Michigan Institute for Plasma Science and Engineering (MIPSE)

14th ANNUAL GRADUATE STUDENT SYMPOSIUM

November 15, 2023
University of Michigan, Ann Arbor, MI 48109

Schedule

I. Special MIPSE Seminar

Room **1013 Dow Building**, North campus, 2300 Hayward St.

1:20 – 1:40 pm	**Registration, refreshments**
1:40 – 1:45 pm	**Prof. Mark J. Kushner**, University of Michigan Director, MIPSE ***Opening remarks***
1:45 – 1:50 pm	**Prof. Sergey Baryshev**, Michigan State University Chair, AVS Michigan Chapter ***Introducing American Vacuum Society Michigan Chapter and Student Chapter***
1:50 – 2:50 pm	Special MIPSE seminar Dr. Cami Collins, Oak Ridge National Laboratory ***Integrating Physics and Engineering for Fusion Reactor Design, Assessment, and Optimization***

II. Student Posters

Atrium, **EECS Building**, North campus, 1301 Beal Avenue

3:00 – 3:30 pm	Poster setup
3:30 – 4:10 pm	**Poster session I**
4:10 – 4:50 pm	**Poster session II**
4:50 – 5:30 pm	**Poster session III**
5:30 – 5:45 pm	Poster removal
5:45 – 6:00 pm	***Best Presentation Award*** **ceremony**

Participating institutions: University of Michigan, Michigan State University, University of Toledo, University of Notre Dame.

Poster session I

1-01	**Sandeep N Ramesh**	UToledo	***A Tunable and High-Isolation Integrated Filter and Plasma Limiter Technology***
1-02	**Grace Zoppi**	U-M	***Steady State Two-Fluid Model for a Rotating Magnetic Field Thruster Informed by Experimental Data***
1-03	**Kwyntero Kelso**	U-M	***X-ray Absorption Spectroscopy Experiments of Radiatively Heated Argon Gas***
1-04	**Yifan Gui**	U-M	***Optimization of Ge/Si Core/Shell Nanoparticles Properties Through Nonthermal Plasma Synthesis***
1-05	**Md Arifuzzaman Faisal**	MSU	***Analyzing Spatial Growth Rate and Starting Current in Smith-Purcell Radiation Using Single- and Two-Layer Grating Structures***
1-06	**Lucas Babati**	U-M	***Calculating Ion Transport Coefficients in Warm Dense Matter***
1-07	**Alexander Loomis**	MSU	***Chemical Vapor Deposition of Silicon Vacancy Ensembles in Low Strain Diamond with a NIRIM Type Reactor***
1-08	**Rebecca Fitzgarrald**	U-M	***Filter Pack X-Ray Spectrum Reconstruction for Betatron Streaking Experiment***
1-09	**Thomas Chuna**	MSU	***Data Driven Discovery of System Equilibration***
1-10	**Daniel Carpenter**	U-M	***A Novel Reduction-Based Scheme for In-Situ Solar Wind Origin Classification Using Machine Learning***
1-11	**Madison Allen**	U-M	***Optimal Experimental Design for Calibrating Anomalous Transport Models***
1-12	**Veronica Contreras**	U-M	***Measuring Coulomb Explosion Ions from OMEGA EP Interactions***
1-13	**Lan Jin**	MSU	***Beam Density Modulation During Emission Using RF and Laser Fields***
1-14	**Tyler Eddy**	U-M	***TFIPS – A Compact, Low-power Heavy Ion Spectrometer for Space Environments***

Poster session II

2-01	**Eli Feinberg**	U-M	***Design of Halfraums for X-ray Flow Experiments on the NIF***
2-02	**Bingqing Wang**	MSU	***Statistic Analysis of Nanoscale Tunneling Electrical Contacts Based on Transmission Line Model***
2-03	**Ryan Park**	U-M	***Demonstrating ThunderBoltz: An Open-Source 0D DSMC Boltzmann Solver for Plasma Transport and Chemical Kinetics***
2-04	**Christopher Sercel**	U-M	***Impact of Magnetic Field Profile on Loss Mechanisms in a Rotating Magnetic Field Thruster***
2-05	**Kazi Kabir**	UToledo	***Chemical Composition of a Power-Efficient Evanescent-Mode Plasma Jet***
2-06	**Sarah Frechette Roberts**	MSU	***An Investigation of the Effects of Low Methane Concentrations on Microwave Plasma Assisted Chemical Vapor Deposition of Single Crystal Diamond***
2-07	**Sankhadeep Basu**	MSU	***Non-thermal Plasma Synthesis of Indium Nitride***
2-08	**William Hurley**	U-M	***Performance Characterization of a Magnetically Shielded Hall Thruster Operating on Molecular Propellants***
2-09	**Tanner Nutting**	U-M	***Propagation of Texas Petawatt Laser Through High Density Gas Jet Targets***
2-10	**Zhongyu Cheng**	Notre Dame	***Accelerating Low-temperature Processing of Printed Nanoinks Using Machine Learning and Bayesian Optimization of Non-thermal Plasma Jet Sintering***
2-11	**Md Wahidur Rahman**	MSU	***The Effect of Space Charge on the Performance of Linear Beam Device for High Frequency Radio Waves***
2-12	**Declan Brick**	U-M	***Bayesian Inference for Calibration of Anomalous Electron Transport in Multi-Fluid Hall Thruster Models***
2-13	**Evan Litch**	U-M	***Low Bias Frequencies for High Aspect Ratio Plasma Etching***

Poster session III

3-01	**Moises Enriquez**	U-M	***Instability-enhanced Friction in Multi-ion Species Plasmas***
3-02	**Kseniia Konina**	U-M	***Atmospheric Pressure Plasma Jet in Treatment of Polypropylene Uneven Surfaces***
3-03	**Kushagra Singhal**	UToledo	***A Power-Efficient Plasma Line Based on Extended EVA Cavity Technology***
3-04	**Collin Whittaker**	U-M	***Experiments and Modeling of a 25 W Porous Electrospray Array***
3-05	**Shailaja Humane**	U-M	***Exploring Multi-fidelity Bayesian Optimization for Inertial Confinement Fusion Design***
3-06	**Andre Antoine**	U-M	***Characterization of Non-Thermal Phase Transitions in Ionic Compounds with Two-color X-ray Pulses***
3-07	**Sophia Bergmann**	U-M	***Design and Initial Operation of an Optically Accessible ECR Magnetic Nozzle Thruster***
3-08	**Yves Heri**	MSU	***Space Charge Effects on Short-Pulse Beam Dynamics in Vacuum Diodes***
3-09	**Julian Kinney**	U-M	***Mean Force Emission Theory for Bremsstrahlung in Strongly Coupled Plasmas***
3-10	**Tanvi Nikhar**	MSU	***Tabletop Microwave Capillary Reactor for Nano Diamond Synthesis***
3-11	**Parker Roberts**	U-M	***Thomson Scattering Measurements of Electron Mobility in Hall Thrusters***
3-12	**Tate Gill**	U-M	***Investigation of a Low-Pressure Cathode Design for High-Current Operation on Chemically Reactive Gasses***
3-13	**Ibukunoluwa Akintola**	Notre Dame	***Temperature Inhibition of Methane Conversion in DBD Plasma-Driven Systems***

A Tunable and High-Isolation Integrated Filter and Plasma Limiter Technology

Sandeep Narasapura Ramesh and Abbas Semnani

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Filters are integral components in communication systems that allow signals within a selected range of frequencies from the receiver antenna to be decoded. When communication systems encounter a high-power threat, it can potentially damage the power-sensitive components. This paper proposes a solution by designing an integrated filter-limiter topology using plasma technology. The proposed device acts as a bandpass filter at low input power levels, thus allowing a desired bandwidth of communication, but switches into a no-pass mode when encountered with high-power threats.

A novel integrated second-order filter-limiter device utilizing a plasma shell is introduced, which consists of two coupled split ring resonators (SRRs), each loaded with a gas discharge tube (GDT), as integrated plasma cells. At low input powers, the device exhibits a bandpass filter behavior whose fractional bandwidth and insertion loss can be controlled by the resonator quality factor, external coupling coefficient to the resonators, and the inter-resonator coupling coefficient. However, when a high-power threat is encountered, plasma forms inside the GDTs, drastically reducing the resonator quality factor by increasing its loss and limiting the signal transferred to the output port. The limiter isolation is proportional to the input power as a higher input power results in more substantial plasma discharges, resulting in higher resonator losses and lower transmitted signals.

We implemented a prototype on a PCB using planar SRRs and commercially available GDTs. The fabricated device performed in agreement with the theory and simulations with over 40-dB isolation during the high input power no-pass state and 2-dB insertion loss during the band-pass state with a 3.5% 10-dB FBW.

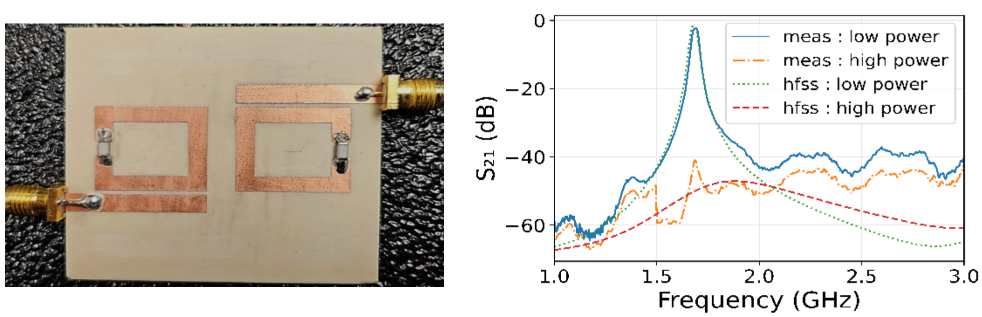

Figure 1 – A prototype of the integrated filter limiter prototype and its measured transmission coefficients in plasma OFF and ON modes, compared to the HFSS simulation results .

* Work supported by the Office of Naval Research (ONR) Grant N00014-21-1-2441.

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Steady State Two-Fluid Model for a Rotating Magnetic Field Thruster Informed by Experimental Data

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The Rotating Magnetic Field (RMF) thruster, a promising high-power enabling thruster archetype, operates by inductively coupling energy into the plasma. This energy transfer mechanism offers notable advantages over other high-power electric propulsion devices including the elimination of plasma wetted electrodes, and the capability to utilize alternative propellants without the risk of cathode poisoning. Presently, the Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan has developed tested a 5kW test article with a three-phase antenna. This latest test article was run under steady state operation to mitigate substantial radiation losses previously observed during pulsed operation [1]. To further improve performance and to gain a deeper understanding of potential limitations of the RMF thruster, a two-fluid steady state model was derived. Through the application of Bayesian inference, employing a delayed rejection adaptive metropolis (DRAM) algorithm, we can learn the free parameters of the model from experimental steady state measurements. The mean and distribution of these free parameters provide valuable insight into RMF loss mechanisms. This validated model can subsequently serve as a vital tool for optimizing future design iterations of the RMF thruster, bringing us closer to harnessing its full potential for advanced propulsion applications.

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[1] T. M. Gill, C. L. Sercel, and B. A. Jorns, "Experimental Investigation into Mechanisms for Energy Loss in a Rotating Magnetic Field Thruster," in 37th International Electric Propulsion Conference, 2022. IEPC Paper 2022-554.

X-ray Absorption Spectroscopy Experiments of Radiatively Ionized Argon Gas*

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Absorption spectroscopy is a diagnostic tool that can characterize the temperature and ionization state of a plasma. This technique requires characterization experiments, careful data calibration, and comparison with atomic models to understand the plasma parameters. We performed radiative ionized wave experiments at the OMEGA Laser Facility the used an ~80 eV x-ray source incident on an argon gas cell at 3 atm. For the diagnostic technique, we used capsule backlighter offset 10 mm from the gas cell, which was absorbed by the ionized agon gas. The absorption analysis is complicated by significant structure in the backlighter spectrum, which arises from the K-shell transitions in sulfur contaminant and higher order lines presented in the data. However, this structure offers independent energy fiducials the increase our confidence in the measured shift of the driven argon K-edge, which is shifted from the characteristic K-edge of argon by about 50 eV due to ionization. We compare the measured absorptions spectrum to two independent atomic models, PrismSPECT and SCRAM, and show that the observed K-edge shift is consistent with ionization to Ar IV, 3 times ionized, and temperatures of about 10 eV at 1.15 mm from the Au foil using a 5 ns drive. Ionization from the diagnostic source is unintended and we provide experimental modifications to mitigate this in future experiments.

*****This work is funded by the U.S. Department of Energy NNSA Center of Excellence under cooperative agreement number DE-NA0003869.

Optimization of Ge/Si Core/Shell Nanoparticles Properties Through Nonthermal Plasma Synthesis*

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Core/Shell nanoparticles (CSNPs) are a type of nanomaterial that consists of two components: a core and outer shell composed of distinct materials. CSNPs have received increasing attention over the past decade due to their tunable optical properties and wide applicability in the biomedicine, semiconductor and catalyst fields. Nonthermal plasma approaches for synthesis of CSNPs have limit agglomeration while enabling crystalline growth at low reactor temperatures. Prior works have shown the capability to synthesize germanium-silicon CSNPs using nonthermal plasmas[1,2]. Despite successes in synthesizing CSNPs, issues such as size uniformity, core and shell purity and dimension variation that occurs under diverse operation conditions may cause inconsistent CSNP performance.

There are only limited number of works that introduce strategies in controlling CSNP specifications when using nonthermal plasmas synthesis approaches. Thus, the aim of this work is to computationally investigate the consequences of operating parameters on the core/shell purity and thickness ratio of Si/Ge CSNPs using the Hybrid Plasma Equipment Model (HPEM) coupled with Dust Transport Simulation Module (DTS). The test system is an inductively coupled plasma (ICP) having two plasma sources intended to separate core and shell synthesis zones for better core/shell purity and dimension control. CSNPs are produced under operating conditions of a few Torr, 10 W of ICP power, with Ar/GeH_4 and Ar/SiH_4 gas mixtures flowing from the top and middle inlets. The effect of three main parameters - gas flow rate, inlet growth species fraction, and coil power - are varied and the corresponding impacts on CSNP properties will be discussed.

* Work supported by Army Research Office MURI Grant W911NF-18-1-0240 the National Science Foundation (PHY-2009219), and the Department of Energy Office of Fusion Energy Science (No.DE-SC0020232).

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[2] Hunter, Katharine I., et al. “Nonthermal Plasma Synthesis of Core/Shell Quantum Dots: Strained Ge/Si Nanocrystals.” ACS Applied Materials & Interfaces **9**, no. 9, Mar. 2017, pp. 8263–70. DOI.org (Crossref), https://doi.org/10.1021/acsami.6b16170.

Analyzing Spatial Growth Rate and Starting Current in Smith-Purcell Radiation using Single- and Two-Layer Grating Structures*

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Smith-Purcell radiation (SPR) is generated when electrons travel close to a metallic periodic grating [1]. For SPR from single-layer grating structure we demonstrated that the spatial growth rate of SPR calculated from the hot-tube dispersion relation has the same scaling with grating parameters as the starting current calculated from PIC simulations [2], [3]. The correlation between the starting current and growth rates was demonstrated for different beam energies. In this study we proposed two-layer gratings (Figure 1) to enhance SPR by improving electromagnetic coupling [4]. Utilizing PIC simulations, we demonstrate that two-layer gratings increase SPR growth rates and reduce the starting currents. By solving the hot-tube dispersion relation for the two-layer grating structure, we observe a consistent scaling relationship (Figure 2) between the starting current (from PIC) and growth rate (from the dispersion relation). Thus, we confirm that the grow rate calculation using hot-tube dispersion relation for single or two-layer grating can be used to predict the optimal grating parameters to minimize the starting current of SPR. Notably, this approach substantially reduces computational costs compared to direct PIC simulations. We anticipate that our dispersion relation methodology for grating optimization holds promise for the study of linear free-electron beam-based vacuum devices in various geometries, including cylindrical configurations.

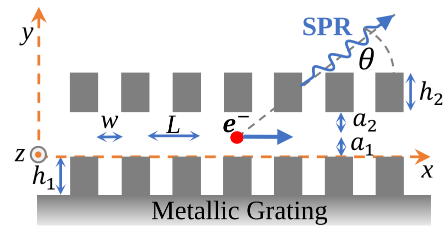

Figure 1 - Schematic of Smith-Purcell from two-layer grating and electron beam configuration.

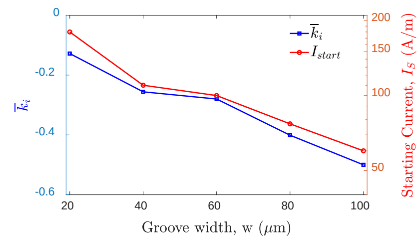

Figure 2 - Spatial growth rates and starting currents for various grating structures in a two-layer grating configuration with constant groove height ($h_1 = h_2 = 100\ \mu m$), period length ($L = 120\ \mu m$), and beam grating distance ($a_1 = a_2 = 10\ \mu m$) and beam energy of 50 keV.

* This work was supported by the Air Force Office of Scientific Research (AFOSR) YIP Grant No. FA9550-18-1-0061, the Office of Naval Research (ONR) YIP Grant No. N00014-20-1-2681, the Air Force Office of Scientific Research (AFOSR) Grant No. FA9550-20-1-0409, and Grant No. FA9550-22-1-0523.

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Calculating Ion Transport Coefficients in Warm Dense Matter*

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In warm dense matter and high energy density plasmas, the traditional Boltzmann description begins to break down. In this regime, collisions are not determined by binary Coulomb collisions, but instead by many body Coulomb collisions. The Mean Force Kinetic Theory (MFKT) [1] provides an alternate closure to the BBGKY hierarchy based on expanding about a perturbation from equilibrium rather than about strength of correlations. The MFKT produces the same fluid equations, with altered transport coefficients and equation of state (EOS), thus existing fluid codes would only need to update transport and EOS tables. A code is presented which solves for transport coefficients in the warm dense matter regime using a Chapman-Enskog expansion for the MFKT. These plasmas contain degenerate electrons, whose screening effect are modeled by the potential of mean force which is obtained using the Quantum Hyper Netted Chain Model (QHNC) [2]. Future work intends to develop a module to expand transport coefficients to an arbitrary order in the Chapman-Enskog expansion, and a model for electron transport properties.

* This material is based upon work supported by the US Department of Energy, National Nuclear Security Administration, under award No. DE-NA0003868.

References

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Chemical Vapor Deposition of Silicon Vacancy Ensembles in Low Strain Diamond with a NIRIM Type Reactor

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Diamond is a great platform for optically active defects for quantum information processing (QIP) applications, able to host hundreds of different color centers within its wide bandgap. It is transparent from infrared to ultraviolet wavelengths and growth with 12C-enriched methane allows for nuclear spin-free material, suppressing spin-spin interactions to improve coherence times. The silicon vacancy (SiV) color center in diamond has particularly favorable properties for broadband quantum memories based on off-resonant Raman transitions. The storage time of a quantum memory in a dense SiV ensemble is determined by its inhomogeneous broadening, and therefore the growth of high-quality material is needed. Diamond growth through chemical vapor deposition (CVD) will allow for the production of high quality SiV ensembles with high optical density to achieve state-of-the-art high bandwidth optical quantum memories. Growth of this material will be made possible through a NIRIM type diamond reactor, Diamond System 11 (DS11), currently in production. As opposed to the MSU type reactors, which feature bell jar reaction chamber, the NIRIM reactor utilizes a thin cylindrical quartz tube. The reduced volume of this chamber enables even lower vacuum pressures down to 10^{-9} mTorr, reducing contaminants between runs. Additionally, laminar flow through the reaction chamber allows for precise control over gas concentrations and improved purity leading to improved sample quality required for quantum memory applications. In this poster, I will introduce the properties of the SiV and the potential of in-situ silicon doping during CVD.

Filter Pack X-Ray Spectrum Reconstruction for Betatron Streaking Experiment*

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(b) Department of Electrical and Computer Engineering, University of Alberta
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(f) Helmholtz Institut Jena
(g) Deutsches Elektronen-Synchrotron DESY

For laser wakefield acceleration, single-shot diagnostic techniques are used to obtain the betatron X-ray spectrum. One method is the use of a filter pack in front of an X-ray camera which allows the calculation of the critical energy of a synchrotron-like spectrum.[1] The pack is made of strips, each with varying thicknesses of aluminum and copper with different mass attenuation coefficients.

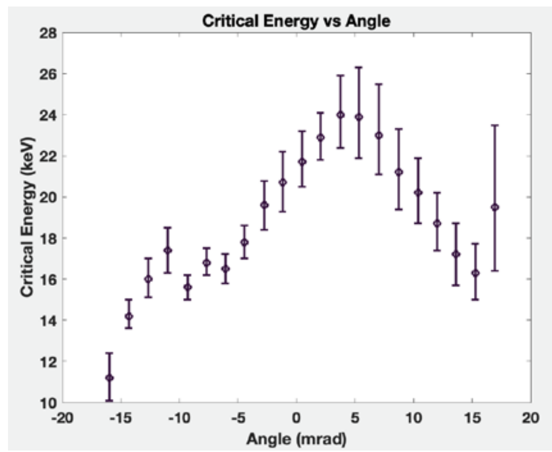

Figure 1 – Critical energy vs angle plot that shows the change in energy as the betatron X-rays streak across the camera, following the wakefield trajectory.

To recover the spectrum, the spatial intensity profile is normalized by taking the background from the empty spaces between the strips and interpolating to recover the profile. This is used to flatten the background intensity. A critical energy is guessed, and transmission data is calculated to be compared with the actual values. The guess is adjusted to minimize the sum of the squares of the residuals between the real and calculated values, and this final value is taken to be the true critical energy.[2]

This method can be applied to betatron streaking experiments, where the wakefield follows a curved trajectory as it travels through a transverse density gradient.[3] Emitted betatron X-rays "streak" across the camera, so the spectrum can be retrieved as the emission angle changes, representing the evolution of the critical energy with time.

* Work supported by DOE Office of Science, Fusion Energy Sciences under Contract No. DE-SC0021246: the LaserNetUS initiative at Advanced Laser Light Source; DOE grant DE-SC0022109; NSF grant 2108075; and DOE grant DE-SC0020237.

References

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[3] Y. Ma *et. al.*, Phys. Plasmas **25**, 113105 (2018).

Data Driven Observations of System Equilibration

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(c) Computational Mathematics, Science and Engineering, Michigan State University, East Lansing, Michigan 48824, USA

Radiation-hydrodynamic codes are the computational workhorse for high energy density (HED) experimental design. In certain inertial confinement fusion (ICF) experiments, the ion mean free path is too long for the system to be sufficiently described by thehydrodynamic equations [1]. To address this difficulty, extended moment hydrodynamic models are employed [2]. Interestingly, the additional moments include dissipative processes that return the system to equilibrium where radiation-hydrodynamic codes are sufficient. An obvious reduced order model is one that reduces the extended moments to their Chapman-Enskog closures (*i.e.* $q = -\frac{5}{2}\partial_x T$) as the system equilibrates. To do this well, the reduced order model must identify when the fewer moments will suffice. In this study, we use data driven techniques to observe Grad's 13 moment hydrodynamic equations reduce to an effective 5 moment (*i.e.* Navier-Stokes) description [3].

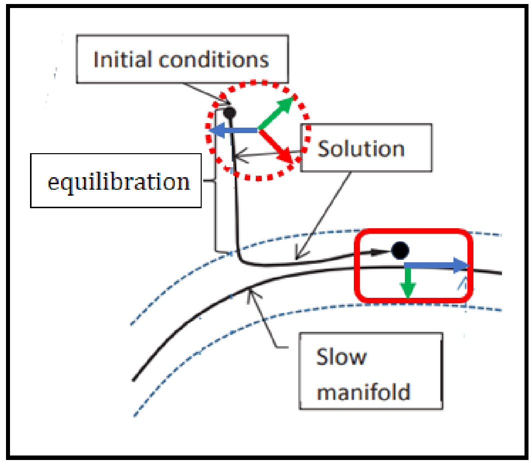

Figure 1 – Image altered from [3]
Visualization of an ensemble of simulations equilibrating to the system's slow manifold.

Our computational tools come from the emerging field of data driven dynamical systems. Modern algorithms, rooted in the Koopman operator framework, have emerged which can represent complex nonlinear dynamics using an infinite-dimensional linear operator. In this study, we employ dynamic mode decomposition (DMD) to observe our dynamical system equilibrate to its slow manifold. [4]. Moreover, we supplement our DMD findings by using dimension reduction techniques to observe equilibration in an ensemble of simulations; this offers a clear visualization of the equilibration process.

* Work supported by Lawrence Livermore National Laboratory

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A Novel Reduction-Based Scheme for In-Situ Solar Wind Origin Classification using Machine Learning

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(b) Baylor University (Henry_Han@baylor.edu)

Determining how in-situ solar wind differs will aid in understanding the physical processes at the coronal features from which they originate. Here, a solar wind origin classification scheme is presented, employing statistical methods alongside a novel machine learning approach where dimensionality reduction algorithms (Principal Component Analysis (PCA) and t-Distributed Stochastic Neighbor Embedding (t-SNE)) are used in conjunction with one another, and clusters are determined using Density Based Clustering and Noise (DBSCAN). The input data is in the form of permutations of parameters from missions such as Advanced Composition Explorer (ACE), Ulysses, WIND and STEREO. Such data includes in-situ plasma parameters (speed, density, temperature, entropy, etc.), as well as elemental composition, and derived quantities such as cross helicity and residual energy. As a result, a multi-category wind classification scheme is constructed, and it is shown that in-situ solar wind can be characterized into distinct, physically meaningful groups using this reduction combination and clustering technique. With the cluster identities, a comparison is made to the source regions via a backmapping technique: the samples are ballistically mapped to (an array of) the source surface point(s), and a Potential Field Source Surface (PFSS) model is used to locate the data to the photosphere. Uncertainties with this approach are discussed. With the resolved zones for the footpoints, remote sensing data is used to analyze the thermal conditions and electron density of the source location (via full disk images from Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) and Extreme ultraviolet Imaging Telescope (EIT)). The outcome of this test for the agreement of each cluster to common properties of the source regions is then presented. The commonalities found between the source region and the in-situ samples are then discussed. Sources and controls for instances of subjectivity are discussed, as well as implications moving forward. The conclusion of this is that the customized approach can be further improved upon and adapted to availability of new data, alongside the scenarios to which the categorization scheme can be applied to.

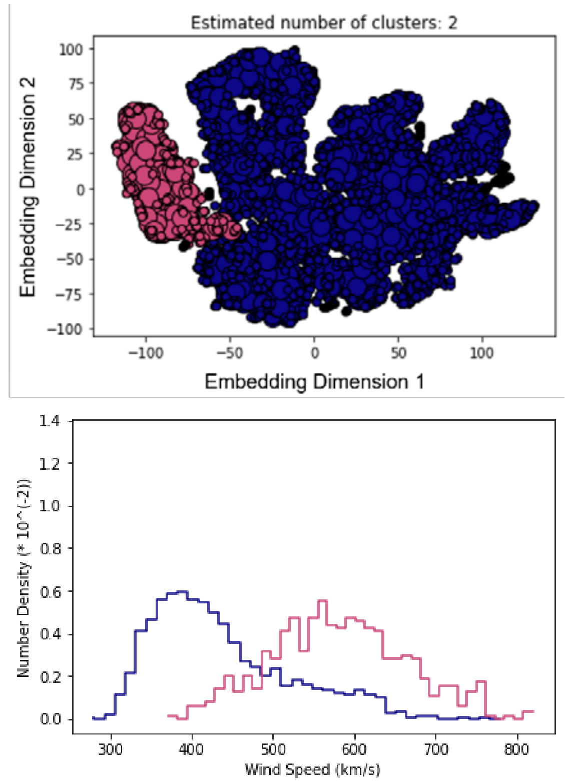

Figure 1 – Example of a trial using PCA+TSNE on in-situ solar wind data, which appears to separate into fast and slow regimes.

Optimal Experimental Design for Calibrating Anomalous Transport Models*

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Hall Effect thrusters are an axisymmetric electric propulsion device that utilize an electric and magnetic field to create a plasma and produce thrust. They have the potential to be applicable to deep space missions but are hindered by the current inability of ground testing facilities to demonstrate on-orbit behaviors of this technology. Simply, state of the art ground testing facilities cannot simulate the deep space environment. Thus, predictive engineering models are being developed to determine on-orbit thruster performance. Unfortunately, these models are not fully predictive due to the limited understanding of anomalous electron transport which impacts ion velocity within the thruster channel. As solution to this problem researchers have incorporated various data-driven models of anomalous transport to Hall thruster simulations that are calibrated to ion velocity profiles.[1] This method has been proven successful, but the diagnostic for collecting the dataset for model calibration can be difficult to obtain. This diagnostic is known as Laser Induced Fluorescence (LIF).[2] In which, ions are excited via a laser and quickly relax emitting photons that can be collected by an optic. The ion velocity distribution can be measured and determined via the Doppler effect at different positions in the thruster channel.

This form of diagnostic is non-invasive but can be very expensive to obtain during thruster operation due to issues like thermal effects. The purpose of this work is to apply an Optimal Experimental Design algorithm to determine a set of positions along the thruster channel to measure and calibrate anomalous transport models with.[3] This dataset is of a reduced size when compared to traditional LIF experiment datasets but produce the same model calibration and predictions.[4] This is conducted by calculating an Expected Information Gain for each possible position and selecting positions where the potential for information gain is highest. By using different anomalous transport models, the optimal design is compared between each model and positions are selected by the predicted information gain across a set of available models. The effect of each model is demonstrated on the change in ion velocity predictions.

* Work supported by a NASA Space Technology Graduate Research Opportunity Grant and JANUS, a NASA research institute

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Measuring Coulomb Explosion Ions from OMEGA EP Interactions*

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Direct laser acceleration (DLA) can generate electron beams with high charge to produce secondary radiation sources. Experiments at the OMEGA EP laser facility were designed to optimize the direct laser acceleration of electrons in an underdense plasma created from a helium gas target. In these experiments, the ponderomotive force expels electrons from the regions of highest laser intensity to form a channel. The charge separation creates a strong transverse electric field that accelerates ions radially through a Coulomb explosion; it is the same radial channel field, along with the electron beam-generated azimuthal magnetic field, that facilitates DLA. Since the channel formation is key to understanding electron acceleration, the accelerated helium ions, measured with a Thomson Parabola Ion Energy (TPIE) spectrometer, provide an interesting complementary measurement for understanding the field strengths inside the channel.

* This work is supported by the Department of Energy / NNSA under Award Number DE-NA0004030. The experiment was conducted at the Omega Laser Facility at the University of Rochester's Laboratory for Laser Energetics with the beam time through the National Laser Users' Facility (NLUF) Program supported by DOE/NNSA.

Beam Density Modulation During Emission Using RF and Laser Fields *

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Free-electron beam-based devices, such as traveling wave tubes (TWTs), free-electron lasers (FELs), and klystrons, utilize the collective interaction of an electron beam with a circuit structure (e.g., either periodic structure or cavity) by beam modulation to convert electron beam energy into electromagnetic radiation. Beam modulation can be achieved by either modulating the velocities of the electrons (velocity modulation) or by controlling the electron emission from the cathode (density modulation). Currently, TWTs mainly rely on the velocity modulation of the electron beam for power amplification. If we can produce an electron beam that direct density modulation can be achieved during its emission, the performance of TWTs can be significantly reinforced.

In this study [1], we explore the temporal profile of pre-bunched electron beams during the emission from a radio frequency (RF) cold cathode under the excitation of an RF field and an optical field (continuous-wave (CW) or pulsed), using an exact quantum model for photo-/field- emission [2-4]. The profile of the produced emission current can be modulated by varying RF field (amplitude and frequency) and optical field (laser wavelength, laser intensity, pulse length) (Fig. 1). Electron emission properties, such as peak current density, current pulse width, the harmonic contents of the current pulse, and electron numbers per RF cycle, are comprehensively analyzed.

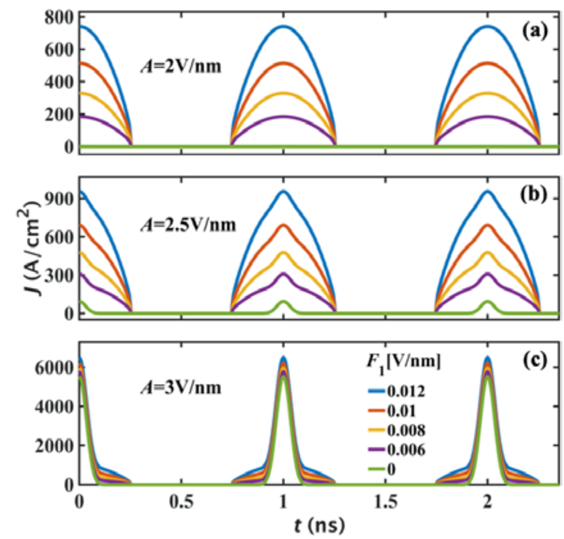

Figure 1 - Emission current density J varies with time t in 2.5 cycles under various CW laser fields with the RF amplitude A = 2, 2.5, and 3 V/nm, respectively [1]. The cathode is assumed to be gold, with nominal work function W_0 = 5.1 eV and Fermi energy E_F = 5.53 eV. The laser wavelength is 200 nm, and the RF field has a frequency of 1 GHz.

* Work supported by ONR YIP Grant No. N00014-20-1-2681, and AFOSR Grant Nos. FA9550-20-1-0409 and FA9550-22-1-0523.

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TFIPS – A Compact, Low-power Heavy Ion Spectrometer for Space Environments

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Heavy ions provide vital signatures that explain the physical processes taking place in the diverse plasmas of space environments. Measurement of particle mass provides compositional information of plasmas whereas charge state unmasks the physical origins that produce the ions. This translates to solutions to critical science questions anywhere in situ heavy ion detections can be made. For example, it is still unknown which physical processes generate the supersonic outflow of the solar wind from the Sun into the Heliosphere. Likewise, the rapid expulsion of plasma during Coronal Mass Ejections (CMEs) produces heated – high charge-state – plasma concurrent with shock accelerated ions and cold filamentary material that interacts with the ambient solar wind. Similarly, in diverse planetary magnetospheres plasma source identification, transport, and energization must be studied to define and quantify a variety of phenomena e.g., global convection patterns, auroral footpoints, solar wind-magnetosphere coupling, and the ionization of neutral matter such as rings, atmospheres, and moon surfaces via interactions with radiation or plasma. To measure the heavy ions of these environments we are developing a low mass, compact, power-efficient time-of-flight (TOF) mass spectrometer called TFIPS or the Triple Fast-Imaging Plasma Spectrometer. The TFIPS instrument concept utilizes heritage design from the FIPS instrument that flew onboard the MESSENGER mission around Mercury for four years. Modifications have been made to include energy detection for triple-coincidence measurements that provide ion species, charge-state, and 3-D velocity distribution between 0.5 – 25 keV/e. We simulate instrument performance using COMSOL Multiphysics to trace the ion optical path through the electrostatic analyzer and time-of-flight chamber. Finally, we are using the state-of-the-art calibration facilities in the Space Physics Research Laboratory and the Solar and Heliospheric Group's Plasma Instrumentation Lab to protype and calibrate the new time-of-flight chamber.

Design of Halfraums for X-ray Flow Experiments on the NIF*

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We present a computational study to design and characterize halfraums for the XFLOWS x-ray flow experiments on the NIF. The propagation of radiative heat fronts in HED experiments has long been a challenging topic to study. Experimental efforts in the past three decades have had success creating relevant data in this regime. However, it has been a challenge for multi-physics simulation tools to accurately and unconditionally predict the behavior of these experiments, a task which is essential to furthering our understanding of Inertial Confinement Fusion and astrophysical processes. The COAX campaign introduced a novel spectroscopic diagnostic to study radiation flows on Omega-60 by measuring temperature and charge state across the heat front [1,2,3]. XFLOWS is the successor to COAX and is fielded at NIF to access higher temperature regimes with stronger shocks and supersonic flows [4]. There is a need to design and characterize the halfraums that are used to drive these radiative heat waves to access the desired hydrodynamic and radiative regimes. Only by accurately characterizing the driving radiation field from the halfraum can we make substantive, quantitative predictions of the resulting flow of energy through the foam.

* This work was supported by Los Alamos National Laboratory, which is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy under Contract No. 89233218CNA000001. And by the U.S. Department of Energy NNSA Center of Excellence under cooperative agreement number DE-NA0003869.

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Statistic Analysis of Nanoscale Tunneling Electrical Contacts Based on Transmission Line Model*

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This study investigates the influence of contact resistances between carbon nanotubes (CNTs) on electron transport and electrical conductivity of carbon nanofibers (CNFs), which profoundly impacts the performance of CNT thin film field effect transistors (FETs)[1]. Utilizing a self-consistent contact model, we integrate a transmission line model with tunneling current [2] to calculate the plethora of parallel CNT-CNT contacts within a CNF fiber. A statistical analysis is conducted, using Gaussian distributions to account for variations in contact lengths, gap distances, and single CNT aspect ratios, to calculate the CNT-CNT contact resistance and the overall resistance of CNT fiber. By scaling our model to a macroscopic level, our results are in good alignment with experimental measurements [3]. Our calculation suggests that while increasing overlap length diminishes individual CNT-CNT contact resistance, it paradoxically increases macroscopic CNT fiber resistance, given a constant CNF mass density. Similarly, greater gap distance also increases both individual and fiber resistance. This research provides a tool for exploring CNT fiber electrical properties, promoting advancement in low-dimensional material-based electronic circuit development.

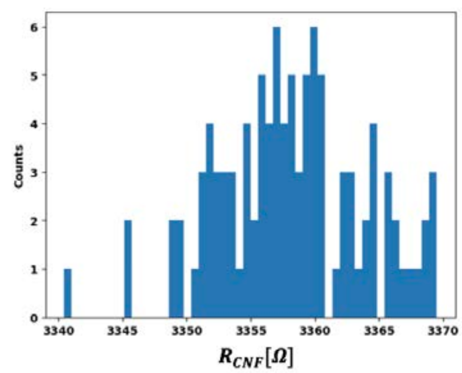

Figure 1. The calculated distribution of the CNT fiber resistance R_{CNF} for a sample size of 100. The mean value of contact length $\mu(L_c)$ =90 nm, CNT-CNT gap distance $\mu(D) = 0.7 nm$ and length of individual CNT $\mu(l) = 400\ nm$. The standard deviations are $\sigma((L_c)$ = 10 nm, $\sigma(D)$ = 0.05 nm, $\sigma(l)$ = 50 nm, $\sigma((l)$ = 50 nm. We consider the mass density of single CNT is $\rho_{mCNT} = 1.3 \frac{g}{cm^3}$, the mass density of CNT fiber is $\rho_{mCNF} = 1.7 \frac{g}{cm^3}$.

* Work is supported by the Air Force Office of Scientific Research (AFOSR) Award No. FA9550-22-1-0523

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Demonstrating ThunderBoltz: An Open-Source 0D DSMC Boltzmann Solver for Plasma Transport and Chemical Kinetics

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Large-scale 3D plasma codes involve a complex assembly of procedures that are not always necessary to test effects of underlying physical models. Here we present ThunderBoltz, a lightweight, publicly available 0D Direct Simulation Monte Carlo (DSMC) code designed to accommodate a generalized combination of species and arbitrary cross sections without the overhead of expensive field solves. It can efficiently produce high-quality electron velocity distributions in applied AC/DC E-field and static B-field scenarios. The code is built in the C++ standard library and includes a convenient Python interface which allows for input file generation from the LXCat data base, electron transport and reaction rate post processing, input parameter constraint satisfaction, calculation scheduling, and diagnostic plotting.

In this work we compare ThunderBoltz transport calculations against Bolsig+ calculations, benchmark test problems, and swarm experiment data, finding good agreement with all three in the appropriate field regimes. In addition to this, we present example use cases where the electron, ion, and background neutral particle species are self consistently evolved providing an ability to model the background kinetics, a feature that is absent in fixed background Monte Carlo and n-term Boltzmann solvers.

Impact of Magnetic Field Profile on Loss Mechanisms in a Rotating Magnetic Field 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]

In recent work, we have shown poor performance for the RMF thruster (<1%), substantiated by plasma probing which suggest that a major loss mechanism is electron thermal losses to the walls[3]. Indeed, subsequent inductive probe measurements show the FRC separatrix to intersect the walls of the device. In this study we parametrically vary the strength and shape of the applied magnetic bias field, in turn changing the shape of the FRC separatrix during device operation. At each operating condition, we measure the efficiency breakdown of the device including assessment of loss mechanisms such as electron wall losses. While we find that moving the separatrix radius inside the walls does reduce wall losses, these improvements to performance can be balanced out for certain field shapes by increased excitation radiative losses owing to increased plasma density close to centerline and by increased divergence losses.

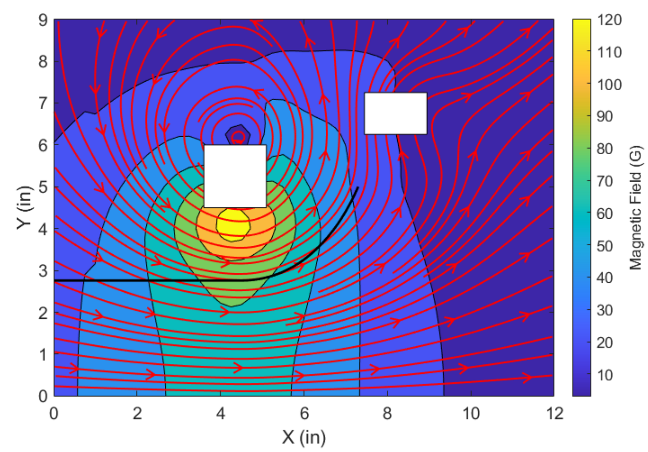

Figure 1 – Magnetic bias field streamlines overlaid on a side profile of the thruster body to illustrate minimal Bfield/wall intersection

*Work supported by NSTGRO Grant # 80NSSC20K1168.

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Chemical Composition of a Power-Efficient Evanescent-Mode Plasma Jet

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Cold atmospheric plasmas have gained much attention due to their ability to produce different reactive species. These chemicals can be easily accessed and used noninvasively in various biochemical applications, from the inactivation of microbacterial organisms to different types of cancer cell treatment [1]. Despite a broad spectrum of reactive oxygen and nitrogen species (RONS) generation, the lifetime of these RONS is very short in the gaseous phase, reducing their practical efficacy. However, the potency can be increased by activating a liquid medium through plasma, also known as plasma-activated liquid (PAL). RONS in PAL have a much larger lifetime, making this technique a versatile tool for a wide range of applications such as food processing, wound healing, water purification, etc.

H_2O_2, NO_2, and NO_3 are the most common long-lived reactive species found in PAL. Hence, this work focuses on these three reactive species. An evanescent mode (EVA) microwave plasma jet device [2] is chosen to generate and tune RONS composition in PAL. At first, in a Helium (He−99.8%) + oxygen (O_2 −0.2%) plasma jet, the RONS tunability was studied at two different gas flow rates in two different purified water. Later on, in Argon (Ar−99.8%)+ O_2(0.2%) plasma jet, the effect of treatment distance is studied at two different powers in deionized water. The device generates energy-efficient NO_2, and NO_3 concentration, showing its potential in agricultural applications.

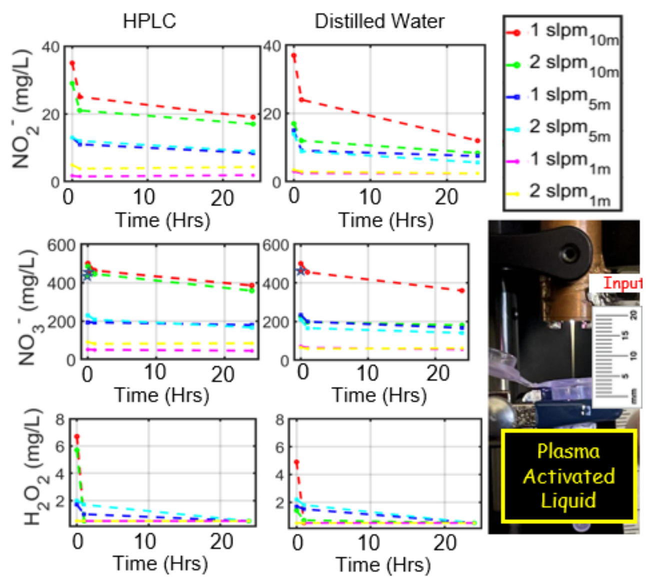

Figure 1 – RONS composition tuning measured right after treatment, 1 hr after treatment and 24 hrs after treatment in plasma activated liquids through an EVA-plasma jet at 10 W input power.

* Work supported by the National Science Foundation under Grant number ECCS-2102100.

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An Investigation of the Effects of Low Methane Concentrations on Microwave Plasma Assisted Chemical Vapor Deposition of Single Crystal Diamond

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Previous work on the chemical vapor deposition (CVD) of single crystal diamond demonstrated the operation of a high power density and high pressure microwave plasma assisted chemical vapor deposition (MPACVD) reactor and studied operation conditions such as pressure, substrate temperature, and methane (CH_4) composition [1]. Because this reactor was designed to increase growth rate, higher gas phase methane concentrations were explored, from 3 percent to 9 percent. However, the effects of methane concentrations below 3 percent on single crystal diamond growth quality were not explored.

Here, low methane concentrations, 3 percent and below, in the gas phase were studied. Three (100) CVD diamond substrates (MTI) were used for three depositions at various low methane percentages. All depositions were performed at 320 mbar (240 torr), 2000-2100 W, and a total gas flow rate of 400 SCCM. The methane percentages used were 3 percent, 2 percent, and 1 percent of the total gas phase gas composition. Each sample was characterized using differential interference contrast microscopy (DICM), birefringence imaging, Fourier Transform Infrared (FTIR) spectroscopy, ultra-violet and visible spectroscopy (UV-Vis), and Raman spectroscopy to determine the quality of the growth. Vertical growth rate was determined by thickness measurements taken before and after deposition on a linear encoder.

Preliminary results show, as methane concentration in the gas phase decreased, growth rate decreased. All samples exhibited step flow growth, indicative of good quality growth. Spectroscopic results showed high purity.

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Non-thermal Plasma Synthesis of Indium Nitride

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Nanomaterials have paved their way deep into our daily lives from electronics, energy storage, sensors to medicine, agriculture, cosmetics etc. For plasma synthesis of nanomaterials, the synthesis parameters play an important role in determining the final properties of the material like size, shape, crystallinity and purity. For the present study, we explore the effects of changing reactor parameters on the final material synthesized. For oxidation prone materials like indium, it is much easier for oxygen to displace nitrogen from the lattice structure and hence synthesis conditions are to be chosen wisely. By tuning of power and flowrates we showed there is a shift from white indium oxide nanocrystals to black indium nitride. Furthermore, attempts have also been made to put in gallium precursor in the reactor to get an alloy of group 3 nitrides. This opens up new paths in understanding the plasma reaction chemistry during synthesis.end of the text.

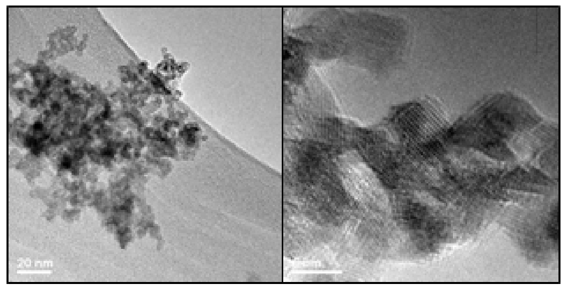

Figure 1 – TEM images of synthesized Indium Nitride nanomaterials

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Performance Characterization of a Magnetically-Shielded Hall Thruster Operating on Molecular Propellants*

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The efficient operation of Hall thrusters on molecular gases could enable air-breathing electric propulsion for both Earth and Mars. Historically, however, Hall thruster performance on these propellants has been low (~20%) [1] when compared with xenon (>50%). [2] Previous poor performance has largely been attributed to low mass utilization efficiency, or fraction of input propellant converted to ions. In this work, we operated a 9 kW magnetically shielded Hall thruster at up to 10 times nominal current density on nitrogen, carbon dioxide, and dry air. Argon was used for the centrally mounted cathode to avoid poisoning. We used an inverted pendulum thrust stand to measure performance, and an oscilloscope to monitor thruster stability. We found that the thruster efficiency monotonically increased on all propellants with increasing discharge current. Indeed, at 150 A, the efficiency was >40% for all gasses. We attribute this increase in efficiency largely due to an increase in mass utilization. Furthermore, from discharge oscillation measurements, we saw the stability of the thruster improve as discharge current increased. These results corroborate the findings of Su et. al. that high current densities improve performance on harder to ionize gases than xenon. [2] Ultimately, this work demonstrates that even with a thruster not optimized for molecular propellants, the performance of Hall thrusters may be competitive for air-breathing propulsion architectures.
*This work was supported by the Joint Advanced Propulsion Institute, a NASA Space Technology Research Institute, and a NASA Space Technology Graduate Research Opportunity (Grant 80NSSC23K1187)

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Propagation of Texas Petawatt Laser Through High Density Gas Jet Targets *

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We report on a recent experimental campaign investigating the propagation of the Texas Petawatt laser through high density (~ 10^19 /cm^3) gas jet targets of hydrogen and deuterium in the direct laser acceleration (DLA) regime. Nominal laser parameters are 140 J delivered in 140 fs pulses. Primary objectives of this campaign included investigation of laser propagation instabilities, ion dynamics, electromagnetic pulse production, shock wave generation, plasma heating, optical observation of ion filamentation, and the effects of apodizing the laser beam. Various sizes and geometries of apertures were employed in the laser near field to improve the spatial quality of the laser on target. Diagnostics used included neutron time of flight detectors, an electron spectrometer, radiochromic film, optical probing (shadowgraphy, schlieren, interferometry), bubble detectors, NaI gamma detectors, and electromagnetic pulse detectors. Initial data analysis indicates the existence of an annular electron beam with a divergence of a few degrees surrounding the on axis electron beam. The structure and quality of this annular beam is correlated to the type of aperture used.

*Funded by DOE LaserNetUS, experiment associated with proposal K189.

Accelerating Low-temperature Processing of Printed Nanoinks Using Machine Learning and Bayesian Optimization of Non-thermal Plasma Jet Sintering *

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Flexible devices, known for their stretchability, transparency, and biocompatibility, have found extensive applications in wearable technology, sensors, touch screens, and related fields. One method employed in producing flexible devices involves applying inks containing nanomaterials using techniques like ink-jet printing and screen printing. After deposition, it becomes necessary to sinter these films to create a uniform layer of the underlying nanomaterial. However, traditional sintering processes require high temperatures, which pose challenges for heat-resistant materials, especially in the context of flexible devices. Non-thermal plasma jet sintering has emerged as a promising solution to tackle this issue. This cost-effective and low-temperature technique utilizes a dielectric barrier discharge (DBD) plasma jet system operating at room temperature and standard pressure. It allows for sintering nanoink thin films without causing harm to the substrate or the film surface. Previous studies have successfully employed this method to enhance the electrical conductivity of silver nanoparticle thin films while maintaining a substrate temperature below 50°C. Our current research aims to optimize the electrical conductivity of indium tin oxide (ITO) thin films while maintaining strict control over the substrate temperature. We have adopted a machine-learning approach called Bayesian optimization to achieve this optimization. This approach helps us identify the ideal settings for critical input parameters, including jet flow rate, applied voltage, input frequency, gap distance, number of cycles, pulse-on time, and pulse-off time. To assess the overall performance of non-thermal plasma jet sintering, we will make a comparison with traditional thermal sintering using identically manufactured ITO films as a benchmark.

* Work supported by the United States Department of Energy.

The Effect of Space Charge on the Performance of Linear Beam Device for High Frequency Radio Waves

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Electron beam-wave interaction is essential for particle acceleration, radiation generation, microwave and mm wave communications, and fusion research. In this work, a high-efficiency RF power amplifier based on inductive output tube (IOT) is used to conduct a comprehensive parametric analysis of beam cavity interaction, considering both small and large signals [1]. To achieve high conversion efficiency, it is important to minimize the potential beam energy [2]. To improve the reliability and efficiency of electron beam systems, we study space charge effects in large signal analysis for beam dynamics, including energy dissipation, alterations in synchronous phase and frequency [3].

The DC and RF currents are investigated for different grid and anode potentials. We study the device parameters, including the beam filling factor and disk thickness of IOT for large signals to analyze the variation in space charge fields and normalized velocity change (Fig. 1). The ratio of stored potential energy to the total beam energy is decreased for maximum conversion efficiency by reducing the beam perveance and increasing the beam filling factor. We compare the disk model with and without space charge to the experimental results, to examine the RF output power, efficiency, gain (dB), and kinetic energy [1,4].

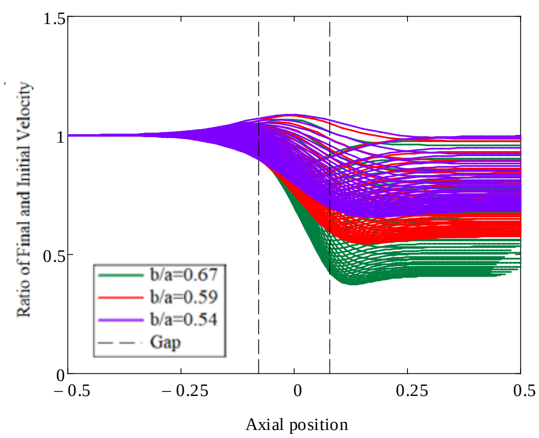

Figure 1 - Normalized electron velocities with axial position for different beam filling factor (b/a) due to space charge, DC grid voltage =-105V, Anode Voltage = 25kV, RF grid voltage = 300V, Input power = 208W, Output power = 11.6kW.

* This work is supported by the Office of Naval Research (ONR) YIP Grant No. N00014-20-1-2681, and Air Force Office of Scientific Research (AFOSR) Grant No. FA9550-20-1-0409, and the Air Force Office of Scientific Research (AFOSR) Award No. FA9550-22-1-0523.

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Bayesian Inference for Calibration of Anomalous Electron Transport in Multi-Fluid Hall Thruster Models

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The current lack of first principles understanding of anomalous electron transport in Hall thrusters has prevented development of a self-consistent closure of the anomalous collision frequency that would enable fully predictive models of thruster operation. In lieu of a closure, the state-of-the-art method is to represent anomalous electron transport using a static but spatially varying profile along the channel centerline of the thruster. An example profile of a Bohm like model, where the anomalous collision frequency is equal to the electron cyclotron frequency multiplied by a coefficient, is shown in Figure 1.

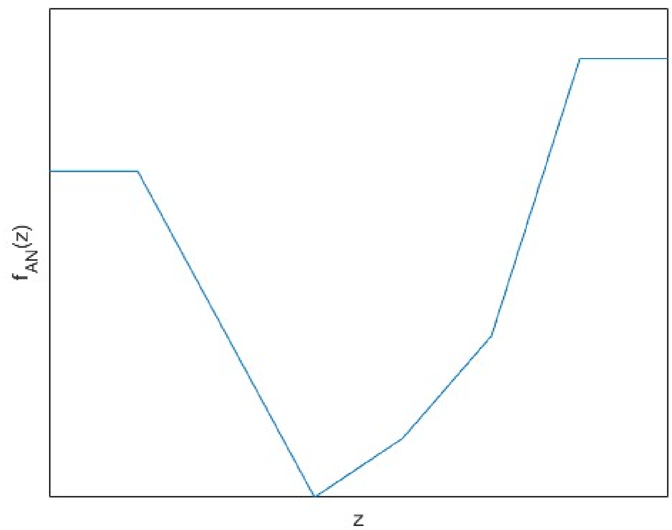

Figure 1 – Example of Anomalous Electron Transport Profile
z is axial position and f_{AN} is the coefficient in Bohm-like model

This profile is typically shaped by hand using user experience and intuition until thruster performance metrics like thruster discharge current, thrust, and ion velocity profile from the model match their experimental values. In this work, we apply a Bayesian inference algorithm to rigorously shape a Bohm-like anomalous electron transport profile and quantify the uncertainty in our confidence of model performance metrics. The algorithm is demonstrated on a multi-fluid code using an experimental dataset from the H9, a 9kW class magnetically-shielded Hall thruster. Extensibility of the calibration algorithm between different operating conditions is investigated.

* This work was supported by the Graduate Research Fellowship Program from the National Science Foundation. This research was supported in part through computational resources and services provided by Advanced Research Computing, a division of Information and Technology Services at the University of Michigan, Ann Arbor.

Low Bias Frequencies for High Aspect Ratio Plasma Etching*

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Semiconductor processing employs inductively plasmas (ICPs) with large substrate biases to fabricate features with high aspect ratios (HAR) for the production of high-density memory. To maintain critical dimensions of these HAR structures, ion energy and angular distributions (IEADs) must have increasingly high energies and narrow angular distributions. To achieve these goals, substrate biases with progressively lower frequencies can reduce these distributions. Since lower frequencies are not efficient at heating electrons and plasma production, these systems are typically ICPs where the wave heating sustains the plasma. The trend towards lower frequencies is intended to extend the maximum ion energy to fully that of the sum of the RF amplitude and DC bias, while narrowing the IAD. However, these lower frequencies also produce nearly quasi-steady state conditions, which affects sheath thickness and flux uniformity, and charging of adjacent surfaces.

In this work, results from a computational investigation of ICPs using very low bias frequencies will be discussed. The simulations, conducted with the Hybrid Plasma Equipment Model (HPEM), investigated a single test system – an ICP sustained in $Ar/Cl_2/O_2$. IEADs and sheath structure across the substrate for bias frequencies as low as 250 kHz will be discussed.

* Work was supported by Samsung Electronics Co. and the US National Science Foundation (2009219).

Instability-enhanced Friction in Multi-ion Species Plasmas

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Kinetic instabilities fulfill an important role in transport processes in low-temperature plasmas. In the case of multi-ion species plasmas, linear dielectric response theory predicts how ion-streaming instabilities could occur and thus increase the friction between ion species through wave-particle scattering [1]. The stability of the plasma has been found to depend on the ion concentrations, electron-ion temperature ratios, flow difference, and mass ratios. This was studied under the context of sheaths, whereby the flow difference between ion species is created through the presheath's electric field. The instability-enhanced friction causes individual sound speeds to merge toward a system sound speed and dictates the plasma flux to the boundaries. The friction force can be calculated by taking the momentum moment of an instability-enhanced collision operator and then comparing it with PIC simulations. Moving forward, the presence of a magnetic field will be integrated into a PIC model to investigate how the instabilities and transport are affected and whether the dielectric function should be modified to account for such effects.

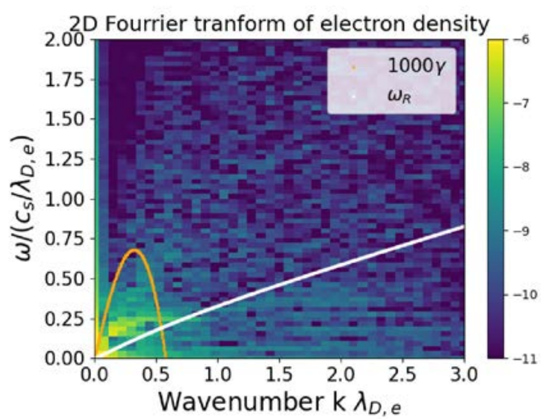

Figure 1 - The FFT of the steady-state electron density data suggests that the linear theory correctly predicts the range of unstable wavenumbers with limited dispersión and a bright spot that matches the wavenumber corresponding to the largest growth rate.

* This research is supported by the U.S. Department of Energy Isotope Program, managed by the Office of Science for Isotope R&D and Production.

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Atmospheric Pressure Plasma Jet in Treatment of Polypropylene Uneven Surfaces*

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Atmospheric Pressure Plasmas (APPs) are commonly used to treat polymers [1]. The most famous examples are commercial packaging and biocompatible polymers. Treatment of polymers primarily provides permanent or temporal changes in the physical properties of surfaces. Adding functional groups (commonly oxygen) alters surface energy, making hydrophobic polymers hydrophilic. Hydrophilicity makes polymers suitable for painting and biocompatibility. Another effect of plasma treatment in polymers is cross-linking. Cross-linking can also affect some physical properties of polymers, such as resistance to temperatures and UV light. Source of plasma, gas composition and surface type can significantly alter the dominant events on the surface as a result of treatment. In this work, an atmospheric pressure plasma jet (APPJ) in contact with an uneven polypropylene surface is investigated in a computational study.

The model that was used in this paper is *nonPDPSIM* [2]. This computational complex is developed to solve sets of plasma and hydrodynamics equations on unstructured mesh. Core equations include Navier-Stockes, Poisson's, continuity and Boltzmann's equations. Gas phase chemistry is implemented with a complex plasma-chemistry mechanism. Surface chemistry is solved using a surface-kinetic model. It is identified that in APPJ with He used as feeding gas, air fluxes to polymer surfaces are limited due to gas composition. As a result, functionalization with oxygen has a minor effect during treatment (Fig. 1). However, the primary effect on the surface composition is provided with photons and ion fluxes (cross-link products and chain scission).

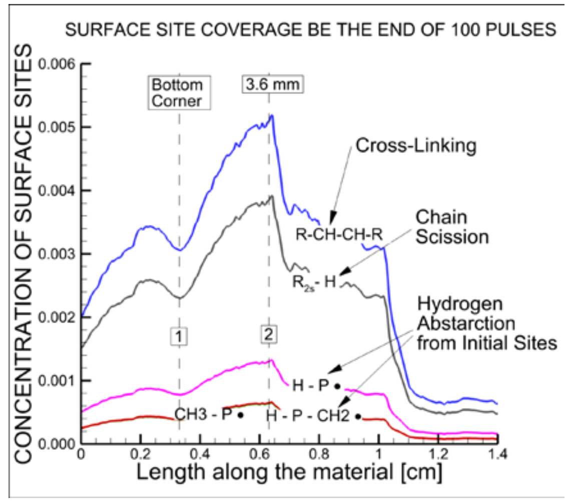

Figure 1 – The concentration of surface chemicals formed due to plasma treatment of uneven polypropylene surface.

* Work supported by the National Science Foundation (PHY-1902878) and the Department of Energy Fusion Energy Sciences (DE-SC0020232), and the ARO MURI Program (W911NF-20-1-0105).

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A Power-Efficient Plasma Line Based on Extended EVA Cavity Technology*

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Atmospheric pressure plasma jets (APPJ) have been a point of attraction, with promising characteristics such as low process temperature and no need for a vacuum system. Thus far, various medical, material processing and surface treatment applications have been explored. An additional attractive feature is to extend the process area of such APPJ to achieve a large throughput. Many configurations have been studied mainly by arraying small plasma jets. However, such plasma jets are power-hungry and have plasma jet-to-jet coupling [1]. To address these challenges, extended microwave resonators can be employed to achieve gas breakdown and a plasma line by utilizing their ability to focus and store microwave power. In our previous work, an evanescent-mode (EVA) cavity resonator-based plasma jet has been reported with power efficiency exceeding 80% and electron density in the range of 10^{15} (cm^{-3}) [2].

This work explores an extended version of the EVA cavity resonator to achieve a power-efficient plasma line. The resonator structure has been designed to resonate at the standard frequency of 2.45 GHz, and a uniform |E|-field of the order of 10^5 V/m has been achieved when the structure was subjected to an input microwave power of 1 Watt, simulated by COMSOL Multiphysics. A uniform and consistent flow line has been carefully designed by channeling a large inflow of gas into multiple smaller outflows, and a uniform outflow has been achieved by utilizing optimization techniques. For precise fabrication of the structure, CNC machining has been employed. Experiments have been performed using the helium gas at flow rates ranging from 1 to 7 slpm and input power levels ranging from 1 to 20 Watts. These experimental parameters provide a comprehensive understanding of the performance and behavior of the resonant microwave plasma line.

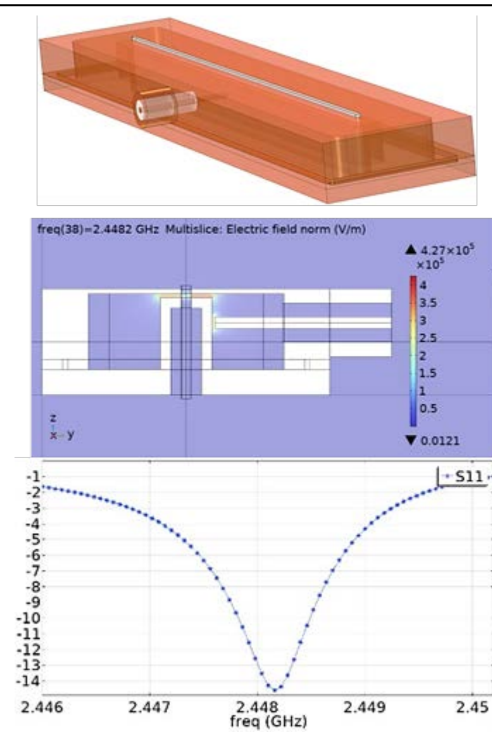

Figure 1 – The extended EVA cavity resonator structure, the electric field concentration, and the simulated reflection coefficient showing a resonance of around 2.45 GHz.

*Work supported by the National Science Foundation under Grant number ECCS-2102100.

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Experiments and Modeling of a 25 W Porous Electrospray Array*

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A porous conical type electrospray array thruster targeting 25 W of power is operated and characterized. The thruster consists of O(10,000) individual cone structures machined from a porous glass substrate [1]. The fabrication of the emitter and extractor chips using conventional machining techniques is described. Individual emitter geometries and the geometry of the assembled thruster as measured by surface profilometry are reported. The emission current of the thruster as a function of electrode bias is measured in a vacuum test facility, with the divergence in the beam measured by a Faraday probe.

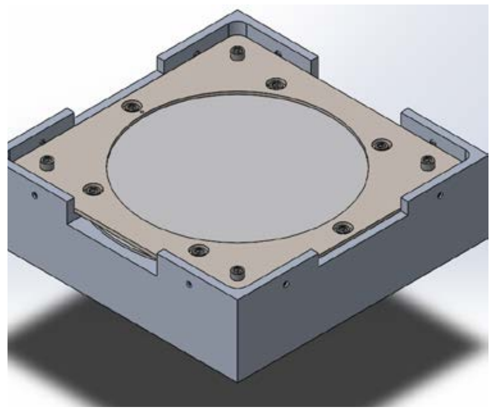

Figure 1 – Representative CAD model of the electrospray array thruster.

The experimental behavior of the thruster is compared with predictions made using a reduced-fidelity emitter model [2], considering uncertainty over emitter geometry and the model parameters. Bayesian inference is applied to update understanding in the model parameters based on the new data acquired.

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

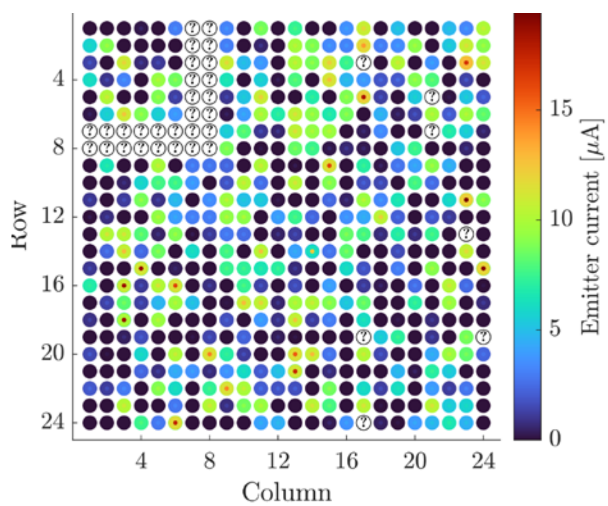

Figure 2 – Representative emitter-by-emitter predictions produced by the model [2] for a thruster of power class 1.3 W [1].

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Exploring Multi-fidelity Bayesian Optimization for Inertial Confinement Fusion Design*

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Inertial confinement fusion (ICF) experiments at the National Ignition Facility are used to study high-energy density plasmas for basic science, stockpile stewardship, and fusion energy applications. Simulating these experiments requires complex coding tools, such as the LLNL-developed HYDRA [1] code, to handle laser propagation, hohlraum radiative response, capsule implosion dynamics, and modeling the subsequent fusion reaction. Such codes are used to guide ICF design work; however, simulations can be costly to run, and the design space is large, spanning at least a few dozen independent parameters.

Here we demonstrate how recently developed automated tools [2] can be applied to a simplified ICF design problem. The tools leverage multi-fidelity Bayesian optimization (BO) techniques to search high-dimensional design spaces for candidate experiments. By utilizing surrogate models, the BO algorithm allows both lower and higher fidelity simulations to inform the search. We compare the search performance between neural network and Gaussian process surrogate models. We close with a discussion of applying these tools to a full ICF design problem, with the potential of neural network surrogates scaling favorably to the large ICF design space.

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Characterization of Non-Thermal Phase Transitions in Ionic Compounds with Two-color X-ray Pulses

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High resolution crystallography has benefited from the availability of x-ray Free Electron Lasers (FEL). It has been possible to resolve hydrogen atoms and water molecules. [1] Intense x-ray FEL pulses interact with samples changing their electronic and atomic structure. To date, the experiments studying the x-ray FEL-matter interaction have predominantly examined semiconductors, such as diamond and silicon [2-3]. There is little known about how x-ray induced bond breaking occurs in a solid with more than one element or in a solid with ionic bonding. A recent calculation has predicted a crystalline to disordered phase transition in the case of the high-intensity x-ray interaction with sodium chloride, an ionic solid [4]. With FEL x-ray pump and x-ray probe pulses, non-thermal phase transitions are predicted and a new material phases can be detected. We have investigated the time-dependent intensity of diffraction peaks in sodium chloride and magnesium oxide.

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Design and Initial Operation of an Optically Accessible ECR Magnetic Nozzle Thruster*

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Electron cyclotron resonance (ECR) magnetic nozzle thrusters possess several advantages over current state of the art thruster technologies. These include propellant agnosticism and the elimination of the need for a neutralizer cathode. Recent advancements have brought their performance within range of miniaturized Hall and ion thrusters, stimulating interest in further improvements.[1] Such improvements are contingent upon an improved understanding of the electron dynamics inside the source region and the acceleration mechanisms in the nozzle region, which are difficult to study experimentally with electrostatic probes. This work presents the design and initial operation of an ECR magnetic nozzle thruster with an optically transparent source region to facilitate direct optical emission spectroscopy (OES), laser-induced fluorescence (LIF), and Thomson scattering measurements. Langmuir probes are used to estimate electron temperature and density downstream in the plume region while OES is used to determine species makeup and electron density in the source region. Thruster stability is also characterized.

*This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1841052.

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Space Charge Effects on Short-Pulse Beam Dynamics in Vacuum Diodes

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Space charge effects play a significant role in restricting the development of free electron beam based electronics, such as high-power vacuum devices and ultrafast atomic resolution electron imaging and diffraction technologies [1]. Child-Langmuir (CL) law provides the classical current density limit that may be drawn from a planar vacuum diode with a continuous electron beam [2]. However, recent theoretical and experimental findings show that a much higher current density may be drawn from a short pulse or limited emitter area than is anticipated by the CL limiting current. This is achieved when dealing with electron pulses of short durations compared to the electron transit time across the gap [3].

In this study, we focus on investigating the influence of space charge effects on the dynamics of square-top and gaussian short-pulse beam profiles using a 1D multiple-sheet model. We consider various factors that contribute to the overall dynamics, including initial profiles, charge densities, pulse widths, gap potential, and gap distance. Specifically, we pay close attention to the current density limit as the pulse length decreases and the beam's distortion as it traverses the gap. The phase-space trajectories of the electrons in the vacuum gap are analyzed and the evolution of the pulse profiles during the transit in the gap is studied. We also investigate the temporal changes in the electric field, potential within the diode. We evaluate our results by juxtaposing them with the single sheet model and the equivalent diode approximation, proposed by [3]. Additionally, we utilize the XPDP1 particle-in-cell code to simulate and analyze the short pulse problem described above.

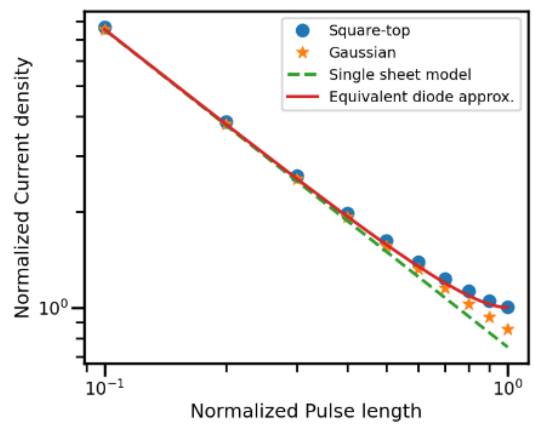

Figure 1 – Normalized critical current density (J/J_{CL}) as a function of the normalized pulse length, comparing the square-top and Gaussian profiles with the two approximate models proposed by [3].

* Work is supported by the Office of Naval Research (ONR) YIP Grant No. N00014-20-1-2681, the Air Force Office of Scientific Research (AFOSR) Grant No. FA9550-20-1-0409, and the Air Force Office of Scientific Research (AFOSR) Award No. FA9550-22-1-0523.

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Mean Force Emission Theory for Bremsstrahlung in Strongly Coupled Plasmas*

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The bremsstrahlung process is an important mechanism for radiation transport in astrophysical, fusion, and industrial plasmas. Furthermore, plasmas created in these systems can often be in an intermediate coupling regime, where the average kinetic energy of particles is on the order of the potential energy at the average interparticle spacing (Γ≅1). In this work we present mean force emission theory, which extends the classical theory of bremsstrahlung emission to strongly coupled plasmas (Γ≥1). For emission greater than the plasma frequency, we find that the radiation spectrum can be described using binary collisions occurring through the potential of mean force. For emission lower than the plasma frequency, we show that the classical spectrum can be described using a velocity autocorrelation formalism that captures the effect of multiple collisions in sequence. This low-frequency limit gives a radiation spectrum that is dependent on the interspecies collision frequency calculated using a generalized Coulomb logarithm. In order to benchmark our theory, we consider a two-component plasma with repulsively interacting species and calculate the emission spectrum from classical molecular dynamics (MD) simulations for coupling strengths between 0.01-100. The theoretical predictions agree well with the MD simulations. We also compare the results to common classical approaches used for weakly coupled plasmas.

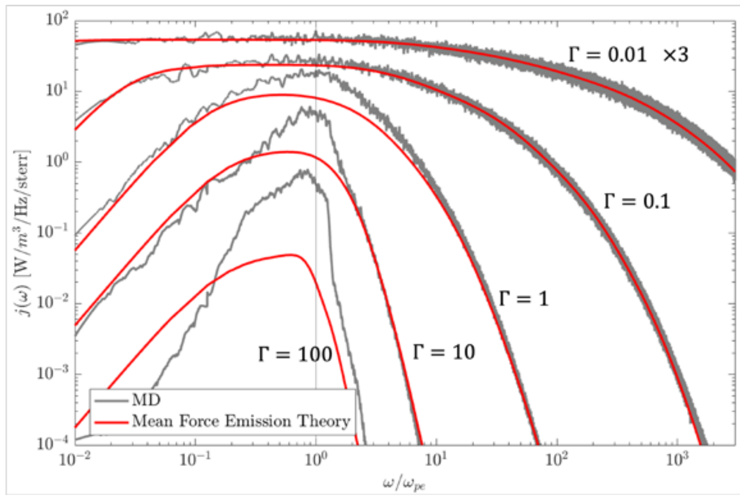

Figure 1 – Emission coefficient from MD simulations (gray) and mean force emission theory (red) over a range of frequencies and coupling strengths (Γ).

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Tabletop Microwave Capillary Reactor for Nano Diamond Synthesis

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Microwave plasma assisted chemical vapor deposition (MWPCVD) technique has been used to efficiently obtain high quality single crystal and nano crystal diamond (NCD) synthesis for both research and commercial applications so far. A conventional diamond CVD reactor is a stationary large size metal pillbox connected to a high-power magnetron through a rigid waveguide network. The power level required for diamond synthesis is in the order of 1kW. Such a system is not portable and is not suitable for additive manufacturing. In addition, diamond deposition in such reactors typically takes place at ~ (800 ± 200) °C of substrate temperature with the substrate being placed in direct contact with the hot plasma. This prevents deposition on any substrate with a low melting point ruling out plastics important for biomedical and electrochemical device manufacturing.

In the present work, a tabletop version of a conventional microwave CVD reactor is developed as shown in Fig. 1. The capillary reactor consists of a quartz tube with precursor gases (H_2, CH_4) flowing through it. A stable plasma discharge (contained in the tube) is obtained when such a tube is placed inside a cylindrical 2.45 GHz MW cavity waveguide. The samples are collected on Si substrates mounted on a stainless steel rod of 1/8” diameter that can be axially inserted into the quartz tube at a desired distance from the plasma.

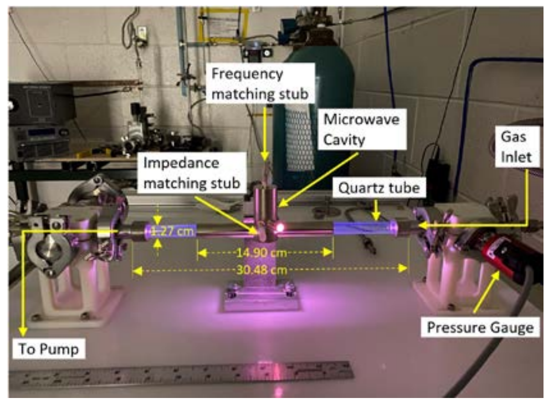

Figure 1. The experimental setup showing the MW capillary reactor.

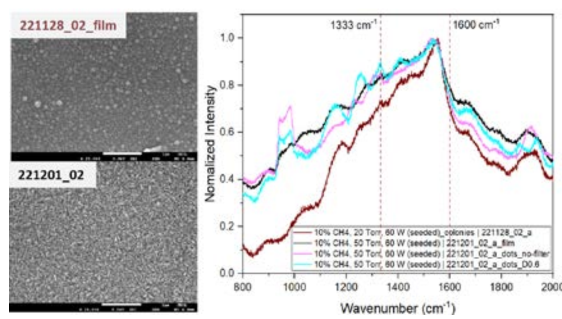

Figure 2. (Left) SEM images, and (right) Raman spectra of NCD films.

The process conditions: pressure, flow rate, H_2:CH_4 ratio, were kept similar to those used to synthesize NCD in a conventional CVD system[1]. The input power, however, was reduced to ~70 W and the sample collection was done in the colder regions of the plasma (gas temperature not exceeding 350-400°C as obtained from plasma simulation). The samples thus obtained resemble NCD evident from the material characterization shown in Fig. 2.

The reduced physical size combined with its ability to produce NCD on colder substrates offers many advantages over existing CVD systems. In addition to having great commercial value, it could potentially become an affordable commodity tool for R&D labs in academia and industry to quickly prototype and optimize photo-electro-chemical and bio-medical devices.

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Thomson Scattering Measurements of Electron Mobility in Hall Thrusters*

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Engineering of low temperature, crossed-field plasma systems such as Hall thrusters relies on a sufficient understanding of electron transport. However, as in many similar plasma environments, the electron mobility in these space propulsion devices is highly non-classical [1]. Because of this, the ability to predictively model Hall thrusters and similar devices has not yet been realized, resulting in the need for expensive vacuum experiments to characterize performance and lifetime at each operating condition of interest. One key step toward a predictive understanding of the physics of low-temperature, $E \times B$ plasmas is the development of reliable, non-perturbative diagnostics to infer the kinetic properties of electrons in the discharge.

In this work, an incoherent Thomson scattering diagnostic [2] is applied to measure the azimuthal velocity distribution of electrons in the acceleration region of a 9-kW class Hall thruster. From measurements throughout the plume of this device, computed fluid properties reveal the gain and loss of electron momentum and thermal energy through the region of strong crossed-field drift. This analysis is then combined with a quasi-1D Ohm's law model of the electron transport to estimate the electron mobility. These results provide the most direct, non-invasive measurement of electron transport in magnetically shielded Hall thrusters, enabling comparison with closure models for the dependence of the turbulent sources of anomalous electron momentum on fluid properties.

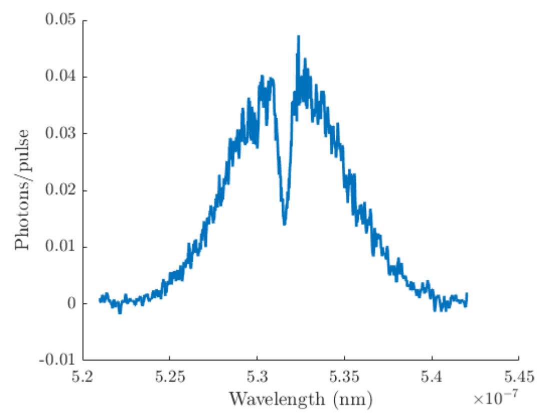

Figure 1 – Thomson scattering spectrum from a hollow cathode plasma for alignment of the Hall thruster diagnostic, showing a Maxwellian electron velocity distribution. The central dip corresponds to notch filtering at the laser wavelength of 532 nm. This spectrum is representative of the electron velocity distribution, and can be used to infer mobility

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Investigation of a Low-Pressure Cathode Design for High-Current Operation on Chemically Reactive Gasses*

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Electric propulsion (EP) systems, particularly Hall thrusters, play a crucial role in modern space exploration and satellite propulsion. High-power Hall thrusters in particular may be a key technology in the first human landings on Mars. However, these thrusters will likely need to operate in the 100-kW class or higher to be practical for these missions [1]. Given the high propellant throughput of this thruster class, operation on non-conventional EP propellants, such as CO_2, H_2O, O_2, and N_2 would be highly enabling. Additionally, reliable operation on these propellants would allow for further novel applications such as air-breathing EP [2] or dual mode architectures [3]. Recently, ultra-high-current-density Hall thrusters have shown superior performance on krypton over xenon [4]. This is the result of krypton's mass utilization increasing with current density. Given this, it may be feasible for a thruster operating at high current densities to also demonstrate high efficiency on hard-to-ionize gases. However, such a device would require the use of a cathode operating in excess of 100 A. A traditional lanthanum hexaboride (LaB_6) hollow cathode operating on these chemically reactive propellants has the potential to rapidly deteriorate and poison. Recent work on radio-frequency cathodes has shown moderate success in addressing the challenges posed by reactive propellants [5]. However, their efficiency in terms of amps per watt is still impractical for high-current cathodes. The high current densities required in these scenarios often necessitate the use of thermionic emitting materials. Fortunately, LaB_6 has shown negligible poisoning even at thermionic temperatures (1400 C) when the partial pressure of oxygen is kept below 1e-4 torr [6, 7]. However, in low-pressure environments, cathode ignition to a keeper becomes non-trivial, as the cathode-to-keeper distance may become prohibitively large. In light of these challenges, our research proposal aims to investigate the potential of a novel LaB_6 cathode design to achieve high efficiency and high current emission in an low-pressure oxygen environment. The proposed research presents the experimental results of a standalone cathode to simulate its operation in a high-current Hall thruster.

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Temperature Inhibition of Methane Conversion in DBD Plasma-Driven Systems

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Low-temperature non-thermal plasmas (LTPs) are known to produce highly reactive chemical environments. The combination of these reactive species with a catalyst can help drive thermodynamically unfavorable reactions and produce a synergistic conversion effect. We are interested in the direct coupling of methane (CH_4) with additive gas to produce value-added chemicals using plasma catalysis. To create effective plasma catalytic systems, it is important to understand the fundamentals of plasma-phase chemistry alone. The knowledge of how bulk reaction temperature affects the system is needed as higher temperatures are necessary to active the catalyst in plasma catalysis but there is limited understanding in how these temperatures affect the plasma. In this work, we use a dielectric barrier discharge (DBD) to investigate the effects of operating conditions, specifically temperature, on the chemical transformation of species (CH_4) and the plasma's electrical properties in various methane-gas mixtures. Results show an increase in temperature leads to a reduction in the conversion of methane. This can be attributed to two possible causes: an increase in the conductivity of the gas pre plasma ignition affecting plasma electrical properties and changes to the thermal chemical reaction kinetics. Both situations then lead to a plasma environment where methane conversion is limited. We also observe a positive correlation between key electrical plasma properties (average charge and lifetime per filament) and conversion at various operating conditions, which provide insight into a relationship between plasma properties and chemical transformations.

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