the T-cubed laser system at the University of Michigan to diagnose the intrinsic spatial resolution of the scintillators based on resolution grids imprints on the proton beam. The signal-to-noise from the laser-driven experiment, where there is significant relativistic electron and x-ray flux, is compared with Cyclotron based data [1]. A configuration where the magnified imprint of a mesh in the proton beam is used to demonstrate that scintillators are capable of comparable overall spatial resolution to RCF for applications in proton beam diagnosis and radiography applications.

* This work was supported by DOE Office of Science, Fusion Energy Sciences under Contract No. DE-SC0019076: the LaserNetUS initiative at the Center for Ultrafast Optical Science.

**References**

[1] M.J.E. Manuel, et al., Nucl. Inst. Meth. Phys. Res. A, **913**, 103 (2019).

# Optimization of a Low Power ECR Thruster using Two-Frequency Heating *

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Magnetic nozzle thrusters, in which plasma is generated via radiofrequency or microwave heating and then accelerated through an expanding magnetic field, address several of the limitations inherent to more mature thruster technologies such as Hall effect and gridded ion thrusters. They lack life-limiting electrodes, require only a single power supply to operate, and can operate at high thrust densities. However, their poor laboratory performance has largely negated many of these advantages, particularly at the low powers that are increasingly important for small satellites [1].

Recent Experiments using Electron Cyclotron Resonance (ECR) heating in a magnetic nozzle have shown great improvements over previous magnetic nozzle thrusters operating at similar power levels. The work showed thrust efficiencies above 10% with specific impulses over 1000 seconds while operating at 30 watts, almost an order of magnitude greater than previous studies using helicon or ICP plasmas [2].

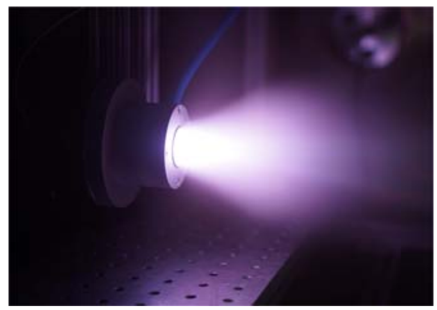

Figure 1 – ECR thruster firing at 20 watts, 2 sccm xenon.

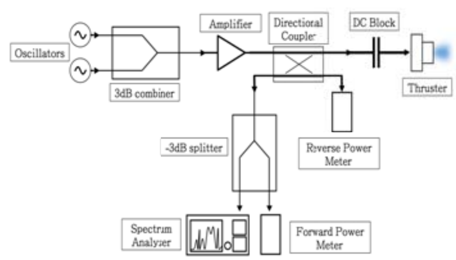



Figure 2 – Schematic of the microwave generation and diagnostic components used in the experiment.

The aim of the experiment presented here is to continue to improve these thrusters by heating the plasma with custom input waveforms. For our initial experiments we use two-frequency heating to optimize thrust efficiency at a set flow rate and power level. This technique has been employed in ECR ion sources and has shown great improvement in resulting charge state and plasma stability [3].

By introducing a second frequency, we have formed a three-variable optimization problem with parameters $f_1, f_2$, and $P_1/P_2$. Because of the numerous challenges associated with accurately measuring thrust produced by these devices, we use electron temperature, measured by a triple Langmuir probe, as a proxy for thrust. The measured temperature is fed to a Bayesian optimization algorithm that selects each successive test point and attempts to find a global maximum.

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

**References**

[1] S.N. Bathgate, M.M.M. Bilek, and D.R. Mckenzie, Plasma Sci. Technol. **19**, 083001 (2017).
[2] T. Vialis, J. Jarrige, A. Aanesland, and D. Packan, J. Propul. Power **34**, 1323 (2018).
[3] Z. Q. Xie and C. M. Lyneis, Rev. Sci. Instrum. **66,** 8 (1995).

# Theory of AC Contact Resistance

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Electrical contact is an important issue to high power microwave sources, pulsed power systems, field emitters, thin film devices and integrated circuits, and interconnects, etc. Contact resistance, and the enhanced ohmic heating that results, have been treated mostly under steady state (DC) condition. We have initiated a study on the considerably more complex problem of AC contact resistance. We consider the simple geometry of two semi-infinite slab conductors of different thicknesses and different electrical properties joint at z = 0 (Fig. 1). We have constructed an exact solution under AC condition, and we have shown that in the limit of zero frequency, our AC solution reduces to those of DC case [1].

New features that accompany AC condition, totally absent in the DC case, include resistive skin effect, inductive, and capacitive effects, as well as radiation losses. They are being examined here. Scaling laws for resistance as a function of frequency have been constructed for several cases. An example of the unique feature of AC contact is shown in Fig. 2, which shows the contact resistance as a function of frequency for the two current channels of equal width but unequal resistivity. There is no contact resistance in the DC limit because the current flow is uniform and constant everywhere, including the joint. Because of the different skin depths in the two regions, the AC contact resistance may become negative (Fig. 2). Physically, this means that the contact region configures the current flow pattern so that it is less dissipative than the bulk currents occupying the same space would be. The theory, together with other new features, will be presented.

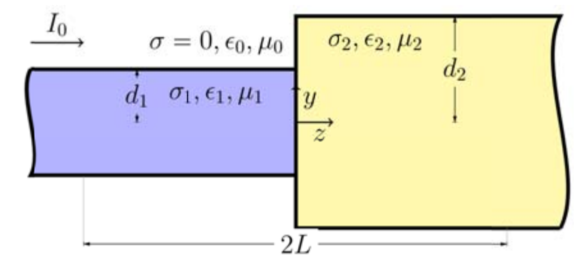


Figure 1 – Model of AC contact. The current $I_0$ is proportional to $e^{-i\omega t}$.

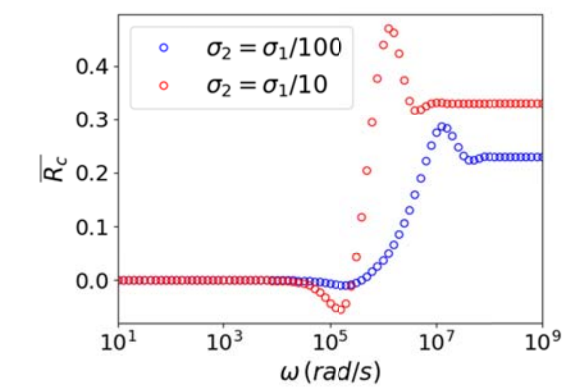


Figure 2 – Normalized contact resistance ($\overline{R_c}$) for a junction between two materials with different conductivity ($\sigma_1 \neq \sigma_2$) but with the same width ($d_1 = d_2$).

* Work supported by Air Force Office of Scientific Research Awards Nos. FA9550-15-1-0097, FA9550-18-1-0153, and L3 Technologies Electron Devices Division.

**References**

[1] P. Zhang and Y. Y. Lau, J. Appl. Phys. **108**, 044914 (2010).

# Optimization of High Repetition-rate Laser Wakefield Accelerators Using Machine-learning Techniques*

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Many potential applications of laser accelerator sources require operation at high repetition rate. Here, 20 milliJoule pulses are generated at kilohertz repetition rate for pulse self-compression and laser wakefield acceleration experiments. A genetic algorithm is implemented using a Dazzler acousto-optic programmable dispersive filter with the laser pulse characteristics from FROG measurements or wakefield electron beam signal optimized onto several different masks used as feedback. This procedure allows a heuristic search for the optimal laser pulse phase characteristics up to 4th order to produce a desired arbitrary wakefield electron beam or a well self-compressed pulse. Additionally, in progress is the implementation of a spiral phase plate in order to produce a Laguerre-Gaussian$_{01}$ laser pulse with optical angular momentum. We're investigating the use of this exotic beam for laser wakefield acceleration experiments.

* Supported by: Department of Energy/HEP - DE-SC0016804

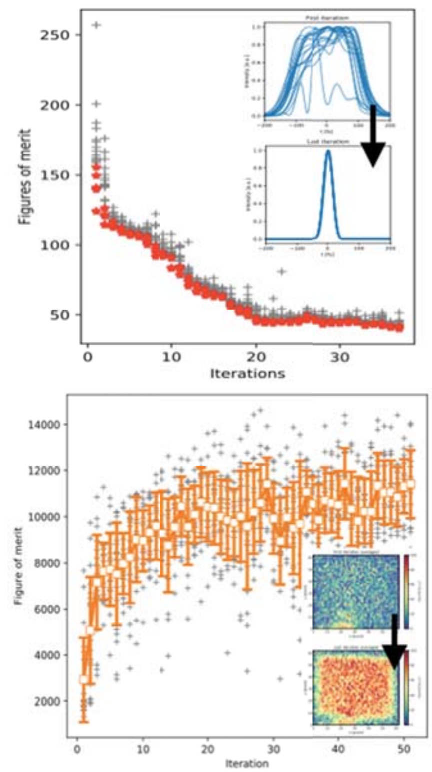


Figure 1 – **Top:** Generation curve showing the Dazzler AOPDF working via the genetic algorithm to *minimze* the product of kurtosis*RMS pulse duration of our laser pulse on lambda cubed. **Bottom:** Generation curve showing the Dazzler working via the genetic algorithm to *maximize* the pixel value on a CCD behind a scintillator screen to show bulk electron beam charge.

# Shock Injection Producing Narrow Energy Spread, GeV Electron Beams from a Laser Wakefield Accelerator*

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The parameters of electron beams produced by a laser wakefield accelerator are in large part determined by the dominant injection mechanism. In shock injection the driving laser pulse crosses abruptly from a region of high plasma density to one of lower density. The sudden change in the plasma wavelength leads to injection of electrons. Shock injection has been successfully employed on lower power (< 100 TW) systems where it produces tunable narrow energy spread electron beams.[1] Here we present an investigation of shock injection on the higher power Gemini laser system (> 200 TW). In this case shock injection can produce high energy (> 1 GeV), narrow energy spread (≤ 5%) electron beams. The injection here is found to be sensitive to the position of shock front within the accelerator, in contrast to previous results at lower power.

* Work supported by the National Science Foundation (grant 1804463)

**References**

[1] A. Buck, J. Wenz, J. Xu, et. al., Phys. Rev. Letters **110**, 185006 (2013).

# Two-surface Multipactor Susceptibility with Two Carrier Frequencies Using Monte Carlo Simulation*

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Multipactor effect is a nonlinear phenomenon when free electrons are accelerated by an rf electric field, which results in secondary electron emission from metallic and dielectric surfaces, leading to an exponential growth of charge. This effect may damage the rf devices such as satellite communications and microwave systems [1]. We apply Monte Carlo (MC) simulation [2-5] to study the multipactor susceptibility in a gap with two-carrier-frequency rf electric field between two parallel metallic electrodes. Vaughan's model [6] is used to obtain the secondary electron yield (SEY) for secondary emission processes, with random initial energy and angle following a preassigned function of distribution [2]. In order to obtain the multipactor susceptibility diagram in the V-fd plane (V is the microwave input voltage, f is the frequency of rf field, and D is the gap distance between the two surfaces), we scan the average SEY for a certain range of magnitude of the input voltage using MC simulation. Our results can predict three separate bands in the susceptibility diagram (Fig. 1), representing the first three odd-order modes (N=1, 3 and 5, where N is the number of half cycles of the fundamental rf field). However, the susceptibility boundaries are slightly different from those of analytical solution, due to the presence of the mixed multipactor mode.

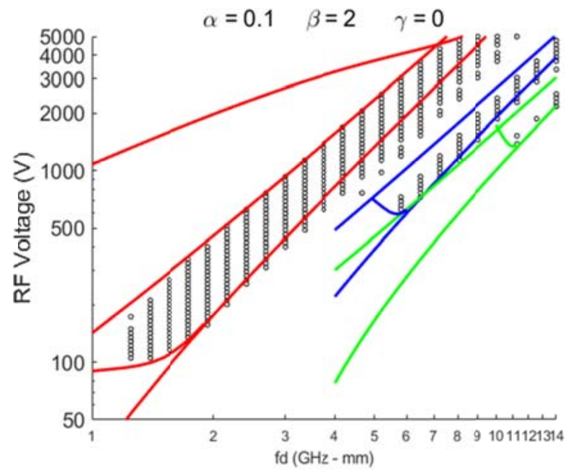


Figure 1 – Multipactor susceptibility diagram in V-fd plane. Dot plot is from the MC simulation. Red, blue and green curves are from analytical solutions for N = 1, 3, and 5 respectively. $\alpha$, $\beta$, and $\gamma$ are the relative strength, frequency, and phase of the second carrier to the fundamental carrier signal, respectively.

* Work supported by AFOSR MURI Grant No. FA9550-18-1-0062.

**References**

[1] Special sessions on Multipactor, I and II, ICOPS, Denver, CO, June 2018.
[2] R. A. Kishek, Y. Y. Lau, L. K. Ang, A. Valfells, and R. M. Gilgenbach, Phys. Plasmas 5, 2120 (1998).
[3] P. Zhang, Y. Y. Lau, M. Franzi and R. M. Gilgenbach, Phys. Plasmas, 18, 053508 (2011).
[4] A. Iqbal, J. P. Verboncoeur, P. Zhang, Phys. Plasmas, 25, 043501 (2018).
[5] A. Iqbal, J. Verboncoeur, P. Zhang, Phys. Plasmas 26, 024503 (2019).
[6] J. R. M .Vaughan, "Multipactor", IEEE Trans. Electron Devices 35, 1172 (1988).

# X-Pinch Diagnostics for the MAIZE LTD*

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Z-pinch implosions are inherently unstable due mainly to a combination of magneto-Rayleigh-Taylor (MRT) and $m$=0 "sausage" instabilities (where $m$ is the azimuthal mode number) resulting in the formation of multiple "micro-pinch" regions. These micro-pinches are ideal for studying high energy density (HED) physics as they compress to very small radii (~1 μm) leading to pressures on the order of ~1 Gbar for currents on the order of ~0.1 MA. In contrast to a typical z-pinch, an X-pinch, formed by the crossing of 2 or more wires, generates a single micro-pinch at a predetermined location in space (i.e., where the wires cross) [1, 2]. When the micro-pinch forms, an intense, sub-ns burst of X-ray radiation is emitted from the central "hot spot" of the pinch. This X-ray source is often used for radiography applications.

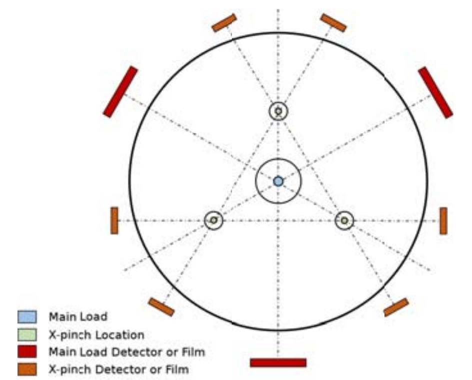

Figure 1 – Diagram of a possible X-pinch hardware design for X-ray radiography on the MAIZE LTD.

To allow for the study of micro-pinches on the Michigan Accelerator for Inductive Z-pinch Experiments (MAIZE) Linear Transformer Driver (LTD), new X-pinch load hardware is being developed. This hardware will host several multi-wire or hybrid X-pinches, in addition to a main load, to run experiments focusing on both the physics and applications of X-pinch micro-pinches. The present focus using this hardware will be to create an X-ray radiography diagnostic for imaging the main load on MAIZE and to develop spectroscopic methods for characterizing micro-pinch physics.

*This work was supported in part by the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764 and in part by the DOE Early Career Research Program under Grant DE-SC0020239.

**References**

[1] S. A. Pikuz, T. A. Shelkovenko, and D. A. Hammer, Plasma Physics Reports. **41**, 291 (2015).
[2] S. A. Pikuz, T. A. Shelkovenko, and D. A. Hammer, Plasma Physics Reports. **41**, 445 (2015).

# Example of wave-particle interactions in Geospace: Oxygen Ions and Magnetosonic Waves

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Wave-particle interactions are an important component of energy transfer inside the Earth's magnetic field in near-Earth space (the inner-magnetosphere). This study aims to understand the relationship between oxygen ions in the inner-magnetosphere and a type of electromagnetic plasma wave called a magnetosonic wave. Oxygen ions are an important component to space plasma physics because increased oxygen content can affect the wave dispersion in the background plasma, wave growth, and minimum resonant energy. [1] [2] [3] In this study, we use satellite observations to investigate oxygen ion behavior when observed simultaneously with magnetosonic waves. Recent satellite observations show that magnetosonic waves are able to energize H+ and He+ ions, but observations of magnetosonic waves energizing O+ ions remain elusive. [4] We report the first observations of O+ ion energization by magnetosonic waves. We also analyze the harmonic structure of the magnetosonic waves observed with O+ ion energization. We find harmonic structures in the magnetosonic waves that match oxygen harmonics, which indicates that magnetosonic waves can transfer energy to oxygen ions. We conclude that magnetosonic waves are able to energize oxygen ions in the inner-magnetosphere and thus the wave-particle interaction plays an important role in modifying space plasma dynamics.

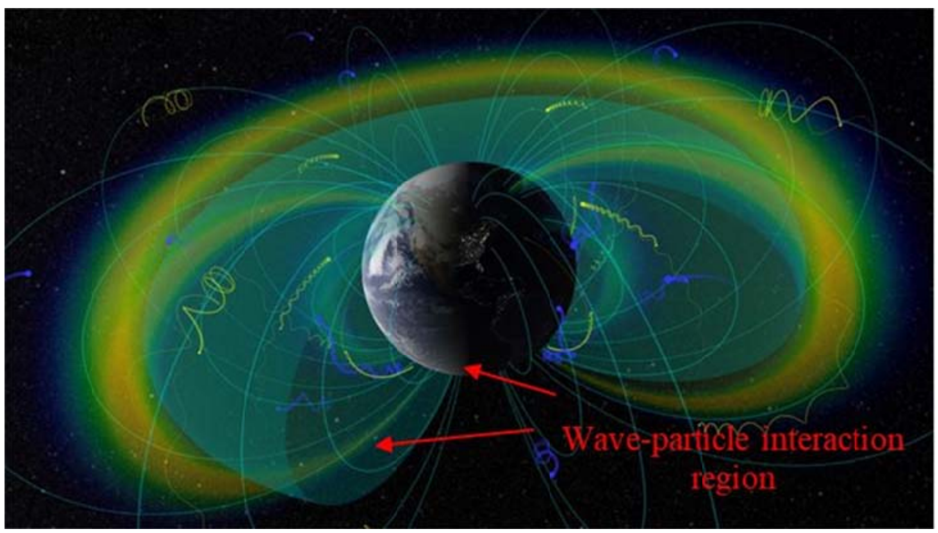


Figure 1 - Wave-particle interactions play a large role in energy transfer in the inner-magnetosphere. The figure above shows the wave-particle interaction region of interest to this study.

**References**

[1] D. Summers, B. Ni, and N.P. Meredith, J. Geophys. Res. **112**(A4), A04206 (2007).
[2] E.A. Kronberg, M. Ashour-Abdalla, I. Dandouras, et al., Space Science Review, **184**(1-4), 173–235 (2014).
[3] X. Yu, Z. Yuan, D. Wang, H. Li, S. Huang, Z. Wang, Q. Zheng, M. Zhou, C. A. Kletzing, and J. R. Wygant, Geophys. Res. Lett., **42**, 1312–1317 (2015).
[4] Z. Yuan, X.Yu, , S. Huang, Z. Qiao, F. Yao, and H. O. Funsten, J. Geophys. Res. Space Physics **123**, 1242–1250 (2018).

# Particle Emission from an Anode Liquid Surface of Electrolyte in Atmospheric Pressure DC Glow*

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Self-organization patterns observed on anode liquid surfaces in atmospheric pressure DC glow discharge represents both a mysterious and beautiful physics phenomenon [1-3]. The mechanism underlying self-organization of plasmas in this context is still poorly understood. In this study, luminous particle emission from the liquid anode under self-organization condition has been observed in figure 1(a). These particles have been collected in flight using witness plates. The particle impacts have the form of splats suggesting that they are melton. The splats were observed to have a great deal of structure including evidence of nano-precipitation. These resulting splats were examined using a scanning electron microscope (SEM) and Energy dispersive X-ray spectroscopy (EDX).

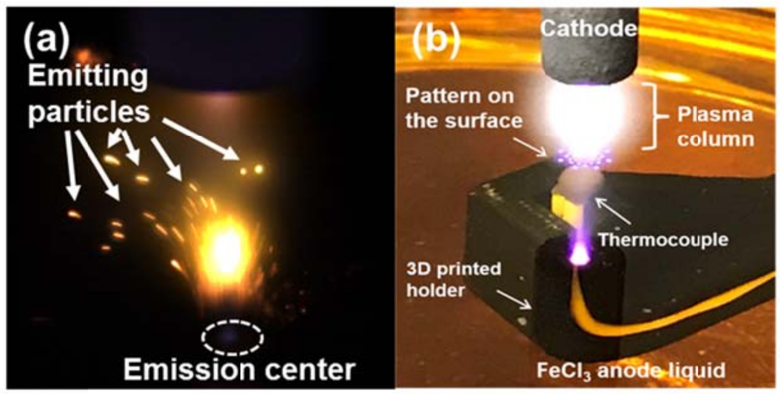


Figure 1 – (a) Particle emissions captured at 1.5 ms by using a high-speed camera and (b) Thermal gradients assessed at 2 mm below the liquid surface where directly underneath the self-organized dots pattern.

Recently, the size range of molten particle droplets was theoretical estimated by converting from the size of impact splats. Furthermore, high-speed camera analysis was used to map the 2D trajectories of emitted particles in order to analyze both the emission force and the drag experienced by the particle during flight. This yields insight into mechanisms of emission. A thermal effect such as localized heating and evaporation is one potential mechanism driving the emission of particles that may be formed in the liquids. Here we examined the local temperature of the liquid water at the emission zone just below the surface (shown in figure 1b). Simultaneously, the local electric field near to the emission surface was investigated by using optical emission spectroscopy (OES) diagnostics. To date, both the local temperature at the plasma attachment and electric field have not been characterized owing to the challenges in interrogating this region. This effort thus provides insight not only into the physics of particle emission, but also potentially into the underlying processes driving the self-organization formation itself.

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

**References**

[1] T. Verreycken and P. Bruggeman, J. Appl. Phys. **105**, 083312 (2009).
[2] N. Shirai, S. Uchida and F. Tochikubo, Plasma Source Sci. Technol. **23**, 054010 (2014).
[3] N. Shirai, S. Ibuka and S. Ishii, Appl. Phys. Express **2**, 036001 (2009).

# Benchmarking the Kinetic Global Model framework (KGMf): EEDF Evaluations in Low-temperature Argon Plasmas*

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Global (volume-averaged) models present valuable tools in predicting macroscopic plasma behavior and showing the ability to evaluate the importance of individual reactions in plasmas, which further helps identify the key reactions for spatial-dependent simulations [1]. The Kinetic Global Model framework (KGMf) was coupled with a Boltzmann equation solver, BOLOS [2, 3] (using two-term spherical approximation) and MultiBolt [4] (multi-term spherical approximation), to self-consistently compute electron energy distribution function (EEDF). By capturing the temporal evolution of the EEDF, the KGMf enables fidelity of the results even for dynamic systems at the cost of higher computational complexity. Adaptive EEDF evaluations are imperative to preserve the high efficiency of the global model while maintaining the accuracy of the solutions.

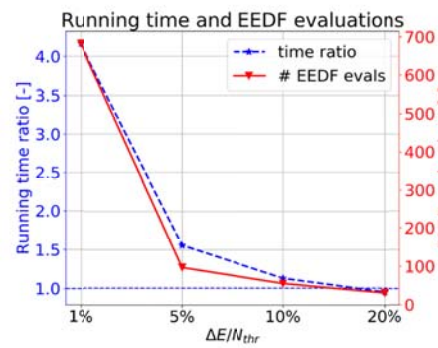


Figure 1 – The simulation run time and the number of EEDF evaluations versus selected values of controlling parameter (reduced electric field $E/N$).

Using the low-temperature argon plasma chemistry at high pressure, we compared different methods of controlling the EEDF evaluation frequency depending on changes of plasma parameters, e.g. reduced electric field ($E/N$) or electron density ($n_e$). For case with constant absorbed power and assuming Ohmic heating of electrons, the KGMf was benchmarked with ZDPlasKin. Both codes were coupled with two-term approximation Boltzmann equation solvers for evaluating EEDF: the KGMf with BOLOS and ZDPlasKin with BOLSIG+. The results from compared codes show a good agreement. Further efforts are also made to observe differences in code implementations and computational performance. Detailed profiling show that codes spend the majority of time evaluating the EEDFs: 61.3% in BOLOS (KGMf) and 90.2% in BOLSIG+ (ZDPlasKin). The performance disparity might be caused by different computational approaches (Python vs. FORTRAN) and capabilities of codes (feature-full-code approach in the KGMf versus minimalistic approach in ZDPlasKin).

One critical difference between the KGMf and ZDPlasKin is the treatment of the energy equation: the KGMf can include the electron energy equation to compute $T_e$, where ZDPlasKin can compute $T_e$ only from EEDF. For the case of RF discharge in argon, breakdown times from the KGMf, ZDPlasKin, COMSOL and PIC were also compared [5].

* Work supported by Department of Energy Plasma Science Center grant DE-SC0001939.

**References**

[1] G. M. Parsey, Ph.D. Thesis, Michigan State University (2017).
[2] A. Luque, https://pypi.python.org/pypi/bolos (2004).
[3] G. J. M. Hagelaar and L. C. Pitchford, Plasma Sources Sci. Technol. **14**, 722 (2005).
[4] J. Stephens, J. Phys. D: Appl. Phys. **51**, 125203 (2018).
[5] S. K. Nam and J. P. Verboncoeur, Comput. Phys. Commun. **180,** 628 (2009).

# Simulations of Photoionization Fronts on the Z-machine Using a Well-characterized Radiation Flux Input*

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In the early universe at the end of the dark ages, the first galaxies and stars started forming. This introduced a sustained ionizing photon flux into the intergalactic medium (IGN) in photoionization (PI) fronts, re-ionizing the universe. PI fronts are heat fronts where PI dominates the energy deposition at the interface.

The Z-machine at Sandia is a very bright source of x-rays, emitting over 1 MJ of soft x-ray energy. This is an attractive platform to make measurements of photoionization fronts. We discuss a study performed with the Helios-CR code for a N gas cell for a potential Z experiment. The radiation-hydrodynamic simulations included inline, self-consistent non-equilibrium atomic physics and photon-energy resolved radiation transport. They were driven with the time-history of a spectrally resolved x-ray flux obtained from VISRAD view factor modeling of the Z radiation environment constrained with power and monochromatic image measurements of the z-pinch. A parameter study over gas pressure and atomic model complexity explores the front propagation with Z as a driving source. A resolution study shows the importance of capturing the photon mean free path in PI front calculations.

*This work is funded by the U.S. DoE NNSA Center of Excellence under grant number DE-NA0003869.

# Design and Calibration of B-dot Probes for Measuring the Strong Magnetic Field of a Magnetized Plasma Experiment Using Commercial Electronic Components*

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Magnetic fields play an important role in the behavior or many HEDP systems [1], however, the scaling of astrophysical relevant phenomena to a laboratory setting requires the generation of strong magnetic fields (>5 T) that can match the high flow velocities and energies achieved by the plasmas commonly created in these experiments [2].

Accurate measurement of such powerful magnetic fields and field geometries requires the use of precise and often disposable measuring devices that can be easily adapted to any experiment. Here, we present a method for fabricating B-dot probes using commercially available inductor elements, commonly used in circuit board construction, with a study of the performance in strong (10 T) pulsed magnetic fields used in HEDP experiments. We show that these probes, in addition to being easy and cheap to manufacture, provide accurate and responsive measurements after being properly calibrated, and serve as a robust and reliable method for measuring magnetic fields.

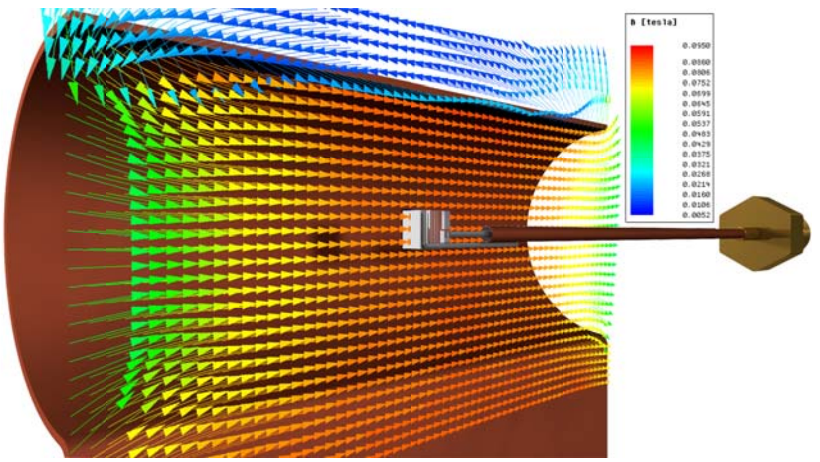


Figure 1 - Calibration of the B-dot probe using a model of a finite, continuous solenoid in Ansys Maxwell.

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**References**

[1] G. C. Burdiak et al., "The structure of bow shocks formed by the interaction of pulsed-power driven magnetised plasma flows with conducting obstacles," Phys. Plasmas, vol. 24, no. 7, 2017
[2] R. P. Young, C. C. Kuranz, R. P. Drake, and P. Hartigan, "Accretion shocks in the laboratory: Design of an experiment to study star formation," High Energy Density Phys., vol. 23, pp. 1–5, 2017.

# High-repetition Neutron Generation from Ultrashort Laser Pulse Irradiation of Electrohydrodynamically Extracted Deuterated Microdroplets*

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We report initial findings of laser-driven fusion neutron yield from the interaction of regeneratively amplified several-mJ, 35 fs laser pulses at 1/2 kHz with spatio-temporally resolved microdroplets from a novel electrohydrodynamic jet nozzle. Femtoliter-scale deuterated droplet targets are produced via pulsed high-voltage electrostatic extraction from a 50 $\mu m$ I.D. / 120 $\mu m$ O.D. stainless steel capillary. High intensity laser pulses (of order $10^{19}$ W/cm$^2$) are focused under vacuum and collide with the microdroplets to create energetic deuterons via the Target Normal Sheath Acceleration (TNSA) mechanism. 2.45 MeV neutron pulses are generated via the $\mathbf{d}(d,n)^3\mathbf{He}$ fusion half-reaction. Neutron flux is measured via zero gamma sensitivity calibrated bubble detectors while neutron spectrum is quantified with plastic scintillators in a pulse-shape discrimination neutron time-of-flight (ToF) setup. To our knowledge, this experiment is the first to demonstrate micron-scale monodisperse droplet generation in vacuum utilizing pulsed electrohydrodynamic jetting.

* This material is based upon work supported by the Air Force Office of Scientific Research under Award No. FA9550-16-1-0121.

# Time-resolved Characterization of a Free Plasma Jet Formed using a Piezoelectric Transformer *

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The time-resolved characteristics of plasma generated by a piezoelectric transformer (PT) have been investigated. A PT is a non-centrosymmetric crystal that converts low-voltage AC input (*e.g.*, a high frequency sinusoidal wave) to high-voltage AC output through an electro-mechanically coupled process. The high voltage gain can be several orders of magnitude, such that a free atmospheric-pressure plasma jet (APPJ) can be formed off the surface of the PT. PTs are attractive for non-equilibrium plasma generation because of their simple operation and low power consumption. In this work, the temporal evolution of the PT-driven plasma was visualized by using an intensified CCD camera. For time-resolved plasma visualization, one period of the input voltage cycle (~14.8 µs) has been separated into 60 phases with a time interval of 250 ns, and APPJ images are taken for each phase. Results visually demonstrate the plasma jet formation within one period. Notably, the plasma formation is a discrete process, appearing at a fixed phase of the sinusoidal input, and the strongest plasma jet appears at the end of the positive cycle. Simultaneous measurements of the current, however, show that the discharge current spikes appear statistically about a microsecond earlier than the strongest plasma jet images, which indicates that the plasma produces a strong afterglow.

* This work is based on support from the National Science Foundation under Award No. PHY-1804091.

# Comparison of a Quantum Model for Photoemission from Metal Surfaces with Three-step Model and Fowler-Dubridge Model*

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Photoemission is one of the fundamental processes to produce electrons, and has long been the focus of investigation for its wide applications in particle accelerators, electron microscopy, and vacuum electronics [1]. An analytical model for electron emission from the metal surface illuminated by a single laser field is presented by solving the time-dependent Schrödinger equation exactly, which considers electrons energy states distribution inside the metal. The model includes the effects of laser electric field (of arbitrary frequency and strength), dc field, and metal properties (Fermi energy and work function) [2,3]. Electron emission mechanisms under various laser wavelengths and laser intensities are analyzed. This quantum model is compared with existing classical models for photoemission, including the three-step model [4,5], Fowler-Dubridge model [6-8], and Monte Carlo simulation. Results demonstrate that the quantum efficiency by the quantum model agrees well with that by the other models in scaling. The difference in magnitude is caused by the absence of the effects of laser penetration and the electron-electron scattering inside the metal in our quantum model.

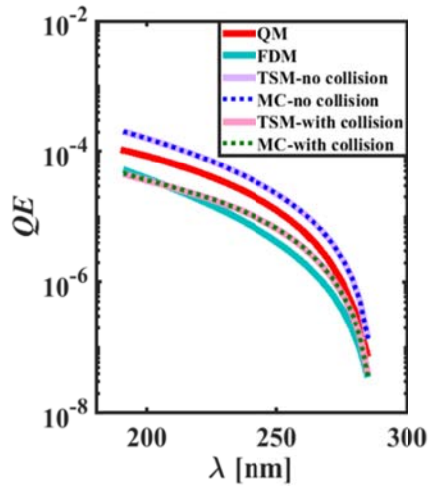


Figure 1 - Quantum efficiency calculated by quantum model (QM), Fowler-Dubridge model (FDM), Three-step model (TSM) (with or without electron-electron scattering effects in model) and Monte Carlo (MC) simulation (with or without e-e scattering effects in simulation). The metal is assumed to be copper, with $W$ = 4.31eV and $E_F$ = 7eV.The laser field input into the quantum model is 0.01 V/nm.

* Work supported by the Air Force Office of Scientific Research (AFOSR) YIP Award No. FA9550-18-1-0061.

**References**

[1] P. Zhang, and Y. Y. Lau, J. Plasma Phys. **82**, 595820505 (2016).
[2] P. Zhang, and Y. Y. Lau, Sci. Rep., 6, 19894 (2016).
[3] Y. Luo, and P. Zhang, Phys. Rev. B, **98**, 165442 (2018).
[4] C. N. Berglund and W. E. Spicer, Phys. Rev. **136**, 1030-1044 (1964).
[5] D. H. Dowell, and J. F. Schmerge, Phys. Rev. Special Topics-Accelerators and Beams **12**, 074201 (2009).
[6] R. H. Fowler, Phys. Rev. **38**, 45 (1931).
[7] L. A. DuBridge, Phys. Rev. **39**, 108 (1932).
[8] J. H. Bechtel, W. Lee Smith, and N. Bloembergen, Phys. Rev. B **15**, 4557 (1977).

# Validation of PERSEUS and Implementing Ionization Energy Models in PERSEUS

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Ultrathin foil liners, with thicknesses of 400 nm, are used in university-scale Z-pinch experiments (~1 MA) to study physics relevant to inertial confinement fusion efforts on larger-scale facilities (e.g. the MagLIF efforts on the 25 MA Z facility at Sandia National Laboratories). We demonstrate the ability of the 3D MHD simulation code PERSEUS [1] to accurately model the implosions of ultrathin liners by comparing general implosion trends and detailed plasma structures in simulation and experiment. In university-scale experiments [2], ultrathin foils have used a central support rod to maintain structural integrity prior to implosion, and we have now used PERSEUS to study these experiments in detail. The results suggest that it is the support rod which enables the helical structures to persist beyond stagnation. In addition, we report on new efforts to include more robust material ionization models in PERSEUS to enhance the code's simulation capabilities.

* Supported by NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764.

**References**

[1] Seyler, C. E., & Martin, M. R. (2011). Relaxation model for extended magnetohydrodynamics: Comparison to magnetohydrodynamics for dense Z-pinches. *Physics of Plasmas*, *18*
[2] Yager-Elorriaga, D. A., et al. (2016). Discrete helical modes in imploding and exploding cylindrical magnetized liners. *Physics of Plasmas*, *23*(12)

# Optimizing Power Delivery in a Pulsed Inductively Coupled Plasma Using Set-Point Impedance Match and Frequency Tuning*

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Inductively coupled plasmas (ICPs) are widely used in microelectronics fabrication, especially for conductor etching. To facilitate power transfer from the radio frequency (RF) supply into the plasma, an impedance matching network (IMN) is placed between the supply and the plasma reactor. By controlling the reactance of the IMN, the impedance of the load that the power supply sees can be tuned to match the impedance of the power source, thereby reducing power reflection. To have a high plasma density with control over production of reactants, pulsed power is often used. The significant change of plasma properties during a power pulse results in significant transients in plasma impedance, which makes impedance matching difficult. The result is undesired power reflection from the plasma reactor. One way to minimize the mismatch is using set-point matching in which the IMN is matched to a particular point during the cycle, but this results in mismatches elsewhere in the pulse cycle. Ideally, one would like the components of the IMN to track the impedance of the plasma in real-time. However, because tuning the circuit components is a mechanical process, the reactance of IMN can not be tuned rapidly enough. An alternate method is frequency tuning, in which the frequency of the RF power source is adjusted in real-time to enable the IMN to match the impedance of the plasma reactor. The frequency of RF power supplies can be adjusted rapidly enough to achieve such matches.

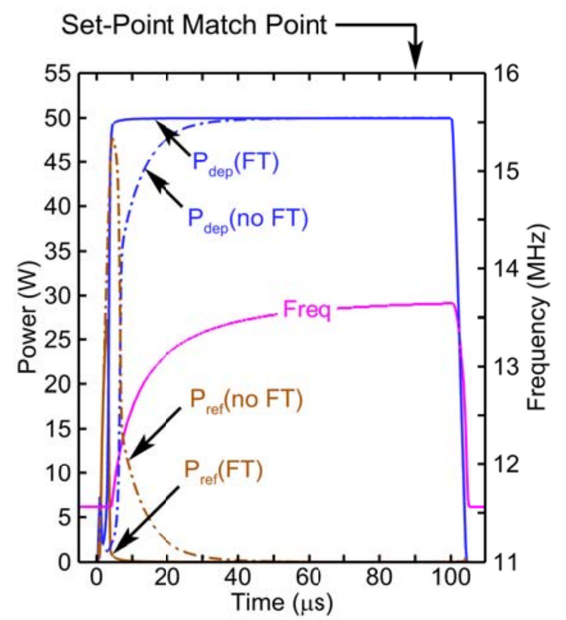


Figure 1 – Comparison of power deposition during pulse-on period with and without frequency tuning. Ar, 15 mTorr, 50 W, PRF = 5 kHz, DC = 50%, set-point match at the end of pulse-on.

Results from a computational investigation of impedance matching of pulsed ICPs using set point and frequency tuning will be discussed. The study was performed using the Hybrid Plasma Equipment Model (HPEM). A circuit model was implemented and interfaced with plasma modules to access power flow and reflection. The plasma was sustained in Ar at 15 mTorr, and the power during pulse-on was 50 W, the pulse repetition frequency was 5 kHz and the duty cycle was 50%. Set-point matching is shown to improve the power delivery over a limited part of the cycle, while frequency tuning was capable of matching the impedance through the whole period.

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

# Development of a Gas-Puff Z-Pinch Experiment for the 1-MA, 100-ns MAIZE Linear Transformer Driver*

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The Z-machine at Sandia National Laboratories is instrumental in plasma physics research across a range of applications. University-scale z-pinch experiments, such as gas-puff z-pinches, can inform the high-value experiments conducted on the Z facility. A gas-puff z-pinch requires gas to be puffed into the anode-cathode gap, which is then pulsed with a high voltage [1]. The gas is ionized, accelerated, and compressed as the current flows across the electrodes, allowing for study of pinch phenomena including fusion reactions [2]. The initial ionization condition of the gas-puff prior to compression is poorly understood. Additionally, how this affects fusion, which is largely the result of micro-pinch instabilities, is also poorly understood. We report on the progress made in developing this experimental capability on the MAIZE Linear Transformer Driver at the University of Michigan (Figure 1).

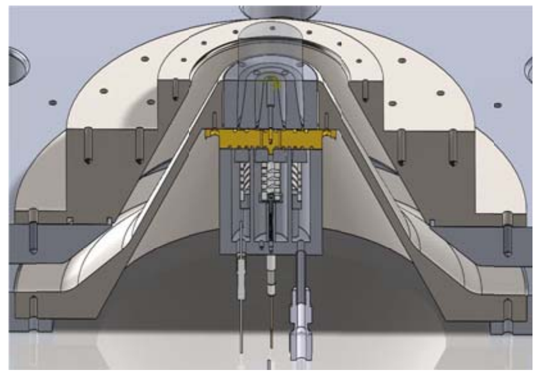

Figure 1 – The gas-puff fast-valve and nozzle system as mounted on a newly designed anode-cathode structure for the MAIZE Linear Transformer Driver. The design was selected after optimization of factors such as inductance and diagnostic access. For example, inductance must be minimized to ensure that the experiment is able to couple maximum driver energy to the load.

Additionally, we are in the process of developing a full LTspice circuit model of the MAIZE facility, including auxiliary parts such as charging lines, protection circuits, and the trigger generator. We report on experimentally verified model results for the MAIZE current pulse as well as the trigger generator current pulse.

* Work supported in part by a seed grant from the Michigan Memorial Phoenix Project and the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764.

**References**

[1] M. Krishnan, “The Dense Plasma Focus: A Versatile Dense Pinch for Diverse Applications”, IEEE Trans. Plasma Sci. **40**, 3189 (2012).
[2] J. Giuliani, “A Review of the Gas-Puff Z-Pinch as an X-Ray and Neutron Source”, IEEE Trans. Plasma Sci. **43**, 2385 (2015).

# Status Update on the BLUE Linear Transformer Driver (LTD) System at the University of Michigan*

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The University of Michigan has received four linear transformer driver (LTD) cavities, which were previously part of the Ursa Minor experiment at Sandia National Labs. The redesigned stack at Michigan, known as BLUE, will be capable of delivering up to 8 kJ of energy in a ~200-ns, ~200-kA pulse for high-power microwave and Z-pinch experiments. The first cavity of BLUE (Fig. 1) has been assembled, and dual 100-kV Spellman power supplies have been prepared to deliver up to 24 kW of charging power. A control panel based on Arduino has been designed to run the charging and firing sequence of the cavity, and a resistive load with a "B-dot" probe has been installed in a small vacuum section for initial testing.

Due to its polycarbonate lid, the architecture of the first BLUE cavity is similar to that of an impedance-matched Marx generator [1], thus ferromagnetic cores are unnecessary. A resistor installed in the oil section will provide a charging current path and dampen the generated power pulse when experiments are run with non-resistive, inductive loads. The charging inductors shown in Fig. 1 are currently being replaced with 30-kΩ, bubble-resistant copper sulfate resistors to provide better brick-to-brick isolation (a brick is 2 capacitors and a spark-gap switch; there are 10 bricks per BLUE cavity–see Fig. 1). Custom solid-state resistor options are also being considered.

Figure 1 – The prototype BLUE cavity with capacitors and switches installed.

A trigger generator for the BLUE cavities has been developed utilizing a single brick. The output pulse of the trigger generator will be twice the charge voltage of the cavity – i.e. 160-kV trigger pulse for a +/- 80-kV cavity charge. This may allow for more reliable operation of BLUE's spark gap switches. A novel method of switch diagnostics using photodiodes and digital-to-analog conversion is also being developed.

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**References**

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

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

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Enhanced star formation triggered by local hot and massive stars is an astrophysical problem of interest. Radiation from the local stars acts to either compress or blow apart gas clumps in the interstellar media. In the optically thick limit (short radiation mean free path), radiation is absorbed near the clump edge and compresses the clump. In the optically thin limit (long radiation mean free path), the radiation is absorbed throughout, acting to heat the clump. This heating explodes the gas clump. Careful selection of parameters, such as material density or source temperature, allows the experimental platform to access different hydrodynamic regimes. A stellar radiation source is mimicked by a laser-irradiated, thin, gold foil, providing a source of thermal x-rays around 80-eV. The gas clump is mimicked by low-density CRF foam. We plan to show preliminary results, in the optically thick limit, where the shock is radiographed at various times.

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# A Semianalytical Framework for 1D Shock Hydrodynamics with Applications to Dynamic Compression Experiments on NIF and OMEGA *

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Interfaces separating media of different densities undergoing strong accelerations play important roles in the shock compression of materials to extreme pressure-temperature states [1,2]. Our objective is to develop a framework for semianalytically solving the one-dimensional Euler equations in planar geometries in the context of designing shock compression experiments to maximize the pressure achieved in a material of interest. By combining a mathematical technique for solving hyperbolic partial differential equations with boundary conditions prescribed by the exact solution to one of the most-studied problems in compressible flow theory, it is found that semianalytical solutions can be obtained for one-dimensional planar flows involving any combination of interactions of shock and rarefaction waves with interfaces. The solutions obtained using this method are computationally less expensive and more physically insightful than their numerical counterparts, evidenced by their comparison to solutions obtained using our in-house, high-order accurate Discontinuous Galerkin code.

The method is applied to support the design of shock-compression experiments exploring the behavior of planetary mixtures at the conditions thought to exist within the interiors of Uranus and Neptune [3]. These studies utilize the diamond anvil cell (DAC) experimental platform [4]. With this platform, an experimental target is isentropically compressed using the vice-like DAC. A shock wave is then generated via laser-plasma interactions in an ablated material which subsequently passes through the DAC and into the precompressed target. It is found that the shock wave passing into the experimental target can be strengthened by bridging the density jump between the DAC and the target with intermediate density steps. Furthermore, it is demonstrated that an exponential density profile between the two materials yields the most efficient shock strengthening. The potential shock strengthening is calculated for a wide range of interface density ratios and incident shock Mach numbers (see Figure 1).

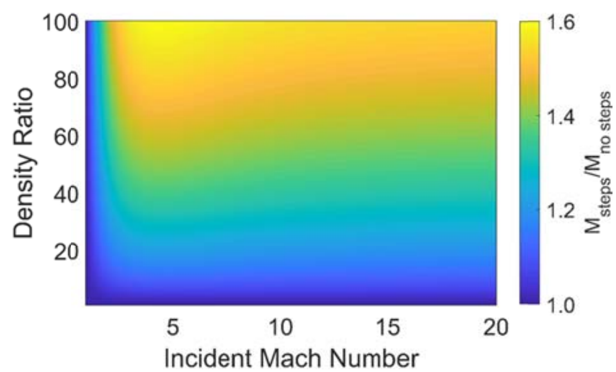


Figure 1 – The shock strengthening, i.e. the ratio of the shock Mach number in the experimental target with and without intermediate density steps, as a function of the incident shock Mach number and the density ratio of the overall interface.

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**References**

[1] Jeanloz et al., Proc. Natl. Acad. Sci. 104 (2004) 25-31.
[2] Brygoo et al., J. Appl. Phys. 118 (2015) 195901.
[3] Millot et al., Nat. Phys. 14 (2018) 297-302.
[4] Loubeyre et al., H. Pres. Res. 24 (2004) 25-31.