Michigan Institute for Plasma Science and Engineering (MIPSE)

12th ANNUAL GRADUATE STUDENT SYMPOSIUM

November 17, 2021
EECS Building, 1301 Beal Avenue, Ann Arbor, MI 48109-2122

Schedule

2:00 – 2:40	Registration, poster set-up	EECS atrium
2:40 – 2:45	**Prof. Mark J. Kushner** Director, MIPSE ***Opening remarks***	EECS atrium
2:45 – 3:30	**Poster session I**	EECS atrium
3:30 – 4:30	Special MIPSE seminar **Prof. Davide Curreli** University of Illinois, Urbana-Champaign ***The Plasma-Water Interface:*** ***Modern Challenges and New Software Tools***	1311 EECS
4:30 – 5:00	**Refreshments**	EECS atrium
5:00 – 5:45	**Poster session II**	EECS atrium
5:45 – 6:30	**Poster session III**	EECS atrium
6:30 – 6:45	Poster removal	EECS atrium
6:45 – 7:00	***Best Presentation Award*** **ceremony**	EECS atrium

Participating institutions:
University of Michigan (U-M), Michigan State University (MSU), University of Notre Dame (ND),
Lovely Professional University, Phagwara, India

Poster Session I

1-01	**Ibukunoluwa Akintola**	ND	***Characterization of CH_4/N_2 Plasmas for Plasma Catalytic Methane Coupling using Optical Emission Spectroscopy***
1-02	**Zach Brown**	U-M	***Non-invasive Measurements of a Hollow Cathode Plume with Incoherent Thomson Scattering***
1-03	**Jason Cardarelli**	U-M	***Characterizing the Growth of Current Filamentation Instability Using Laser Wakefield Accelerated Beams***
1-04	**Raul Melean**	U-M	***Pulsed-power Magnetized Shocks under an External Magnetic Field***
1-05	**Michael Wadas**	U-M	***Formation and Scaling of Vortex Rings Ejected from Shock-accelerated Interfaces***
1-06	**Asif Iqbal**	MSU	***Multipactor Discharge in the Parallel-plate Geometry with Two-frequency rf Fields and Space-charge Effects***
1-07	**Leanne Su**	U-M	***Performance at High Current Densities of a Magnetically-shielded Hall Thruster***
1-08	**Garam Lee**	ND	***Multi-Modal In-situ/Operando Spectroscopy Combining PM-IRAS, OES, and MS for Observing Plasma-Stimulated Activation of Surface Species***
1-09	**Jordyn Polito**	U-M	***Computational Investigation of Nucleation Processes Leading to Silicon Nanoparticle Growth in a Low Temperature Capacitively Coupled Plasma***
1-10	**Ryan Sandberg**	U-M	***Phase Matched Plasma Wakefield Photon Acceleration***
1-11	**Tate Gill**	U-M	***Far-Field Measurements of a Rotating Magnetic Field Thruster***
1-12	**Jinyu Yang**	ND	***Spatiotemporally-resolved Characterizations of Electric Field around a Piezoelectric Transformer Using Electric-field Induced Second Harmonic (E-FISH) Generation***
1-13	**Lucas Beving**	U-M	***Simulations of Ion Heating in the Presheath Due to Ion-acoustic Instabilities***
1-14	**Senthil Kumaran**	Lovely Professional University	***Electron Acceleration by Elliptical q-Gaussian Laser Driven Electron Plasma Wave in Collisionless Plasma**** *(*Remote)*

Poster Session II

2-01	**Donovan White**	U-M	***Beryllium Probe Neutron Diagnostic for a Gas-Puff Z-Pinch Neutron Source on a 1-MA, 100-ns Linear Transformer Driver***
2-02	**Khalil Bryant**	U-M	***Future Experiment at the Wisconsin Plasma Physics Laboratory (WIPPL)***
2-03	**Dion Li**	U-M	***A Relativistic and Electromagnetic Correction to the Ramo-Shockley Theorem***
2-04	**Shadrach Hepner**	U-M	***Anomalous Thermal Conductivity in an Expanding Magnetic Field***
2-05	**Kseniia Konina**	U-M	***Atmospheric Pressure Plasma Jet Treatment of Skin with Hair Follicles***
2-06	**Stephen Langellotti**	U-M	***Experiments on Coaxial Multipactor***
2-07	**George Dowhan**	U-M	***Updates to the X-Pinch Platform and Faraday Ratation Imaging Diagnostic on the MAIZE Facility***
2-08	**Lucas Stanek**	MSU	***Entropy Generation in Ultracold Neutral Plasmas***
2-09	**Parker Roberts**	U-M	***Time-Resolved Investigation of Hall Thruster Pole Ion Heating***
2-10	**Hongmei Tang**	U-M	***Relativistic Intensity Laser Channeling and Direct Laser Acceleration of Electrons from an Underdense Plasma***
2-11	**Brendan Sporer**	U-M	***A Platform to Study High-field FRC Formation on the Maize Linear Transformer Driver***
2-12	**Mackenzie Meyer**	U-M	***Plasma-Produced Reactive Species Reactions with Liquid Water Droplets***
2-13	**Christopher Sercel**	U-M	***Indirect Azimuthal Current Measurement in an RMF Thruster***

Poster Session III

3-01	**Joshua Woods**	U-M	***Performance Model for a Rotating Magnetic Field Thruster***
3-02	**Yang Zhou**	MSU	***Theory of Laser-induced Photoemission from Dielectric-coated Metal Surfaces***
3-03	**Louis Jose**	U-M	***Kinetic Theory of Strongly Magnetized Plasmas***
3-04	**Collin Whittaker**	U-M	***Targeted Experimental Measurements to Refine an Operational Model for Porous Electrospray Thruster Arrays***
3-05	**Austin Brenner**	U-M	***Plasma in Earth's Magnetosphere: Applying the Virial Theorem to High Fidelity Simulation***
3-06	**Steven Lanham**	U-M	***Controlling Nanoparticle Growth in Low Temperature Plasmas Using Pulsed Power***
3-07	**Matthew Byrne**	U-M	***Scaling Law for the Dependence of the Hall Thruster Plume on Facility Pressure***
3-08	**Ryan Revolinsky**	U-M	***Investigation of Recirculating Planar Magnetron with Coaxial All-Cavity Extraction***
3-09	**Brandon Russell**	U-M	***Generation and Measurement of Extreme Magnetic Fields***
3-10	**Thomas Marks**	U-M	***Evaluation of Algebraic Models for Hall Thruster Electron Transport***
3-11	**Akash Shah**	U-M	***Effects of Pre-Ionization on Current Distribution in a Gas-Puff Z-Pinch***
3-12	**Florian Krüger**	U-M	***Controlling Charged Particle Dynamics and Nanometer Scale SiO_2 Etching in $Ar/CF_4/O_2$ Plasmas via Voltage Waveform Tailoring***
3-13	**Eli Feinberg**	U-M	***Direct Laser Impulse Effects on Titanium***
3-14	**Benjamin Wachs**	U-M	***Optimization of a Low Power ECR Thruster Using Pulsed Heating***

Abstracts

Poster Session I

Characterization of CH_4/N_2 Plasmas for Plasma Catalytic Methane Coupling using Optical Emission Spectroscopy

Ibukunoluwa Akintola [a], Deanna Poirier [b], Gerardo Rivera-Castro [b], Jinyu Yang [a], Jason C. Hicks [b] and David B. Go [a, b]

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Non-thermal plasmas (NTPs) can produce reactive chemical environments including electrons, ions, radicals, and vibrationally excited molecules. The integration of a catalyst with reactive NTPs can drive thermodynamically unfavorable chemical transformation at low temperatures and pressures. In particular, we are interested in the direct coupling of light hydrocarbons (e.g. methane) and nitrogen to produce value-added liquid chemicals (e.g. pyrrole and pyridine) in a plasma-assisted catalytic process. To design effective catalysts and plasma-catalytic systems requires comprehensive understanding of the plasma-phase chemistry alone, including thorough characterization of plasma-phase properties. While there have been many studies on nitrogen (N_2) and methane (CH_4) plasmas, there is limited understanding on how operating parameters (i.e. feed N_2/CH_4 gas ratio, plasma power) affect the plasma properties. In this work, we vary different plasma parameters and optically characterize the plasma using optical emission spectroscopy (OES) to determine relevant thermodynamic information such as the electron temperature and electron density to better understand their effects, if any, on product formation during methane coupling.

Non-invasive Measurements of a Hollow Cathode Plume with Incoherent Thomson Scattering

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While electric propulsion devices are an enabling technology for in-space propulsion, it is crucial for the development of these technologies to be able to perform accurate and comprehensive measurements of their performance and behavior. For these plasma-based devices, it is often difficult to accurately measure even the most basic properties such as temperature and density. Historically, the use of invasive techniques such as electrostatic probes have sufficed, but these methods can be very imprecise and may alter the operation the device being studied. Recent advances in optics technology now allow the use of non-invasive laser techniques to measure the density, temperature, and the electron velocity distribution function for many electric propulsion systems[1].

The hollow cathode, the electron source commonly used in ion and Hall thrusters is a prime example of an electric propulsion system where it is critical to have non-invasive plasma measurements of key properties such as electron temperature and density. These devices are susceptible to large scale plasma oscillations that self-organize and may drastically increase the erosion rate[2]. The cathode erosion due to these so-called plume mode oscillations may limit the lifetime of the overall system[3]. Recent experimental work has characterized the oscillatory properties of the instability, and although the onset criterion remain elusive, these results have suggested the importance of resistive turbulent heating of the electrons[5]. However, there are many open questions about the plume mode related to the role of variable temperature and density. Direct probing methods are too perturbative and imprecise in this turbulent environment to address these questions. The need is apparent for non-invasive diagnostics to perform these measurements. In this work we apply incoherent Thomson Scattering (ITS) to study the hollow cathode plume mode.

Thomson scattering diagnostics make use of the laser scattering properties of electrons. An electron in a plasma with velocity (Ve) along the vector between the laser and scattering wavevector Doppler shifts the scattered radiation by: $\Delta\lambda = \frac{2v_e \sin\left(\frac{\theta}{2}\right)}{c}$

where λ_i is the laser wavelength, $\Delta\lambda = \lambda_s - \lambda_i$ is difference between the scattered (measured) radiation wavelength λs and the laser line, and θ is the scattering angle. By measuring the intensity of the scattered wave at various wavelengths the electron velocity distribution function can be resolved.

References

[1] Vincent, B., Tsikata, S., Potrivitu, G., and Mazouffre, S., "Incoherent Thomson scattering diagnostic development for plasma propulsion investigations," *35th International Electric Propulsion Conference*, 2017.
[2] Csiky, G. A., "Measurements of Some Properties of a Discharge from a Hollow Cathode," Tech. rep., NASA Technical Note, 1969.
[3] Sengupta, A., Brophy, J., Anderson, J., Garner, C., Banks, B., and Groh, K., "An Overview of the Results from the 30,000 Hr Life Test of Deep Space 1 Flight Spare Ion Engine," *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 2017
[4] Georgin, M., Jorns, B., and Gallimore, A., "Plasma Instabilities in the Plume of a Hollow Cathode," *2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum*, 2018.

Characterizing the Frowth of Current Filamentation Instability Using Laser Wakefield Accelerated Beams*

J. A. Cardarelli [a], Y. Ma [a], P. T. Campbell [a], A. F. Antoine [a], M. Berboucha [b,c], R. Fitzgarrald [a], R. Hollinger [d], B. Kettle [b], K. Krushelnick [a], S. P. D. Mangles [b], J. Morrison [d], R. Nedbailo [d], Q. Qian [a], J. J. Rocca [d], G. Sarri [e], D. Seipt [f], H. Song [d], M. J. V. Streeter [e], S. Wang [d], L. Willingale [a] and A. G. R. Thomas [a]

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Relativistic plasma instabilities provide a rich and active focus of research in fields ranging from high energy astrophysics to inertial confinement fusion. Current Filamentation Instability (CFI), characterized by the formation of high-density filaments as a relativistic beam current travels through a cold background plasma, is one such instability which has had a wealth of research to understand its properties in recent years. [1, 2, 3]

In this work a laser wakefield accelerator produces a relativistic electron beam which traverses through a cold background plasma of controllable length. Snapshots of the growth of CFI at different times may be captured by tuning the background plasma length. These experimental results are compared to theoretical frameworks for the CFI growth rate that relate the measured filament growth to properties of the beam and background plasma. Experimental results are also compared to Particle-in-Cell (PIC) simulations using the OSIRIS 4.0 PIC code.

*Acknowledgement to the DOE Fusion Energy Sciences Lasernet US (grant # DE-SC0021246) and the NSF (grant # 1804463)

References

[1] C. M. Huntington, et al., Phys. Rev. Lett. **106**, 105001 (2011).
[3] J. R. Peterson, et al., Phys. Rev. Lett. **126**, 215101 (2021).
[2] F. Califano, et al., Phys. Rev. E, **58.6**, 7837 (1998).

Pulsed-power Magnetized Shocks under an External Magnetic Field*

Raul F. Melean, Rachel P. Young, Sallee R. Klein, Akash P. Shah, Trevor J. Smith, George Dowhan, Brendan Sporer, Paul C. Campbell, Nicholas M. Jordan, Ryan D. McBride, R. P. Drake and Carolyn C. Kuranz

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We present the results from our second experimental campaign with the goal of characterizing magnetized plasma jets and magnetized shocks on the Michigan Accelerator for Inductive Z-Pinch Experiments (MAIZE) in the Plasma, Pulsed Power, and Microwave Laboratory at the University of Michigan. We aim to explore the interactions of magnetized plasma jets created by conical wire-arrays and the behavior of shocks generated by collisions with a solid obstacle in the presence of an external magnetic field. We focus on the structure and development of the shock layer as well as flow instabilities as a function of magnetic field strength. To generate the magnetized plasma flows, we used MAIZE to ablate 100-micron, aluminum wire arrays with currents in the order of 500 kA with a rise time of 250 ns. We use a conical array to drive an axial plasma jet, while an externally powered Helmholtz coil provides a uniform axial magnetic field, we can vary from 0.5 to 5 T. Our primary diagnostic consists of laser shadowgraphy (532 nm), captured by an intensified, fast framing camera, showing the structure and evolution of the plasma flow. In addition, we show preliminary results from a newly installed laser interferometry diagnostic.

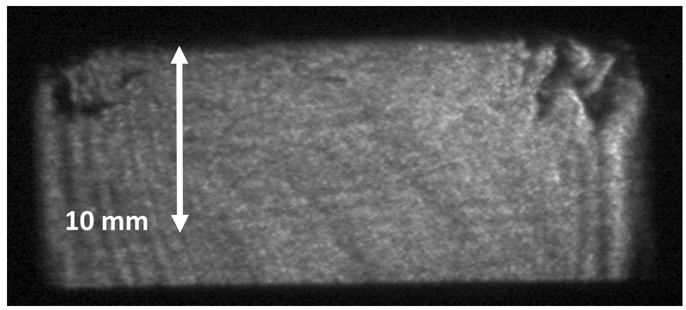

Figure 1 – shadowgraph of expanding, magnetized plasma shock interacting with 5 tesla, axial magnetic field. Magnetized shock and turbulence can be observed at the upper corners.

* This work is supported by the U.S. Department of Energy's NNSA SSAP under cooperative agreement numbers DE-NA0003869 and DE-NA0003764.

Formation and Scaling of Vortex Rings Ejected from Shock-accelerated Interfaces*

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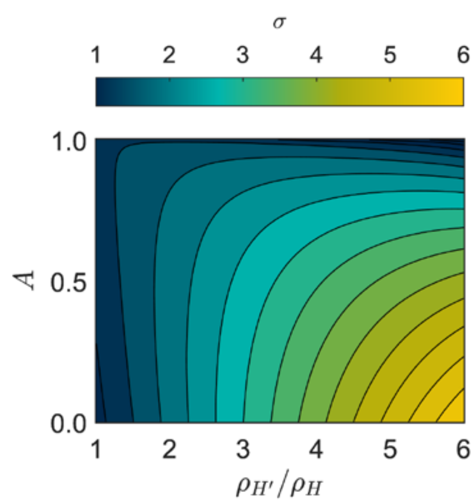
The mixing induced by the interaction of a shock wave with an interface separating two materials is ubiquitous in inertial confinement fusion (ICF) and astrophysics. Any misalignment between the pressure gradient, which points perpendicular to the shock front, and the density gradient, which is often dominated by and points perpendicular to the interface, leads to the deposition of baroclinic vorticity that sets the Richtmyer-Meshkov instability (RMI) into motion. Though they have long been observed in both experiments and simulations of the RMI, the effects of vortex rings that often escape the confines of the mixing region have only recently been explored [1-2]. Given their prevalence and importance to the development of the RMI, a robust understanding of vortex rings emerging from shock-accelerated interfaces may be the key to significant advancements in ICF and astrophysics research.

While the importance of vortex rings in RMI-relevant applications is only beginning to be understood, their behaviour in a more classical fluid dynamics setting is well known. The scaling law proposed in the seminal research on the topic states that the circulation, impulse, and energy of the ring formed by ejecting a column of fluid length L through a circular orifice of diameter, D, are fully saturated when the column aspect ratio, dubbed the formation number, is in excess of $L/D \approx 4$ [3].



The factor, σ, by which the vortex ring formation number increases versus shock strength, $\rho_{H'}/\rho_H$, and Atwood number, A.

Our objective is to generalize the fundamental fluid dynamics concepts concerning classical vortex rings to uncover the details of their formation and scaling behaviour in the shock-accelerated, RMI-dominated flows found in ICF and astrophysics. We find that the formation number for such vortex rings increases by a factor which is a function of the shock strength and the density jump across the interface, given by the Atwood number, as shown in the figure. Our theory is verified with high-order-accurate numerical simulations, and our findings highlight the importance of mitigation strategies of the RMI in ICF implosions seeded by both capsule surface pits and the fill tube [4]. In addition, our findings suggest a specific mechanism occurring in tandem with the RMI that may explain the earlier-than-anticipated emergence of heavy elements following supernovae explosions such as SN1987A.

*This work is supported by the Lawrence Livermore National Laboratory (LLNL) under Subcontract No. B632749 and by the U. S. DOE as part of the Stewardship Science Graduate Fellowship (SSGF) Program under grant DE-NA0003960.

References

[1] Thornber et al., Phys. Rev. B. 86 (2012) 056302. [2] Thornber et al., Phys. Plasmas. 22 (2015) 032309. [3] Gharib et al., J. Fluid. Mech. 360 (1998) 121-140. [4] Baker et al., Phys. Plasmas. 27 (2020) 112706.

Multipactor Discharge in the Parallel-Plate Geometry with Two-Frequency RF Fields and Space-Charge Effects*

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This work investigates multipactor discharge in the parallel-plate geometry [1] with two-frequency rf electric fields and space-charge effects. Using Monte Carlo and CST Particle Studio simulations, we find that multipactor susceptibility is sensitive to the relative strength and phase of the second carrier mode of the rf electric field [2,3]. Compared to single-frequency operation, multipactor susceptibility bands (especially the first band) shrink for different configurations of two-frequency rf operation (Fig. 1). Under two-frequency operation, multipactor modes are observed where electrons take fixed times to complete a round trip between the two surfaces. However, the time for electrons in the forward and return trips to traverse the gap within each round trip is different.

CST simulation reveals that space charge introduces effects such as the virtual cathode effect [4], disruption of the resonant electron motion, and reduced SEY due to the reduced impact energy of primary electrons. As a result, electron growth rate over a long period of time is lowered and multipactor susceptibility bands shrink in the presence of space charge [5].

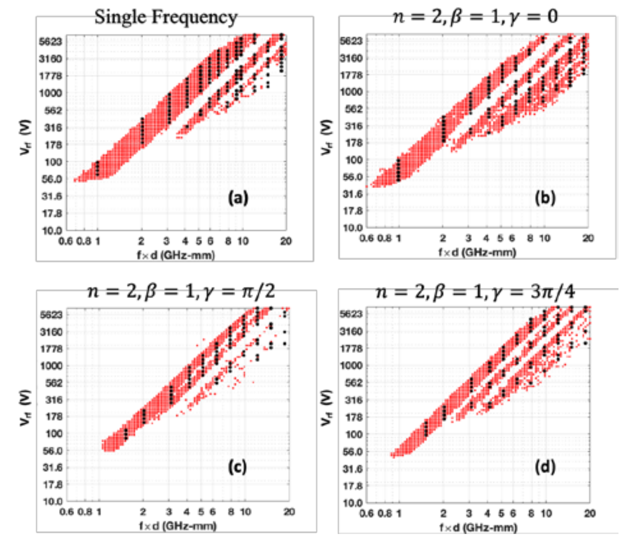

Figure 1 – Multipactor susceptibility charts in the $V_{rf} - fd$ space calculated from MC simulation (red dots) and from CST simulation (black dots) without space-charge effects for (a) single frequency rf operation, (b)-(d) two-frequency rf operations with relative strength of the second carrier $\beta = 1$, frequency ratio between the two carrier modes $n = 2$, and relative phase of the second carrier, (b) $\gamma = 0$, (c) $\gamma = \pi/2$, and (d) $\gamma = 3\pi/4$. We use fundamental rf frequency, $f = 1$GHz.

*Work supported by AFOSR MURI Grant No. FA9550-18-1-0062 and FA9550-21-1-0367.

References

[1] J. R. M. Vaughan, IEEE Trans. Electron Devices, vol. 35, no. 7, pp. 1172–1180 (1988).
[2] A. Iqbal, "Multipactor Discharge with Two-Frequency RF Fields", Ph.D. Thesis, Michigan State University, Michigan, United States (2021).
[3] A. Iqbal, J. Verboncoeur, and P. Zhang, Phys. Plasmas **25**, 043501 (2018).
[4] P. Zhang, Á. Valfells, L. K. Ang, J. W. Luginsland, and Y. Y. Lau, Appl. Phys. Rev., vol. 4, no. 1, p. 011304 (2017).
[5] G. Romanov, Am. J. Phys. Appl., vol. 5, no. 6, p. 99 (2017).

Performance at High Current Densities of a Magnetically-Shielded Hall Thruster

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Hall thrusters are a type of electric propulsion device with decades of heritage. With the advent of magnetic shielding, a technology that shapes the magnetic field lines in the thruster channel such that the erosion of channel walls by energetic ions is greatly reduced, Hall thruster lifetimes and mission spaces have been greatly expanded. One key remaining challenge is scaling to high powers in the 100-kW range, which is critical for the use of these thrusters for human exploration of the solar system. Historically, there have been issues associated with high-power, high-current density operation on unshielded thrusters. The need is then apparent for an investigation of performance of high current densities on a magnetically-shielded Hall thruster.

In this work, we operate the H9, a 9-kW magnetically-shielded Hall thruster, in the Large Vacuum Test Facility at the University of Michigan. Keeping voltage constant at 300 V, we vary the current from nominal operating values of 15 and 20 A up in 5 A increments to 40 A. We used a null-type inverted pendulum thrust stand to measure thrust, and a probe suite to measure various plasma parameters used to inform an efficiency model that breaks down the anode efficiency into various contributions. Our results show that we are able to run safely and stably up to 12 kW at 300 V, 40 A, achieving a maximum thrust of 700.1 mN and 65.8% anode efficiency here. Additionally, the thrust, specific impulse, and efficiency of the thruster increases monotonically with current, although we do observe diminishing returns in efficiency as we approach 40 A. Our probe analyses indicate that the mass utilization efficiency is primarily responsible for the increase in efficiency, with most other efficiencies decreasing with rising current density. We then speculate that our efficiency is maxed out at 40 A as the mass utilization approaches unity. We discuss these results in context of scaling single-channel Hall thrusters to the 100-kW range.

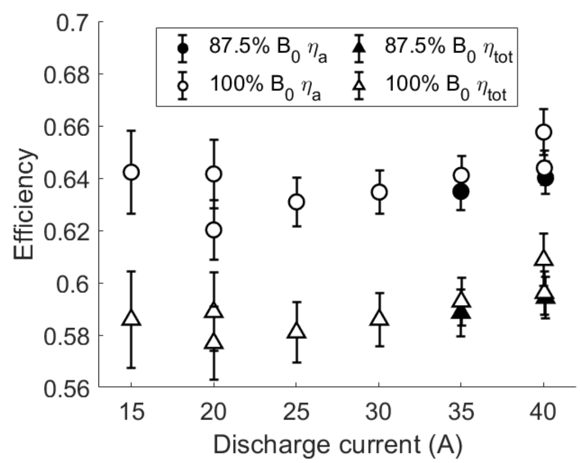

Figure 1 – Anode and total efficiencies for the H9 operating at 300 V and various currents. The different marker colors designate different magnetic field settings.

* Work supported by National Science Foundation Graduate Research

Multi-Modal In-situ/Operando Spectroscopy Combining PM-IRAS, OES, and MS for Observing Plasma-Stimulated Activation of Surface Species*

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There has been a growing interest in the integration of conventional heterogeneous catalysis with reactive chemical environments (i.e. electrons, ions, radicals, and vibrationally-excited molecules) induced by non-thermal plasmas (NTPs) to promote catalytic activities and/or selectivities, and even novel chemical transformations. Unveiling the full potential of plasma-catalytic processes requires a comprehensive understanding of the synergy between plasma and catalyst, including characterization of plasma-catalytic surface interactions. In this work, we report on a newly-designed multi-modal spectroscopic instrument combining polarization-modulation infrared reflection-absorption spectroscopy (PM-IRAS), mass spectrometry (MS), and optical emission spectroscopy (OES) for the investigation of plasma-surface interactions. Specifically, this tool has been utilized to correlate plasma-phase chemistry to both surface chemistry and to gas-phase products in-situ (1) during the deposition of carbonaceous deposits via NTP-promoted non-oxidative coupling of methane, and (2) subsequent plasma-stimulated activation of the surface deposits with an atmospheric pressure and temperature argon plasma jet on both nickel (Ni) and silicon dioxide (SiO_2) surfaces. This tool allows the direct observation of the activation of carbonaceous surface species by a NTP on Ni and SiO_2 surfaces to form hydrogen gas and C_2 hydrocarbons. Differences in PM-IRAS and OES measurements with Ni and SiO_2 during the activation suggest that the activation may takes place through different pathways. This unique tool for studying plasma-surface interactions could enable more rational design of plasma catalytic processes.

* This work is based on support from the National Energy Technology Laboratory (NETL) under Award No. DE-FE0031862.

Computational Investigation of Nucleation Processes Leading to Silicon Nanoparticle Growth in a Low Temperature Capacitively Coupled Plasma*

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Silicon nanoparticles (NPs) are industrially relevant for a variety of applications including deposition materials for electrodes in lithium-ion batteries [1] and tunable metamaterials for optical devices [2]. Low temperature plasmas (LTPs) represent viable means for synthesizing silicon NPs (a few – tens of nms diameter) [3]. Reactor operating conditions such as pressure, gas composition, and reactor geometry can be used to tune NP properties such as size, composition, luminescence, and structure. NP synthesis occurs by nucleation – an initial formation and growth of small clusters and growth – agglomeration of small clusters to form larger NPs. Nucleation of silicon NPs occurs through reactions of neutral or radical silane dissociation products with anion clusters, though the conditions for the onset of nucleation are unclear. Understanding of the processes governing NP nucleation in LTPs can lead to better control of desired NP properties, especially size and charge distribution.

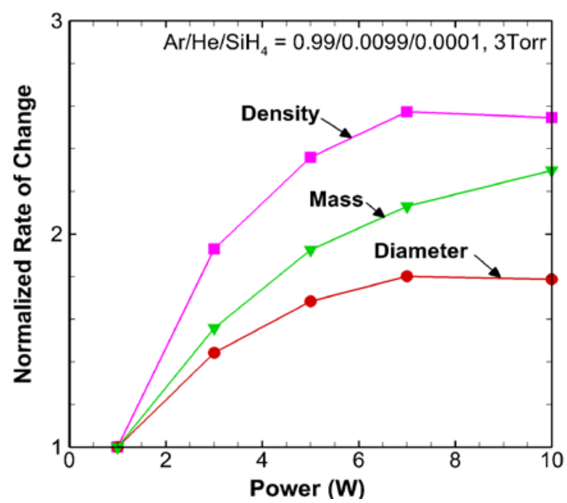

Figure 1 – Rate of change in the nucleation regime for density, mass, and diameter of Si_xH_y (x ≥ 13) particles (0.75 – 1 nm) in an Ar/He/SiH_4 low temperature CCP at various rf power.

In this work, we computationally examine silicon NP growth in a flowing Ar/He/SiH_4 LTP. The Hybrid Plasma Equipment Model (HPEM), a 2D reactor scale multi-physics model, was used to examine changes in particle properties and growth regimes. Changes in particle density, mass, and diameter in the nucleation regime as functions of reactor operating conditions (power, pressure, inlet silane fraction, and reactor geometry) are discussed. Comparison to experiments for determining optimum configuration for promotion of particle nucleation is also discussed.

* This work was supported by Army Research Office MURI grant W911NF-18-1-0240 and the National Science Foundation (PHY-2009219).

References

[1] U. Zywietz et. al. ACS Photonics. 2, 7 (2015).
[3] T. Yoon et. al. J. Electrochem. Soc. 162, 12 (2012).
[2] U. R. Kortshagen. Plasma Chem. Plasma Proc. 36, 73 (2016).

Phase Matched Plasma Wakefield Photon Acceleration*

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We present Phase Matched Plasma Wakefield Photon Acceleration (PMPA), a scheme for dephasingless photon acceleration in a particle-beam-driven wake. This work is motivated by the increasing need for high-frequency, high intensity with wavelengths less than 120 nm. Such radiation can provide high-resolution imaging, fine-scale material ablation, and ultrafast pump-probe techniques. Sources of XUV radiation include nonlinear frequency mixing, high harmonic generation, XUV lasing, and photon acceleration.

The concept of photon acceleration was first presented by Wilks et al. [1] Recent developments include frequency downshift [2], a tunable ionization front [3], and a varying density in an ionization front [4].

The mechanism of photon acceleration is that electromagnetic radiation seeing a decreasing plasma gradient shifts up in frequency. In PMPA, a laser pulse is situated in the wake behind a relativistic electron bunch so that it sees a decreasing density gradient. We use a tapered density profile to keep the witness laser pulse at the phase in the wake where the density is.

One dimensional simulations were performed with the code OSIRIS [5] and quasi-3d results were performed with FBPIC [6]. In 1d simulations, the laser pulse sees more than 10x frequency shift at 7.2% energy transfer efficiency from the electron beam to the witness laser pulse. Quasi-3d simulation results show 8x frequency shift

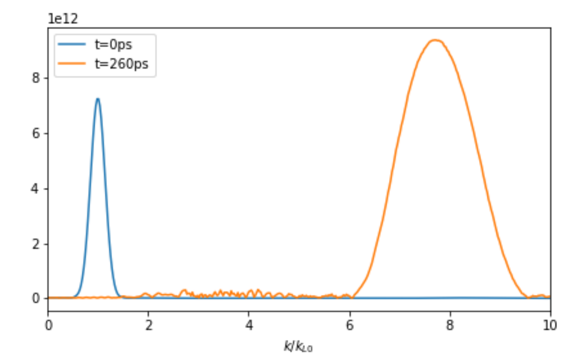

Figure 1 – Initial and final spectra from the simulation of a laser pulse going through the phase matched plasma wakefield photon accelerator. The central frequency is shifted by a factor of 8. The simulation was performed in effectively 3 dimensions with FBPIC [6] using the two lowest-order angular modes.

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Computational resources were provided by Advanced Research Computing at the University of Michigan. 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] S. Wilks et al., Phys. Rev. Lett. **62**, 22 (1989).
[2] Z. Nie et al., Nat. Photonics. **12**, 489 (2018).
[3] A. Howard et al., Phys. Rev. Lett. **123**, 12 (2019).
[4] M. Edwards et al., Phys. Plasmas, **25**, 5 (2018).
[5] R. Fonseca et al., Lectures in Comp. Sci., 342-351 (2002). R. Hemker, Dissertation, UCLA (1999).
[6] R. Lehe et al., Comp. Phys. Comm. **203**, 66 (2016).

Far-Field Measurements of a Rotating Magnetic Field Thruster*

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Electric propulsion (EP) devices such as Hall effect thrusters (HETs) are a proven technology that demonstrate substantial gains to specific impulse over conventional chemical propulsion. Inductive pulsed plasma thrusters (IPPTs) are an alternate form of EP that, while nascent, indicate favorable attributes when scaled to high powers above 100 kW [1]. Although IPPTs have demonstrated efficiencies of over 50% [2, 3], they have remained limited due to the large voltages required to drive their theta-pinch-like mirror currents. The Rotating Magnetic Field (RMF) thruster shares the advantages of IPPTs but reduces circuit stress by instead using a high frequency rotating magnetic field to drive plasma currents. In light of this advantage, the capabilities of RMF thrusters have been explored experimentally. However, across the board, the measured efficiencies of RMF thrusters have remained below 10% [4, 5]. Given that the root cause for this low efficiency is unknown, the goal of this work is to perform plasma plume measurements of a 5-kW class RMF thruster to improve our physical insight of the characteristic low performance.

This experimental campaign was conducted in the Large Vacuum Test Facility (LVTF) at U of M. The test article for this campaign was the PEPL RMFv2 thruster which has demonstrated steady state operation and thrust greater than 500 mN during RMF discharge [5]. For this study, we employed a Faraday probe (FP) and a Retarding Potential Analyzer (RPA) to measure the thruster plume. We collected FP data in an arc at 5-degree increments from 0 to 180 degrees, and RPA measurements were performed along the thruster axis. The operating conditions for this study consisted of a peak bias magnetic field of 120 G, 2 kA pk-pk RMF antenna currents, and a neutral xenon flow rate of 60 sccm. In Fig. 1 we show the results of our FP measurements. This plot shows the ion charge collected by the FP as a function of probe angle relative to the thruster and time form the start of the RMF pulse. From this result, we are able to calculate how much neutral mass the RMF can ionize and how well the plume is collimated. Additionally, using the RPA measurements we can evaluate to what energy the RMF thruster is accelerating the ions. Leveraging these new insights, we can inform design changes for the next iteration of RMF thruster technology.

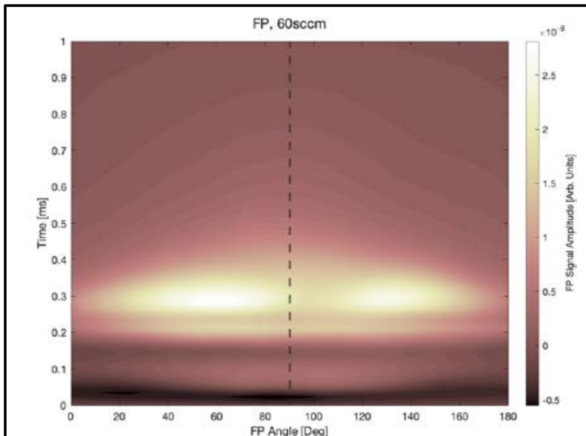

Figure 1 - Time-resolved FP measurements showing an anular thruster plume.

* Work supported by NASA NSTGRO grant number 80NSSC20K1168 and NASA NSTRF grant number 80NSSC18K1190

References

[1] K. A. Polzin, et al. Aerospace **7(8)**, 105 (2020).
[2] P. G. Mikellides and C. Neilly, J. Prop. Power **23(1)**, 51-58 (2007).
[3] K.A. Polzin, J. Prop. Power **27(3)**, 512-531 (2011).
[4] T. E. Webber, U. of Washington Thesis. (2010)
[5] C. L. Sercel, et al. AIAA Prop. and Energy 2021 Forum. (2021).

Spatiotemporally-resolved Characterizations of Electric Field around a Piezoelectric Transformer Using Electric-field Induced Second Harmonic (E-FISH) Generation

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Electric-field induced second harmonic (E-FISH) generation was utilized in this work to characterize the electric field distributed around the distal end of a piezoelectric transformer (PT). When a PT is actuated at its second harmonic frequency by a low input voltage of ~ 10 V_{rms}, the generated electric field at the distal end can be sufficient to breakdown the surrounding gas, making it attractive power source for non-equilibrium plasma generation. Understanding the surface potential and electric field distribution around the distal end is important for effectively using PTs for plasma generation. In this work, the spatiotemporally-resolved characteristics of the electric field generated by a PT operating in open air have been investigated using E-FISH method. Absolute calibration of the E-FISH signal was obtained by measuring a known uniform electric field generated within the gap of parallel plates. Electric field components were determined by simultaneously conducting E-FISH measurements with the incident laser polarized in both vertical and horizontal directions. Results show the spatial distribution of the electric field around the PT's output distal end and how it evolves in time. Notably, the strongest electric field appears on the face of the PT's distal end and when operated just below the breakdown threshold, is 30.4 kV/cm, consistent with the breakdown field of air. The time delay between PT's input voltage and measured electric field indicates that there is an about 0.45π phase difference between the PT's input and output.

* This work is based on support from the United States Department of Energy under DE-SC0021083 and the United States National Science Foundation under Award No. PHY-1804091. E-FISH experiments were conducted at the Sandia Low-Temperature Plasma Research Facility at Sandia National Laboratory in the United States through the support of a United States Department of Energy/Sandia National Laboratory grant 2020F0015. Seong-kyun Im is supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) under Award No. NRF-2020R1C1C1006837.

Simulations of Ion Heating in the Presheath Due to Ion-acoustic Instabilities*

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We find that ion-acoustic instabilities result in significant ion heating near the sheath edge. The heating extends into the presheath since some of the wave power reflects from the sheath. Particle-in-cell simulations were designed to test whether the instability was the source of heating by varying the source electron temperature across the threshold for exciting the ion-acoustic instability. The simulations confirm the instabilities cause heating and demonstrate that the electron-to-ion temperature ratio is locked to the threshold for instability in the unstable region near the sheath edge. The instability heating effect is significant at low pressures, but is eliminated at higher pressures where the instability is damped by ion-neutral collisions. This effect is distinct from the well understood ion heating caused by inelastic collisions with neutrals. Low temperature plasma systems that utilize a presheath for ion acceleration, such as etching and ion beam sources, could experience unwanted and significant ion heating due to this effect.

* This work was supported by DOE grant No. DE-SC0016473.
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Electron Acceleration by Elliptical q-Gaussian Laser Driven Electron Plasma Wave in Collisionless Plasma

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Theoretical investigation on propagation dynamics of an elliptical q-Gaussian laser beam in a plasma by considering the ponderomotive nonlinearity has been presented. The bell shaped q-Gaussian amplitude structure over the cross section of the laser beam creates a radial redistribution of the plasma electrons resulting to an index of refraction resembling to that of graded index fiber. This in turn produces the self focusing of the laser beam. The study is then extended to investigate the electron plasma wave excitation by the q-Gaussian laser beam. Following variational theory the nonlinear wave equations governing the evolution of laser beam and plasma wave have been reduced to a set of coupled ordinary differential equations for the beam widths of pump beam and EPW. Further the acceleration of electrons by the EPW excited by the laser beam has been investigated. The results obtained from numerical analysis reveal a stronger self-focusing of the q-Gaussian laser beam, which is desirable to excite a large amplitude electron plasma wave (EPW) for electron acceleration by extending the interaction length. Our results show that electron plasma wave excited by a q-Gaussian beam can accelerate the plasma electrons to higher energies compared to that by ideal Gaussian beam.

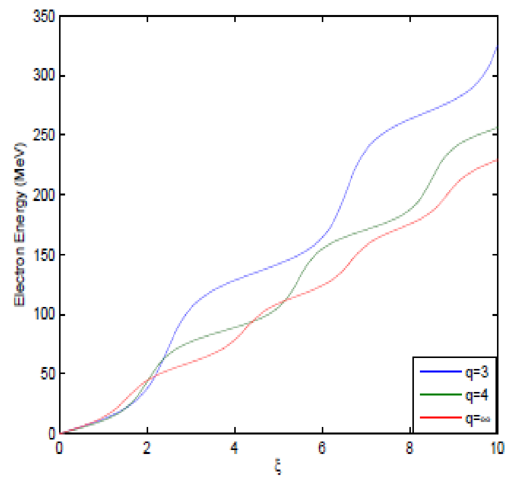

Figure 1 – Variation of electron energy with distance of propagation for different values of deviation parameter q.

Poster Session II

Beryllium Probe Neutron Diagnostic for a Gas-Puff Z-Pinch Neutron Source on a 1-MA, 100-ns Linear Transformer Driver

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The purpose of this study is to develop a diagnostic suite for studying neutron production in gas-puff z-pinch experiments on the Michigan Accelerator for Inductive Z-Pinch Experiments (MAIZE). Of particular interest is measuring neutron yields from deuterium-deuterium (DD) fusion reactions. MAIZE is a 1-MA, 0.1-TW, 100-ns Linear Transformer Driver (LTD) [1]. The intense current pulse generated by MAIZE is used to implode cylindrical plasmas, with applications in inertial confinement fusion, x-ray source development, material properties, and laboratory astrophysics [2]. A gas-puff z-pinch is a specific load configuration where an annular column of gas is ionized and pinched by the magnetic Lorentz force, $\mathbf{J} \times \mathbf{B}$. The gas puff is injected into the load region on MAIZE by a nozzle and fast-valve assembly. The injected column of gas becomes the load, completing the circuit by bridging MAIZE's anode-cathode gap. Neutron production has been demonstrated recently on MAIZE [3], but accurate measurements of the neutron yield are needed. One way to obtain accurate yield measurements is through the use of scintillation techniques, where ionizing radiation is detected by the light produced in a scintillator material. Most scintillation materials convert the kinetic energy of charged particles into detectable light, where the conversion is linear, and the light yield is proportional to the deposited energy over a wide range. The decay time of the luminescence is short where fast signal pulses are generated [4]. The diagnostic developed for this study is comprised of a beryllium (Be) probe detector, with Be rods in a scintillating material, and a photomultiplier tube (PMT), all within a shared housing. We also used a suite of instrumentation from ORTEC, including ORTEC's Minibin and Power Supply, 5-kV Detector Bias Supply, Constant-Fraction Discriminator, and EASY-MCS Multichannel Scaler. In this presentation, the scientific background and experimental setup of the diagnostic will be discussed. Of particular importance is the configuration of the Be detector and the procedure used to analyze and configure the Multichannel Scaler data for neutron yields [5].

* This work was supported by the DOE-NNSA through the SSAA Program under Cooperative Agreement No. DE-NA0003764.

References

[1] R. M. Gilgenbach et al., "MAIZE: A 1 MA LTD-driven Z-pinch at the University of Michigan," in Proc. AIP Conf., Jan. 2009, vol. 1088, no. 1, pp. 259–262, doi: 10.1063/1.3079742.
[2] R. D. McBride et al., "A Primer on Pulsed Power and Linear Transformer Drivers for High Energy Density Physics Applications", IEEE Trans. Plasma Sci. vol. 46, pp. 3928–3967 (2018), doi: 10.1109/TPS.2018.2870099.
[3] A. P. Shah et al., "Development of a Gas-Puff Z-Pinch Neutron Source for the 1-MA, 100-ns MAIZE Linear Transformer Driver", manuscript in preparation (2021).
[4] G. Knoll, "Radiation Detection and Measurement", 4th ed. John Wiley & Sons (2010).
[5] C. L. Ruiz et al., "Novel beryllium-scintillator, neutron-fluence detector for magnetized liner inertial fusion experiments," Phys. Rev. Accel. Beams, vol. 22, no. 4, p. 042901, Apr. 2019, doi: 10.1103/PhysRevAccelBeams.22.042901.

Future Experiment at the Wisconsin Plasma Physics Laboratory (WIPPL)*

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(b) University of Wisconsin – Madison

The Sun, being an active star, undergoes eruptions of magnetic fields and charged particles that reach the Earth and cause the aurora near the poles. Some eruptions may be more powerful than others, resulting in an Interplanetary Coronal Mass Ejection (ICME) that can cause major damage to our modern electrical systems without warning. We want to form a better understanding of how the ICMEs interact to create a more predictive model for them to more effectively defend our systems from a potentially devastating ICME. To explore solar phenomena, we use the Big Red Ball (BRB) facility at the Wisconsin Plasma Physics Laboratory (WiPPL). The BRB is a 3-meter diameter plasma confinement system equipped with around 200 ports for diagnostic access. Using the BRB, we can explore the interactions between an ICME and the Earth's _eld by using a spherical permanent magnet as the analog to the Earth, a light background plasma as the analog to the interplanetary medium (IM), and a compact torus (CT) of plasma as the ICME. My presentation will detail the desired parameters as well as describe preliminary results of the upcoming experiment.

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A Relativistic and Electromagnetic Correction to the Ramo-Shockley Theorem*

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The classical Ramo–Shockley (RS) theorem [1] gives the current induced on perfect conductors by the motion of nearby charges, assuming nonrelativistic motion of those charges in electrostatic fields. It has been widely used in vacuum and solid state electronic devices, radiation detection, discharge physics, and protein dynamics. We illustrate, for the first time, how relativistic and electromagnetic effects modify RS with explicit, closed form analytic solutions. We calculated the induced current distribution due to the motion of a line charge moving parallel and perpendicular to conducting plates [2]. The results have been verified by several methods, including particle-in-cell simulations. They are compared with RS' classical electrostatic theory (Fig. 1). New insights into the limitation and validity of RS are provided. Electromagnetic shocks are discovered, which are totally absent in RS, when the line charge strikes a plate. Explicit, closed form solutions for the shocks are obtained. The implications of these novel solutions will be addressed.

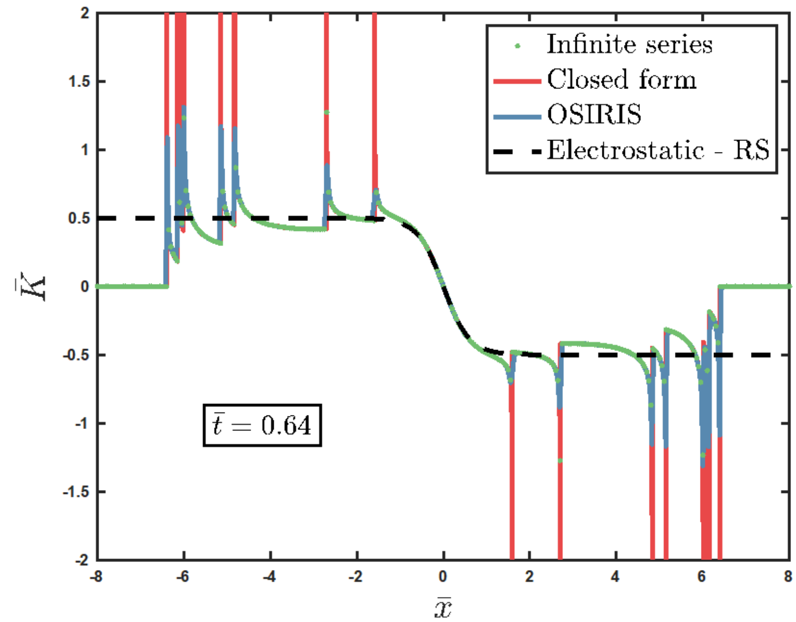

Figure 1 – Validation of the electromagnetic induced current distribution for a line charge moving perpendicular to two parallel plates, using three very different numerical algorithms: Infinite series [in green], closed-form solution [in red], and OSIRIS code [in blue]. Also included are the quasi-static results of Ramo and Shockley [black dashed line] for comparison. (From Ref. [2]).

* This work was supported by AFOSR Grants FA9550-18-1-0153 and FA9550-18-1-0062, and by the L3Harris Electron Devices Division.

References

[1] S. Ramo, *Proc. IRE*, **27**, 584 (1939); W. Shockley, *J. Appl. Phys.*, **9**, 635 (1938).
[2] D. Li, D. Chernin, and Y. Y. Lau, *IEEE Trans. Plasma Sci.* (2021), doi: 10.1109/TPS.2021.3099512.

Anomalous Thermal Conductivity in an Expanding Magnetic Field

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Magnetic nozzles heat a plasma and expand it through a magnetic field to convert thermal energy into thrust. They are theorized to exhibit high lifetimes and propellant ambivalence, thus being ideal candidates for long missions requiring in-situ resource utilization. However, the physics behind how these devices operate is still not fully understood.

One question regarding magnetic nozzle operation that remains open is that of electron heat conduction, which in part determines thruster performance [1]. The electrons exhibit a downstream decay in temperature as they expand. However, a classical Fourier law has been shown to predict a heat flux that exceeds the power levels typically put into these devices [2]. The present work explores the theory that a Fourier law may apply if the collision frequency used is an effective wave-induced (or "anomalous") collision frequency.

Previous work has identified a lower hybrid drift instability that exhibits significant propagation both perpendicular and parallel to the magnetic field [3]. This field-aligned propagation induces an effective collision frequency in this direction that inhibits heat conduction. In this work, we use a suite of electrostatic probes to measure these waves and to determine the heat flux from a Fourier law with the anomalous collision frequency. This analysis finds that the heat flux is likely lower than the power delivered to the thruster universally.

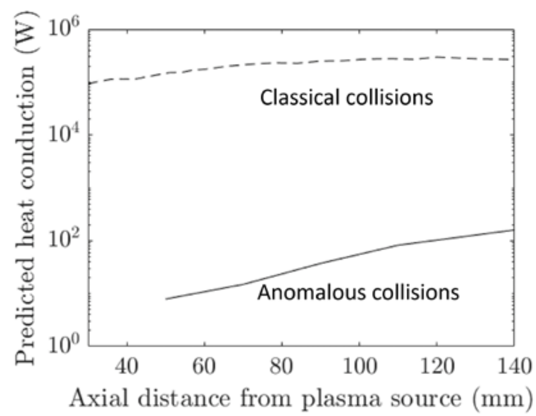

Figure 1 – Total heat flux predicted from a Fourier law at varying locations downstream of an expanding plasma source.

The relation between heat flux and observed parameters may be quantified by a polytropic index. In this work, we develop a theory to predict the polytropic index induced from the waves and compare it to the directly observed value. We find that the anomalous heat conduction predicts the polytropic index reliably.

* Work supported by NSTRF grant number 80NSSC17K0156.

References

[1] Merino, Mario, and Eduardo Ahedo. IEEE Transactions on Plasma Science 43, no. 1 (2015): 244–51.
[2] Little, J.M., and E.Y. Choueiri. Phys. Rev. Lett. 117, no. 225003 (2016).
[3] Hepner, Shadrach, Benjamin Wachs, and Benjamin Jorns. Appl. Phys. Lett 116, no. 263502 (2020).

Atmospheric Pressure Plasma Jet Treatment of Skin with Hair Follicles

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Atmospheric pressure low-temperature plasmas (LTPs) have a variety of applications. In recent decades, reactive oxygen and nitrogen species (RONS) that are formed in plasmas were shown to have a significant effect on biological tissues. If applied to the skin, plasmas interaction spans on hair follicles. Hair follicle treatment by plasma is attractive for several reasons. First, the skin and hair shaft gap is relatively small for traditional liquid treatments but accessible for plasmas. At the same time, hair follicles may contain critical for surgeries concentrations of pathogens. Secondly, stimulation of follicles by plasma may promote hair growth [1]. In this work, a computational investigation of atmospheric pressure plasma helium jet interaction with hair follicles is discussed.

The computations in this work were performed using a 2D plasma-hydrodynamic program *nonPDPSIM* [2]. It solves the Navier-Stokes equation to represent fluid flow for neutrals. Poisson's equation for electrical potential is solved implicitly on an unstructured mesh simultaneously with the continuity equation for charged species and neutrals. Transport and rate coefficients are obtained from the solution of Boltzmann's equation. Radiation transport is addressed with Green's function approach. Human tissues are represented as dielectric materials with resolved epidermis, dermis, fat, muscles and hair. In the simulations, helium flow with impurities is propagating into ambient humid air. Plasma is generated and propagates onto the top of the skin surface. It is determined that plasma can propagate into follicles since most of the gaps between hair shaft and skin exceed the Debye length. Some patterns of plasma propagation into follicles of different idealized geometries are investigated. Key trends of plasma behavior in follicles are identified for empty and hair-containing follicles of different sizes with varied angles with respect to the skin surface (Fig. 1).

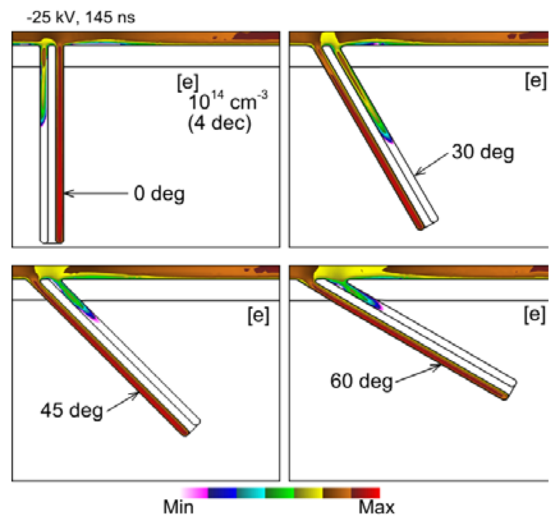

Figure 1 – Electron density at 145 ns for slanted follicles with angles in the range 0-60 degrees.

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References

[1] J. Kim, et al, Appl. Sci. **7**, 1 (2017).
[2] S. A. Norberg, et al Plasma Sources Sci. Technol. **24**, 035026 (2015).

Experiments on Coaxial Multipactor*

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Multipactor is a discharge phenomenon that occurs in radiofrequency vacuum electronic devices.[1] These discharges are driven by electrons impacting electrode surfaces and undergoing secondary electron emission. Multipactor has a number of negative effects such as cavity loading, signal attenuation/distortion, and localized heating leading to catastrophic failure of the device. Preventing multipactor is essential to ensure reliable operation of RF vacuum electronic devices, particularly in satellite communication systems where repairs are impossible. This work presents experimental results on a new S-band coaxial multipactor test cell that will be used to evaluate new methods for mitigating multipactor.

Ongoing experiments have focused on measuring the multipactor breakdown threshold. Figure 1 shows the multipactor breakdown threshold as a function of the product of the RF frequency and the gap between the electrodes in the coaxial transmission line. These data are compared to CST Particle Studio simulations.[2] Experimental data fell into two main regimes. When the electrodes were "fresh", or recently exposed to air, the breakdown threshold is extremely inconsistent and far below are simulated prediction. The second regime occurs when the electrode surfaces have been conditioned by the multipactor discharge. These data agree very well with our simulated results.

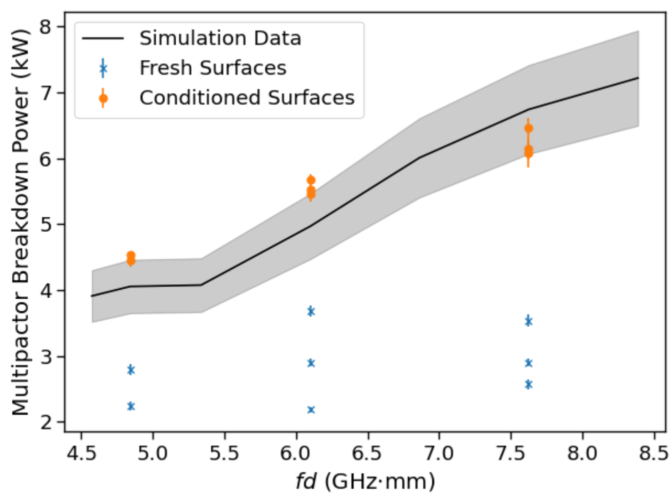

Figure 1 – Experimental measurements of the multipactor breakdown threshold compared to CST particle studio simulations (black). [2] The gray shaded region represents 10% agreement between the simulations and the experiments.

Future research includes testing various strategies for mitigating multipactor. Some such methods include plasma cleaning treatments and the application of low secondary emission yield coatings. Other work includes measuring the delay for multipactor onset and comparing our experimental data to Siddiqi and Kishek's chaos model.[3]

* This research was supported by AFOSR MURI #FA9550-18-1-0062 and #FA9550-21-1-0367 through Michigan State University, L3Harris Electron Devices Division, and by the Directed Energy Professional Society.

References

[1] R. Kishek, Y.Y. Lau, L. Ang, A. Vefells, and R. Gilgenbach, Phys. Plasmas **5**, 2120 (1998).
[2] S. Langellotti, N, Jordan, Y.Y. Lau, and R, Gilgenbach, IEEE Trans. Plasma Sci. **48**, 1942 (2020).
[3] M. Siddiqi and R. Kishek, IEEE Trans. Electron Devices **66**, 4403 (2019).

Updates to the X-Pinch Platform and Faraday Ratation Imaging Diagnostic on the MAIZE Facility

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X-pinches, formed by driving intense current through the crossing of 2 or more wires, provide an excellent platform for the study of "micro-pinches" due to their propensity to generate a single micro-pinch at a predetermined location in space (i.e., where the wires cross) [1,2]. Ideally, micro-pinches are areas of run-away compression to very small radii (~1 μm) leading to pressures on the order of ~1 Gbar for currents on the order of ~0.1 MA. However, the fraction of the total current that is driven through the dense micro-pinch plasma at small radii versus that being shunted through the surrounding coronal plasma at larger radii is not well known. To allow for the study of micro-pinches and their current distribution on the 1-MA MAIZE facility, a Faraday rotation imaging diagnostic (1064 nm) [3], as well as corresponding modular X-pinch load hardware, was developed. Presented is the status of these developments including preliminary experimental results characterizing X-pinches on the MAIZE LTD.

*This work was supported by the DOE Early Career Research Program under Grant DE-SC0020239 and by the NNSA SSAP under Cooperative Agreement DE-NA0003764.

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).
[3] G. F. Swadling et al., Review of Science Instruments, **85**, 11E502 (2014)

Entropy Generation in Ultracold Neutral Plasmas*

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Ultracold neutral plasmas [1] (UNPs) are strongly coupled, non- equilibrium systems created by photoionizing laser cooled atoms in a vacuum. As a result, experimental platforms are developed to elucidate the properties of UNPs such as their [2] spatial expansion and temperature relaxation. Data from these experiments are used to validate theories and computational models that aim to model UNPs. One such computational model is derived from a multi-species BGK [3] kinetic theory. In this poster, we aim to highlight some of the capabilities of a multi-component BGK code by simulating a multi-species UNP. We explore entropy generation as UNPs are subject to disorder-induced heating, arising from the fact that UNPs are not in equilibrium.

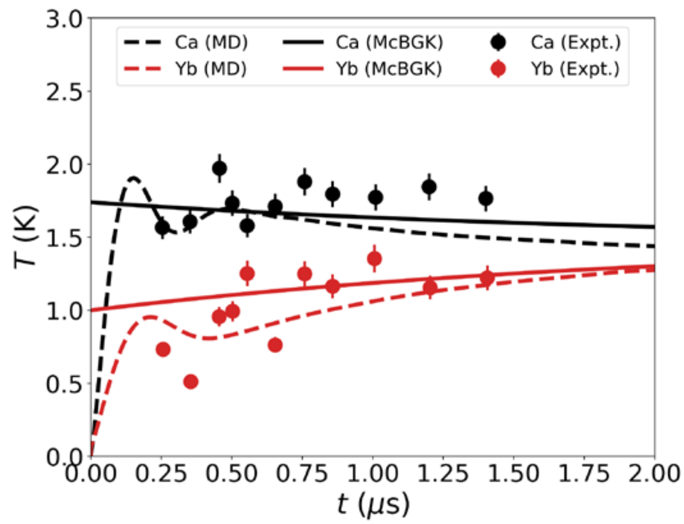

Figure 1 - Temperature relaxation of an Ca-Yb UNP. Molecular dynamics and the multi-component BGK model agree well with experimental data giving confidence in their use for extending the range of experimental data.

* This work is supported by the U.S. Air Force Office of Scientific Research under grant number FA9550-17-1-0394.

References

[1] T. C. Killian et al. “Ultracold neutral plasmas”. Physics Reports 449.4 (2007), pp. 77–130.
[2] L. G. Silvestri et al. “Relaxation of strongly coupled binary ionic mixtures in the coupled mode regime”, Physics of Plasmas 28, 062302 (2021)
[3] J. R. Haack et al. “A conservative, entropic multispecies BGK model.” *Journal of Statistical Physics* 168.4 (2017): 826-856

Time-Resolved Investigation of Hall Thruster Pole Ion Heating*

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Hall thrusters are crossed-field plasma sources which enable fuel-efficient electric spacecraft propulsion. Discharge channel erosion in Hall thrusters can be mitigated with magnetic shielding, a particular contour of the magnetic field lines which reduces energetic ion flux to the discharge channel walls [1]. However, these shielded thrusters have shown wear of the inner front pole surface, suggesting plasma sputtering in that region (Fig. 1). Classical simulations underpredict the rate of this pole erosion [2]. There is thus a pressing need to understand the plasma physics governing the erosion of the front pole in order to model and mitigate this wear mechanism in Hall thrusters and increase their working lifetime.

It has been proposed that various plasma waves propagating in the discharge may anomalously heat the ion population in the pole region to sufficient temperatures to explain the observed erosion levels [3]. High-speed image processing techniques reveal large-amplitude gradient-driven waves which propagate azimuthally in the cathode plume of Hall thrusters [4]. These electrostatic waves may accelerate the ions in such a way as to produce a time-averaged “heating” effect which widens the velocity distribution and increases ion energies near the pole.

Figure 1 – Photograph of a Hall thruster with magnetic shielding after a 150-h wear test, demonstrating the sputtered surface of the inner and outer magnetic poles due to pole erosion [2].

In this work, we apply time-resolved laser-induced fluorescence (LIF) velocimetry techniques to directly resolve the impact of these waves on the cathode ion population. We use an azimuthal LIF diagnostic in a laboratory Hall thruster with magnetic shielding and find that the predicted velocity oscillations are directly observable with this technique. Standard erosion models are evaluated based on these results in order to compare this wave heating with other proposed mechanisms.

* Work supported by a NASA Space Technology Graduate Research Opportunity (Grant 80NSSC20K1229)

References

[1] Mikellides, I. G. et al. (2014). Magnetic shielding of a laboratory Hall thruster. I. Theory and validation. *Journal of Applied Physics*, **115** (4).

[2] Mikellides, I. G., & Lopez Ortega, A. (2014). Assessment of Pole Erosion in a Magnetically Shielded Hall Thruster. *AIAA Propulsion and Energy Forum*, 1–20.

[3] Lopez Ortega, A. et al. Anomalous Ion Heating and Pole Erosion in the 12.5-kW Hall Effect Rocket with Magnetic Shielding (HERMeS). *AIAA Propulsion and Energy 2020 Forum*, 1–23.

[4] Jorns, B. A., & Hofer, R. R. (2014). Plasma oscillations in a 6-kW magnetically shielded Hall thruster. *Physics of Plasmas*, **21** (5). https://doi.org/10.1063/1.4879819

Relativistic Intensity Laser Channeling and Direct Laser Acceleration of Electrons from an Underdense Plasma

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The channeling of a high-intensity laser pulse through an underdense plasma and simultaneous direct laser acceleration of electrons to superponderomotive energies are dynamic and complex processes. For all laser-plasma interactions the transfer of the laser energy to the electrons is the fundamental step and has applications in producing secondary radiation like bright, directional X-ray beams. A wide variety of parameter scans were performed using the OMEGA EP facility to explore the effect of experiment conditions, i.e. laser pulse duration, focusing geometry, plasma density, on the channel evolution and relativistic electron acceleration. Proton deflectometry observed the channel evolution, instabilities and filament formation. Corresponding particle-in-cell simulations illustrate the laser modulation, channel electromagnetic fields development and electron movement in interaction with laser pulse, giving insight into the energy transfer mechanism. Using simulations, we study double pulse interactions to separate the channel and quasi-static field formation by a leading pulse, to enable a trailing laser pulse to be better guided in the preformed channel and therefore more effectively couple energy to the electrons.

* This work is supported by the Departmentof Energy / NNSA under Award Number DE-NA0003944.

A Platform to Study High-field FRC Formation on the Maize Linear Transformer Driver*

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Field-reversed configurations (FRCs) have become attractive targets for magneto-inertial fusion, a.k.a. magnetized target fusion (MTF), which may offer a more economical path to fusion gain greater than unity. Slutz et al [1] has simulated FRC formation and compression via a solid imploding liner on the Z-machine (20+ MA, 100 ns), located at Sandia National Labs. These FRC targets would be unique for an MTF campaign in that they would be formed with very strong fields (10-100 T), be centimeter-scale in size, and be formed in-situ (requiring no translation stage). With a 30 T bias axial field, LASNEX simulations suggest fusion yield from the compressed FRC could approach liner kinetic energies typically obtained in MagLIF [2].

Formation of the FRC would occur in a helical AutoMag- type liner [3], which produces a reversing axial field via a ~1 MA pre-pulse provided by the Z-machine. This presents a unique opportunity for a 1-MA class machine, such as the MAIZE linear transformer driver (LTD) at the University of Michigan, to demonstrate FRC formation and lifetimes suitable for compression on the Z-machine.

To this end, a platform is being developed to study high-field FRC formation on MAIZE (1 MA, 200 ns). External Bz coils are being developed which produce global bias fields approaching 10 T. Helical fast coils, 3D-printed in steel or bronze and coated with dielectric material, carry the MAIZE current to reverse the field. Fast-framing camera images have shown plasma columns forming in 12 mm ID quartz tubes containing low-pressure argon, with and without seed ionization by a triggered spark gap. An update will be given on experimental results and diagnostic development.

*This work was supported by the NNSA Stewardship Sciences Academic Programs under DOE Cooperative Agreement DE-NA0003764

References

[1] Slutz, Stephen A., and Matthew R. Gomez. "Fusion gain from cylindrical liner-driven implosions of field reversed configurations." Phys. Plasmas 28.4, 042707 (2021).

[2] Gomez, Matthew R., et al. "Experimental demonstration of fusion-relevant conditions in magnetized liner inertial fusion." Phys. review letters 113.15, 155003 (2014).

[3] G. A. Shipley et al., "Implosion of auto-magnetizing helical liners on the Z facility", Phys. Plasmas 26, 052705 (2019).

Plasma-Produced Reactive Species Reactions with Liquid Water Droplets*

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Interactions between liquids and low temperature, atmospheric pressure plasmas are foundational to applications like water treatment and plasma medicine. Chemical activation of the liquid by plasma-produced reactive species is limited by transport of the reactive species to the liquid. These transport limits can be mitigated by a high surface to volume ratio of the liquid and producing the reactive species near the surface of the liquid.

Using a global plasma chemistry model and a 2D model, the interaction between one short-lived reactive species (OH_{aq}) and formate ($HCOO^{-}_{aq}$) dissolved in the droplet is computationally investigated. Formate consumption by OH_{aq} gives an estimate of OH transport to the droplet. The global model shows chemistry occurring on long timescales, while the 2D model provides spatial resolution. The reactor modeled is a radio frequency (RF) glow discharge.[1] The plasma is formed in He with air impurities. For the global model, a constant power of 13.6 W is deposited into the plasma over the residence time of the 56 µm diameter droplet in the plasma (10 ms). The chemistry is tracked until 100 ms. In the 2D model, 15 W of power is deposited over one RF cycle. The diameter of the droplet is increased to 80 µm for computational speed.

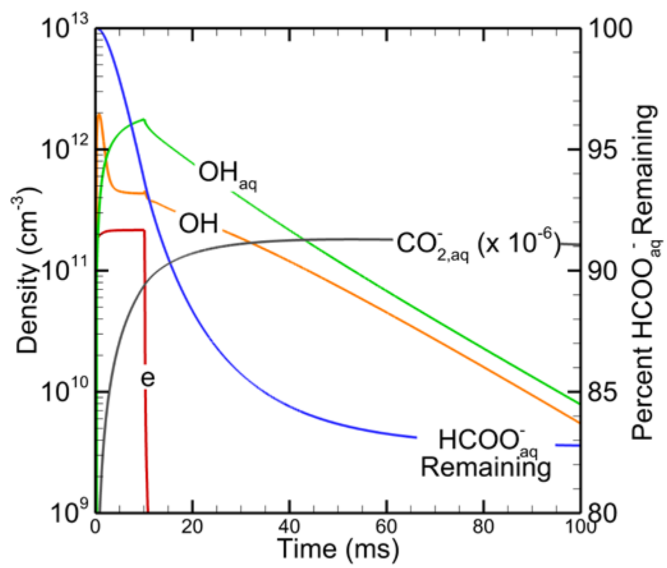

Figure 1 – Densities of electrons, OH, OH_{aq}, and $CO^{-}_{2,aq}$ predicted by the global model. Also shown is percentage $HCOO^{-}_{aq}$ remaining.

The predicted species densities from the global model are shown in Figure 1. During the residence time of the droplet in the plasma, the electron density is constant. The gas phase OH density initially increases and then decreases to a constant value by the end of the residence time. The OH_{aq} density continues increasing throughout the pulse. The percentage of $HCOO^{-}_{aq}$ remaining decreases throughout the residence time as it is consumed through reactions with OH_{aq}. Since $CO^{-}_{2,aq}$ is the product of the reaction between OH_{aq} and $HCOO^{-}_{aq}$, the density of $CO^{-}_{2,aq}$ increases throughout the residence time. After the residence time of the droplet in the plasma, OH and OH_{aq} densities decrease, and $CO^{-}_{2,aq}$ and percentage $HCOO^{-}_{aq}$ remaining reach constant values. The results of the 2D model show that OH_{aq} is located near the surface of the liquid and $CO^{-}_{2,aq}$ is produced primarily within 8 µm of the surface of the liquid.

* Work supported by the National Science Foundation (PHY-1902878) and the Department of Energy Fusion Energy Sciences (DE-SC0020232).

References

[1] G. Oinuma et al, Plasma Sources Sci. Technol. **29**, 095002 (2020).

Indirect Azimuthal Current Measurement in an RMF Thruster*

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The Rotating Magnetic Field (RMF) thruster is an example of an inductive pulsed plasma thruster (IPPT) which employs a rotating magnetic field to induce an azimuthal current in a plasma. This current interacts with the radial component of a stead bias magnetic field, resulting in an axial body force on the plasma, ejecting the propellant in a slug and generating impulse. As an IPPT, the RMF thruster is highly throttleable, in-situ resource utilization (ISRU) compatible, and boasts very high specific power.[1] Unlike other IPPTs, the RMF thruster has the added benefit that, under nominal operation, driven plasma current is proportional to the frequency rather than the magnitude of the driving magnetic field, allowing for significantly relaxed power supply requirements and better power supply longevity.[2]

Initial performance measurements of the RMF thruster show poor performance, despite coupling relatively large amounts of energy into the plasma (up to 700 J/mg), suggesting the current drive or acceleration mechanism may not be functioning as anticipated.[3] Further, performance was seen to improve with increased RMF field strength despite Jones and Hugrass penetration limits having been met, which should ensure that driven current depends only on RMF frequency.[4] In light of these uncertainties regarding the current drive mechanism, there is a pressing need for time-resolved azimuthal current density measurements throughout the thruster and plume.

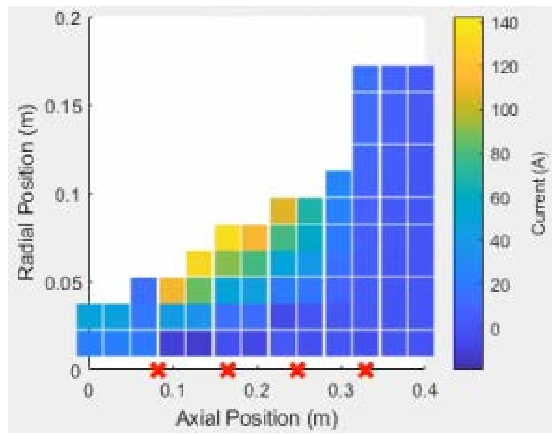

Figure 1 – Posterior mean current map for the 45 sccm Xe, 2.5 kA peak antena current condition at 125 us into the 200 us pulse.

To approach this problem, the time-resolved induced axial magnetic field was measured at four points along thruster centerline for a variety of operating conditions, using standard inductive probing practices.[5] By discretizing the r-z plane of the thruster into current elements, Bayesian methods can be used to fit a current map to the magnetic field data, using previous understanding of the current drive mechanism as the prior.

*Work supported by NSTRF Grant # 80NSSC18K1190

References

[1] Polzin, K., Martin, A., Little, J., Promislow, C., Jorns, B., and Woods, J., “State-of-the-Art and Advancement Paths for InductivePulsed Plasma Thrusters,”Aerospace, Vol. 7, No. 8, 2020, p. 105.
[2] Blevin, H. A., and Thonemann, P. C., “Plasma confinement using an alternating magnetic field,”Nuclear Fusion Supplement,Part 1, 1962, p. 55.
[3] Sercel, C. L., Gill, T., Woods, J. M., and Jorns, B., “Performance Measurements of a 5 kW-Class Rotating Magnetic FieldThruster,”AIAA Propulsion and Energy 2021 Forum, 2021, p. 3384.
[4] Jones, I. R., and Hugrass, W. N., “Steady-state solutions for the penetration of a rotating magnetic field into a plasma column,”Journal of Plasma Physics, Vol. 26, No. 3, 1981, pp. 441–453

Poster Session III

Performance Model for a Rotating Magnetic Field Thruster

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Rotating magnetic field (RMF) thrusters are a type of inductive pulsed propulsion device theoretically suited for high power operation. It utilizes a rotating magnetic field to produce an azimuthal current in the presence of a steady background field with a radial gradient to eject plasma at high velocity and repetition rates [1]. Historically, performance of RMF thrusters has been low. The highest observed efficiency is 8% [2]. To better understand the device, the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL) developed an RMF test article capable of operating over a number of conditions. The thruster was tested at power levels at or below 4 kW. There was little to no thrust measured and coupling efficiency was less than 5% for all cases [3].

A lumped circuit model approach is used to predict performance of the RMF thruster, thereby illuminating techniques for increasing efficiency and specific impulse. The equivalent circuit is derived by modeling the driving antennae and plasma as a collection of current loops interacting via mutual inductance and Lorentz forces. Several physically relevant assumptions are applied to reduce the complexity of the system. The resulting set of equations require five free circuit parameters that must be determined experimentally. Data from performance measurements of the PEPL RMF v2 thruster is used to calibrate the model. While the model tends to underpredict performance, it mirrors operational trends observed during the experiment. Thruster performance is discussed in the context of the fundamental scaling of the model as well as the individual scaling of the free parameters. Several methods for increasing performance are proposed, including increasing specific energy, flow rate, and background magnetic field strength to achieve higher impulse and efficiency.

References

[1] Slough, John, David Kirtley, and Thomas Weber, "Pulsed Plasmoid Propulsion: The ELF Thruster," IEPC-2009-265, 31st International Electric Propulsion Conference, Ann Arbor, Michigan, September 20 – 24, 2009
[2] Weber, T., "The electrodeless Lorentz force thruster experiment," Ph.D. thesis, University of Washington, 2010.
[3] Sercel, C. L., Woods, J. M. , T. M., Gill, and Jorns, B.A., "Performance Measurements of a 5 kW-Class Rotating Magnetic Field Thruster", VIRTUAL, August 9, 2021

Theory of Laser-induced Photoemission from Dielectric-coated Metal Surfaces*

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Photoelectron emission [1, 2] plays an important role in many applications, such as free electron lasers (FELs), ultrashort X-ray sources, time-resolved electron microscopes, ultrafast electron diffraction, and novel nano-electronics [3, 4]. For stable and long-term operation of cathodes, surface coatings are fabricated to protect them from degradation by ions and electrons bombardment and oxidization. There are also natural coatings formed on emitters due to oxides and adsorbates under poor vacuum conditions. These coatings have strong impacts on electron emission.

In this study, we construct an analytical quantum theory for photoemission from metal surfaces coated with an ultrathin dielectric under a dc bias, by exactly solving the one-dimensional (1D) time-dependent Schrödinger equation. The theory applies to arbitrary metal (of any work function and Fermi level), dielectric (of any thickness, relative permittivity, and electron affinity), laser field (of any strength and wavelength), and dc field. Results show that the introduction of dielectric coating can induce resonance emission behavior (see Fig. 1), which is ascribed to the electron wave interference inside the dielectric. Dielectric-coated cathodes can outperform the bare cathode in photoemission current density, when the dielectric has a relatively smaller permittivity or larger electron affinity, as highlighted by the yellow blocks in Figs. 1(a) and 1(b). For the special case of zero laser field, an empirical relation between the threshold dielectric thickness and threshold dielectric relative permittivity is given [5]. This work provides insights for designing cathodes of higher efficiency and better stability.

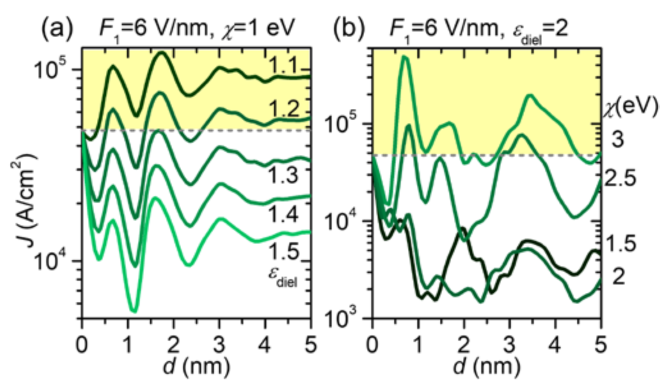

Figure 1 - Photoemission current density J from a dielectric-coated flat gold surface as a function of dielectric thickness d under different (a) relative permittivity ε_{diel}; (b) electron affinity χ. The dc electric field F_0 = 0 and the laser field $F_1 = 6$ V/nm.

* Work supported by AFOSR Grant No. FA9550-18-1-0061, ONR Grant No. N00014-20-1-2681, and AFOSR Grant No. FA9550-20-1-0409.

References

1. Y. Zhou, and P. Zhang, J. Appl. Phys. 127, 164903 (2020).
2. Y. Zhou and P. Zhang, J. Appl. Phys. 130, 064902 (2021).
3. P. Dombi, et al., Rev. Mod. Phys. 92(2), 025003 (2020).
4. P. Zhang and Y. Y. Lau, Sci. Rep. 6, 19894 (2016).
5. Y. Zhou and P. Zhang, Phys. Rev. Res. 2, 043439 (2020).

Kinetic Theory of Strongly Magnetized Plasmas*

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Novel transport properties exhibited by plasmas that are strongly magnetized in the sense that the gyrofrequency exceeds the plasma frequency are not well understood. Here, we develop a generalized kinetic theory that can treat Coulomb collisions in plasmas across all magnetization strength regimes and which asymptotes to the traditional Boltzmann kinetic theory in the weakly magnetized limit. The theory also spans the weak to strong Coulomb coupling regimes by incorporating the mean force kinetic theory concept. To demonstrate the utility of the generalized theory, it is used to compute the friction force on a massive test charge moving through a strongly magnetized one-component plasma. Recent works studying weakly coupled plasmas have shown that strong magnetization leads to a transverse component of the friction force that is perpendicular to both the Lorentz force and velocity of the test charge; in addition to the stopping power component. Recent molecular dynamics simulations have also shown that strong Coulomb coupling in addition to strong magnetization gives rise to a third "gyrofriction" component of the friction force in the direction of the Lorentz force. Here, we show that the theory captures these effects and agrees well with the molecular dynamics simulations over a broad range of Coulomb coupling and magnetization strengths. The transverse force is found to strongly influence the average motion of a test charge by changing the gyroradius and the gyrofriction force is found to slightly change the gyrofrequncy of the test charge resulting in a phase shift.

* This material is based upon work supported by the U.S. Department of Energy, Office of Fusion Energy Sciences, under Award No. DE-SC0016159, and the National Science Foundation under Grant No. PHY-1453736. It used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by NSF Grant No. ACI-1548562, under Project Award No. PHYS-150018.

Targeted Experimental Measurements to Refine an Operational Model for Porous Electrospray Thruster Arrays*

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The current-voltage ("I-V") characteristic of an electric thruster based on a porous electrospray emitter array is measured, and these experimental measurements are used to infer the parameters of reduced-fidelity models for the behavior of porous electrosprays. Specifically, an AFET-2, a porous electrospray thruster designed as a laboratory testbed [1], was manufactured and operated in a vacuum facility. The operating voltage of the thruster is gradually increased to determine the onset threshold for electrospray, and then the thruster voltage is stepped up to determine the current response. The thruster current is measured both as that delivered by the power supply and by placing a probe into the electrospray plume to intercept the entire beam. The manufacture of the thruster is described and the measured I-V curve is compared to measurements taken on a different thruster of the same design [3].

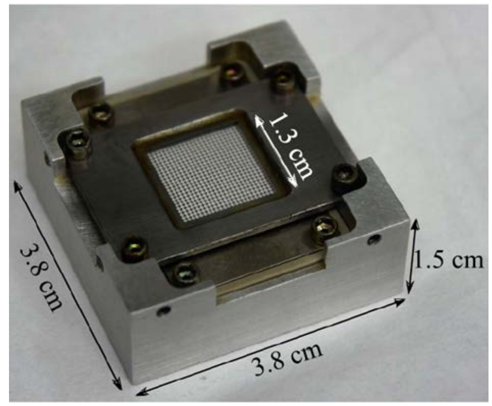

Figure 1 – A picture of an assembled AFET-2 [1]

These data are then used to infer the model parameters of two reduced-fidelity models for electrospray behavior: 1) the model of Coffman et al [2] predicting the current from an electrospray emission sites operating in a purely ionic regime, and 2) the empirical model of St. Peter et al [3] predicting the onset of multiple emission sites per electrospray emitter. This inference is performed within the context of arrays of emitters, for which finite manufacturing tolerances can cause differences in behavior between individual emitters. These results are compared with previous analysis for single emitters [4].

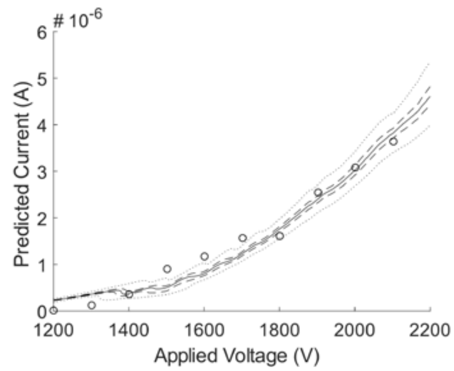

Figure 2 – Probabilistic performance predictions for emitter current as a function of applied voltaje (solid: median, dashed, 33rd and 66th percentile, dotted: 2.5th and 97.5th percentile), compared with experimental data (circles) from a previous study [4]

* This work was supported by a NASA Space Technology Graduate Research Opportunity and by an Early Stage Innovations grant from NASA's Space Technology Research Grants program.

References

[1] Natisin et al 37th IEPC, 522 (2019).
[2] C. Coffman et al, Appl. Phys. Letter. **109**, 23 (2016).
[3] B. St. Peter et al, Aerospace. **7**, 91 (2020).
[4] C. Whittaker et al, AIAA P&E 2020 Forum (2020).

Plasma in Earth's Magnetosphere: Applying the Virial Theorem to High Fidelity Simulation*

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Plasma is found naturally in the near space environment around our planet (geospace) in the magnetic cavity carved out by its intrinsic dipole field known as the magnetosphere. Geospace plasma can generally be well described by the ideal magnetohydrodynamic (MHD) equations, save for specific regions where kinetic effects must be considered. During periods known as geomagnetic storms, there can be strong coupling between the ambient solar wind plasma and the magnetosphere, which causes magnetic perturbation to the earth's surface magnetic field. This can lead to ground-induced currents and severe damage to critical infrastructure. In order to better understand the connection between energy flux across the magnetospheric boundary, the energy state of the magnetosphere system, and the ground magnetic perturbation, two distinct calculations of magnetic perturbation are employed on a fully-coupled global simulation of the solar wind-magnetosphere-ionosphere system during a storm event in February 2014.

The virial theorem [1] utilizes momentum conservation to relate the stress on the boundary of a closed volume to the energy contained within. In the MHD limit, it can be used to predict the magnetic perturbation at earth's surface given the energy state of the magnetosphere and stress on its boundary. Results of magnetic perturbation using this analysis show good agreement with the traditional method of the Biot-savart law as well as observed perturbations during the real event. The individual contributions of stresses and energies on and within the magnetopause boundary are compared and the implications for solar wind magnetosphere interactions are discussed.

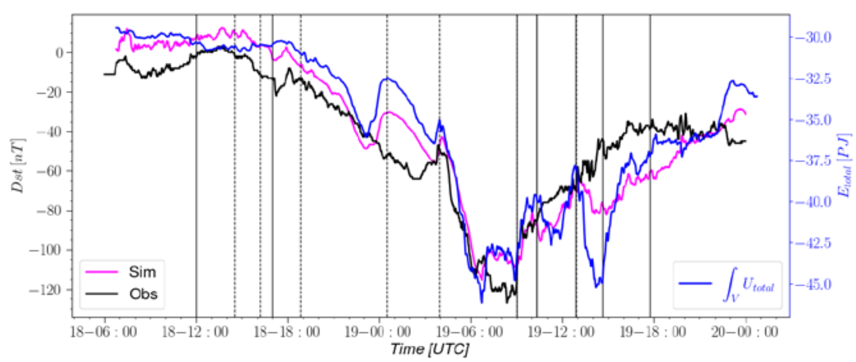

Figure 1 - Magnetic perturbation in nT as measured by the Disturbance Storm Time (Dst) index for simulation using the Biot-Savart law and ground observations. Right axis shows integrated total energy within magnetosphere volume. Vertical lines are key times during the storm event.

* Work supported by Solstice NASA drive center

References

[1] Carovillano, R. L. and Siscoe, G. L. (1973). Energy and momentum theorems in magnetospheric processes. Reviews of Geophysics 11, 289–353. doi:https://doi.org/10.1029/RG011i002p00289

Controlling Nanoparticle Growth in Low Temperature Plasmas Using Pulsed Power*

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Low temperature plasmas can be used to create high quality nanoparticles (NPs) that would be difficult to make using traditional methods. NPs immersed in low temperature plasma primarily charge negative, and experience mutually repulsive forces which prevent agglomeration, resulting in narrow size distributions. Negative charged particles can also become trapped by the positive plasma potential, giving particles more time to grow from radical precursors formed in the plasma. The optical properties of NPs are a strong function of particle size, and greater control over particle growth could be lucrative.

In this work, we report the results of a computational investigation into how modulating the applied power affects NPs synthesized in the plasma. Plasma conditions were modeled using the Hybrid Plasma Equipment Model (HPEM), a plasma multi-fluid simulator. Particle growth was modeled using the Dust Transport Simulator (DTS), a 3d kinetic code that tracks particle positions and sizes coupled self-consistently with the plasma simulation. The test-case for this study is silicon NP synthesis from a dilute SiH_4 precursor in a lab-scale tube reactor. Pulsing was found to be an effective method to control particle size due to the modulation in plasma potential and particle charges affecting particle trapping. These results indicate that pulsing may be an under-utilized method for controlling NP synthesis in low temperature plasmas.

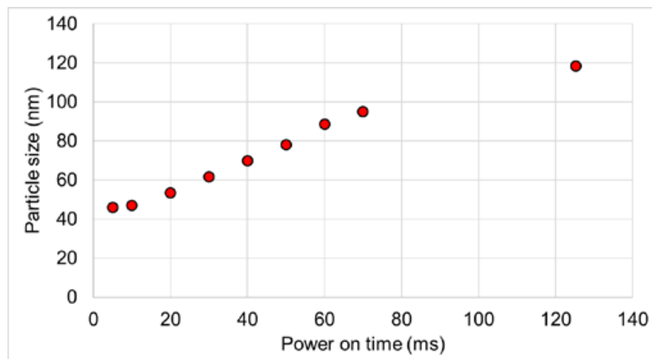

Figure 1 – Simulation results of growing Si nanoparticles in a plasma tube reactor. Particle size can be tuned by modulating the power to the plasma.

* 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).

Scaling Law for the Dependence of the Hall Thruster Plume on Facility Pressure

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While Hall thrusters are one of the most successful and mature forms of electric propulsion flown today, there is an open question about the fidelity of the test environments that are currently employed to qualify these systems. Indeed, there are a number of so-called “facility effects" that are known to impact thruster operation. Notable examples include the presence of electrically conducting walls, back-sputter from the facility, and the impact of finite facility pressure. Each of these facility effects has been shown to impact performance of the thruster. This invites a potential concern that ground test results may not necessarily be representative of on-orbit behavior. In light of this potential risk, there have been several studies that have attempted to characterize facility effects on various thruster properties [1]. For facility pressure effects in particular, it is becoming an increasingly common method to perform parametric investigations. The facility pressure is systematically lowered while key aspects of the thruster operation and plume are measured. Models are then fit to the trends in the data to make extrapolations toon-orbit conditions. With that said, one of the major potential limitations of this approach stems from the confidence in the models used to fit the trends in data. Since these modes are not necessarily rooted in a first-principles description of the thruster’s operation, it invites the question as to whether it is reasonable to expect a trend to persist at pressures lower than the measured dataset. In order to mitigate this possibility, in this work we have identified physics-inspired scaling laws for the downstream plume parameters which we fit to the parametrically-generated datasets using a Nested Sampling MCMC routine [2]. The calibrated model is shown to agree within uncertainty to experimental data over a wide range of pressures for the SPT-100 [1]. This result is discussed in the context of the physical implications of the model as well as its extensibility to extrapolating parametric pressure studies to on-orbit operation.

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

Investigation of Recirculating Planar Magnetron with Coaxial All-Cavity Extraction

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Experimental power and frequency behavior of the Recirculating Planar Magnetron with Coaxial All-Cavity Extraction (RPM-CACE) are being investigated to explore its potential for frequency and phase locking. The RPM-CACE prototype is a novel crossed-field magnetron that implements modified planar cathodes that increase the surface area, enabling usage of higher currents [1-3]. Further, potential benefits of the RPM design over conventional cylindrical magnetron designs are the straightforward scalability of the system to achieve higher RF frequencies. Microwave output power from the 6-waveguide outputs (12-cavities) are being measured and correlated [1,2]. Previous simulations predicted operating parameters of RPM-CACE at 360 MW total output at 1.9 GHz when driven by -300 kV and 4 kA. Pulsed power is supplied through Marx-Abramyan Generator (Michigan Electron Long Beam Accelerator, MELBA). Current experimental results show total microwave powers of 10's MW. Further experiments are underway to explore the deviation in microwave output powers from the simulations.

(a) (b)

Figure 1 – (a) Internal front-view of Anode-Cathode structure inside of RPM-CACE (b) Overall view of RPM-CACE Experiment attached to MELBA.

* Work supported by the Air Force Office of Scientific Research Award No. FA9550-21-1-0184

References

[1] Gilgenbach, Lau, Hoff, French, Luginsland and Franzi, "Crossed Field Device" US Patent # 8,841,867 B2 (issued Sept. 23, 2014)**;** Hoff, B. W. (2019). Crossed Field Device (U.S. Patent No. 10,181,388 B1). U.S Patent and Trademark Office. https://patents.google.com/patent/US10181388B1/en.

[2] N. M. Jordan et al., "Experiments on the Recirculating Planar Magnetron with Coaxial All-Cavity Extraction," 2020 IEEE 21st International Conference on Vacuum Electronics (IVEC), 2020, pp. 69-70, doi: 10.1109/IVEC45766.2020.9520514.

[3] M. A. Franzi et al., "Recirculating-Planar-Magnetron Simulations and Experiment," in IEEE Transactions on Plasma Science, vol. 41, no. 4, pp. 639-645, April 2013, doi: 10.1109/TPS.2013.2242493.

Generation and Measurement of Extreme Magnetic Fields*

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Next-generation laser facilities may reach extreme intensities (>10^{23} W/cm^2), allowing for the effects of quantum electrodynamic (QED) processes on plasmas to be studied. In the interaction of such high intensity pulses with solid targets it is expected that ~0.1 MT magnetic fields may be generated, potentially allowing for the experimental study of extreme astrophysical phenomena. Currently, there is no theoretical description for how such extreme laser intensities affect the magnetic field generation and strength. For example, the magnetization that ultra-intense laser interactions will achieve may be limited by QED processes, i.e. radiation reaction, and therefore cannot be accurately predicted. Using the QED module in the OSIRIS particle-in-cell code, we perform several 2D and quasi-3D simulations to study magnetic field generation at these extreme laser intensities. In the expected range of magnetic field strengths standard proton deflectometry techniques cannot be used due to the extremely large deflections of the protons. We propose an electron radiography method to measure the properties of these magnetic fields.

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Evaluation of Algebraic Models for Hall Thruster Electron Transport*

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The development of fully predictive simulations of crossed-field plasma discharges such as Hall effect thrusters is a longstanding goal of the low temperature plasma propulsion community. However, in many cases, there are aspects of the underlying physics such as anomalous cross-field transport that are not sufficiently understood to produce fully predictive models. With this limitation in mind, we apply Bayesian inference to several algebraic models for the anomalous transport in a Hall effect thruster. These models include a two-zone Bohm model [1], a first-principles plasma turbulence model [2], and a data-driven model [3]. Using the output of validated simulations as surrogate data, we calibrate these models and obtain a posterior distribution of the model coefficients. We then sample from the distributions of model coefficients and run a high-fidelity multi-fluid Hall thruster discharge simulation at each sampled coefficient set. We simulate the H9 magnetically shielded Hall thruster, which was not part of the training dataset, at several operating conditions, obtaining probabilistic predictions of key thruster performance parameters, including thrust, discharge current, specific impulse and anode efficiency at each. These are then compared to data. We note similarities in the predicted performance and plasma properties across models and provide some physical insight into why these similarities may occur.

* Work supported by the Air Force Office of Scientific Research

References

[1] K. Hara et al, J. Appl. Phys. 115, 203304 (2014)
[2] T. Lafleur et al. Physics of Plasmas 23, 053503 (2016)
[3] B. Jorns, Plasma Sources Sci. Technol. 27 104007 (2018)

Effects of Pre-Ionization on Current Distribution in a Gas-Puff Z-Pinch*

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The Z-machine at Sandia National Laboratories is instrumental in plasma physics research across a range of applications. University-scale gas-puff z-pinch experiments at lower currents (~1-MA), can inform the higher-current (~20-MA) experiments conducted on the Z-machine. A gas-puff z-pinch puffs gas into the anode-cathode gap, which is then pulsed with a high voltage. The gas is ionized, accelerated, and compressed as the current flows across the electrodes, allowing for study of pinch phenomena including fusion reactions. The initial ionization or pre-ionization condition of the gas-puff prior to compression is poorly understood [1]. The effects of pre-ionization on the current distribution through the gas-puff as the implosion progresses is also an open question. Quantifying how the pre-ionization and current distribution affect x-ray and fusion production, which are largely the result of micro-pinch instabilities, is crucial to understanding z-pinch physics. We report on the development of, and initial results from, the gas-puff experiment for the 1-MA, 100-ns MAIZE Linear Transformer Driver.

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References

[1] J. Giuliani, “A Review of the Gas-Puff Z-Pinch as an X-Ray and Neutron Source”, IEEE Trans. Plasma Sci. **43**, 2385 (2015).

Controlling Charged Particle Dynamics and Nanometer Scale SiO_2 Etching in $Ar/CF_4/O_2$ Plasmas Via Voltage Waveform Tailoring

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High aspect ratio (HAR) plasma etching of nanoscale features using halogen containing gas mixtures faces major challenges posed by shrinking feature sizes, increased aspect ratio and less tolerance for feature distortion. Electrostatic charging and the resulting deflection of electrons and ions can be a cause of feature distortion and etch rate reduction during the processing of non-conductive materials such as SiO_2.

The use of non-sinusoidal voltage waveforms as a means of power coupling is a method to control electric field and charged particle dynamics in the sheath region above the wafer. In this talk, we will discuss the influence of tailored voltage waveforms on the energy and angular distributions of electrons and ions onto the wafer in a capacitively coupled plasma sustained in fluorocarbon gas mixtures and operated at 40 mTorr. This investigation was performed using the Hybrid Plasma Equipment Model (HPEM). The applied waveform consists of 5 consecutive harmonics with a base frequency of 1 MHz and fixed relative amplitudes. Using fluxes provided by the HPEM, the etching of a HAR via in SiO_2 was simulated using the Monte Carlo Feature Profile Model (MCFPM). The resulting features were evaluated with respect to surface charge distribution, feature deformation and etch rate.

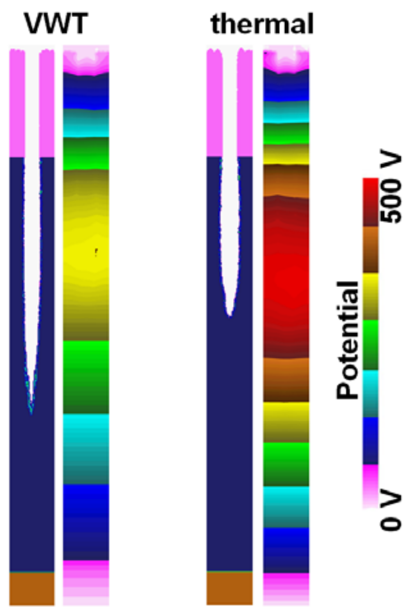

Figure 1 – Influence of the electron energy and angular distribution on the etch feature and potential.

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Direct Laser Impulse Effects on Titanium*

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Direct Laser Impulse (DLI) is an experimental platform in which a high-power optical laser strikes a tamper material to emulate the impulse and shock generated by x-ray deposition in metal. Here, we present analysis of DLI experiments on titanium alloys. Simple, flat titanium targets adhered to a tamper were subjected to a direct laser impulse on the Orion Laser at the UK's Atomic Weapons Establishment. In this analysis, we will compare the response of titanium in these DLI experiments to experiments on the National Ignition Facility (NIF) in which x-ray photons directly interacted with metal to generate a thermo-mechanical shock. Such comparisons will inform the design of future NIF x-ray experiments as well as experiments on a new NIF DLI capability coming online in 2022.

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Optimization of a Low Power ECR Thruster using Pulsed Heating*

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Magnetic nozzle thrusters are an ideal architecture for low-power in-space propulsion. These thrusters work by heating a plasma using radiofrequency or microwave power and subsequently converting the plamsa’s thermal energy into directed thrust through an expanding DC magnetic field. This technology avoids several limitations inherent to more mature thruster technologies such as Hall effect and gridded ion thrusters. It does not require plasma contacting electrodes, can operate using only a single power supply, and enables the use of reactive propellants. However, for over a decade, laboratory experiments using this technology demonstrated poor thrust efficiencies (~1%) at low input powers (< 100 W), largely negating many of its potential advantages [1].

Recent experiments using Electron Cyclotron Resonance (ECR) as the heating source for magnetic nozzle thrusters have shown much higher performances than pervious designs. These thrusters have demonstrated 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]. While these results show that magnetic nozzle thrusters can be competitive with established propulsion technologies, much work is left to further improve efficiency.

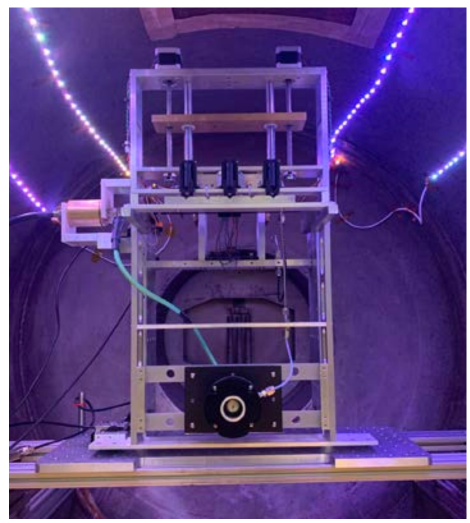

Figure 1 – ECR thruster mounted to PEPL thrust stand

We present the results of an optimization experiment aiming to improve performance by pulsing the input microwave power to the thruster. Pulsed power is commonly used in plasma processing to control ion and electron distribution functions, however these techniques have not been applied to magnetic nozzle thrusters [3]. Our experiment seeks to improve thruster efficiency, defined as $\eta = T^2/(2\dot{m}P_{in})$, by varying the duty cycle and pulse period of the input microwave power. The experiment uses a set total average input power and flow rate. We use a thrust stand to directly measure the output thrust and efficiency. Each test point is selected using a surrogate-based global optimization algorithm.

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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] S. Banna, A. Agarwal, G. Cunge, M. Darnon, E. Pargon, and O. Joubert, J. Vac. Sci. Technol. **30**, 4 (2012).

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