Plasma Propulsion Research in Academia

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Co-authors

B. Jorns,[1] University of Michigan, Plasmadynamics and Electric Propulsion Laboratory
A. Yalin, Colorado State University, Center for Laser Sensing and Diagnostics
M. Walker, Georgia Institute of Technology, High-Power Electric Propulsion Laboratory
J. Little, University of Washington**,** Space Propulsion & Advanced Concepts Engineering Lab.
K. Hara, Texas A&M University, Plasma Dynamics Modeling Laboratory
Y. Raitses, Princeton Plasma Physics Laboratory, HTX
A. Smolyakov, University of Saskatchewan, Theoretical Plasma Physics
I. Kaganovich, Princeton Plasma Physics Laboratory
M. Cappelli, Stanford University, Stanford Plasma Physics Laboratory

Contributors

J. Williams, Colorado State University, CSU Electric Propulsion & Plasma Engineering Lab.
I. Boyd, University of Michigan, Nonequilibrium Gas and Plasmadynamics Laboratory.
A. Gallimore, University of Michigan, Plasmadynamics and Electric Propulsion Laboratory
E. Choueiri, Princeton University, Electric Propulsion and Plasmadynamics Laboratory
M. Keidar, George Washington University, Micropropulsion and Nanotechnology Lab.
R. Wirz, UCLA, Plasma & Space Propulsion Laboratory
R. Sedwick, University of Maryland, Space Propulsion and Power Laboratory
S. Cohen, Princeton Plasma Physics Laboratory
J. Rovey, University of Illinois Urbana-Champaign, Electric Propulsion Laboratory
D. Levin, University of Illinois Urbana-Champaign
E. Ahedo, Universidad Carlos III de Madrid, Plasma & Space Propulsion Team
U. Shumlak, University of Washington, Aerospace and Energetics Research Program
S. Mazouffre, National Center for Scientific Research, ICARE
S. Tsikata, National Center for Scientific Research, ICARE
J-P. Boeuf, Laboratoire plasma et conversion d'énergie, GREPHE
K. Lemmer, Western Michigan University, Aerospace Laboratory for Plasma Experiments
P. Lozano, Massachusetts Institute of Technology, Space Propulsion Laboratory
M. Micci, Penn State University

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[1] bjorns@umich.edu, (734)-764-8224

Overview: Plasma-based electric propulsion (EP) is an enabling technology for the exploration and commercialization of space. This stems from its ability to offer substantial savings in mass and cost compared to traditional chemical rockets. Industry projections[2] suggest that half of all commercial spacecraft in the next ten years will have EP on board. This technology similarly is a key enabler for the new paradigm of "smallsats" as well as future deep space exploration.

Although EP is ultimately an applied technology, the study of basic, low temperature plasma (LTP) dynamics has proved to be a critical foundation for this field. Indeed, many of the research questions related to EP are fundamental in nature with direct implications for improving the basic understanding of the plasma state. This white paper, compiled by a cross-section of academics in EP, highlights six of the most active of research areas:

- Cross-field transport
- Self-organization
- Plasma-material interaction
- Developmental & testing challenges
- Diagnostic development
- Modeling & simulation

These topics are cross-cutting, extending beyond EP to other plasma fields ranging from materials processing to space plasma physics. The work on these topics similarly has a far-reaching educational impact, helping train the next-generation of researchers in both aerospace engineering and plasma physics. Graduates from EP programs across the country each year enter careers in a wide range of science and engineering disciplines in industry, national laboratories, and academia.

Support for academic work in plasma-based EP in the past decade has come from a number of sources. The Air Force Office of Scientific Research (AFOSR) has been a major sponsor, helping set many of the priorities listed above for the field. Academic work in LTP in these areas also has direct relevance to and has been supported by portfolios in NSF, DoE, ONR, DARPA, and NASA. Looking to the future, EP remains a rich field with many unanswered questions directly related to the plasma state. From the academic perspective, it is anticipated that work in plasma-based EP will continue to yield fundamental, cross-cutting knowledge of LTP.

Cross-field transport

State of the art: While anomalously high cross-field transport of plasma across magnetic field lines is pervasive—spanning many branches of plasma physics—it is particularly problematic for EP devices.[3] The lack of understanding of this process has precluded the development of the types of predictive, numerical models that are highly desirable both for analysis and design. In light of this challenge, there have been a number of studies and community-organized workshops in the past decade dedicated to transport processes in EP devices.[4] These efforts have led to an emerging consensus that this process likely can be attributed to non-classical effects such as self-organized oscillations and micro-scale turbulence.

Knowledge gaps and challenges: There are a number of remaining knowledge gaps about transport process in EP systems. In Hall effect thrusters (HET)s, for example, there are several discrepancies between modeling results and experimental measurements related to the shape, saturation, dominant energy modes, direction of propagation, and degree of influence of micro-turbulence on transport. For another form of EP where transport occurs, the magnetic nozzle, aspects of the mechanisms that allow ion and electron detachment similarly remain unresolved.[5] In an effort to address these open questions, on-going modeling efforts are focusing both on building direct numerical simulations enabled by increased computational capabilities as well as

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[2] C. Henry, SpaceNews, Aug. 22, 2017. Link

[3] J. Bouef. *Journal of Applied Physics* **121** (2017). Link

[4] Proceedings of 2015 (Pasadena, CA), 2017 (Toulouse, FR), and 2018 (Princeton, NJ) E × B Workshops

[5] E. Ahedo and M. Merino, *PSST* 23 (2) (2014). Link

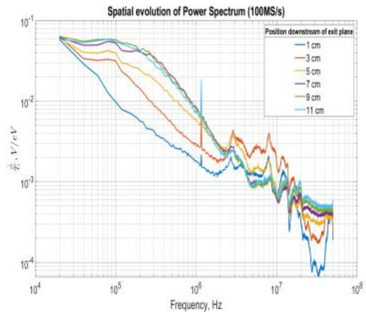

Figure 1: Spatially-resolved power spectrum of transport-related turbulence in a HET. Shows evidence of energy cascade to smaller frequencies.[6]

physics-based fluid/hybrid models that can approximate non-classical transport. Experimental efforts are working toward expanding capabilities and accessibility. New diagnostics will need the ability to measure mechanisms such as energy coupling across lengths,[6] the phase relation between microscale electric field and density, and particle distribution functions.

Outlook: Looking to the future, a major challenge will be coordinating efforts on cross-field transport. Given that many forms of EP are proprietary or controlled (e.g., domestic commercial HETs that are subject to ITAR restrictions for access), export laws have been a major impediment to formal collaborations between experimentalists and modelers—particularly across international borders. A sponsored, standardized test article, much like the GEC cell, could help coordinate parallelized efforts. Indeed, with this type of standard test article combined with modern diagnostics and advanced simulation codes, there is high confidence in the community that the problem of anomalous transport could be solved in the decade.

Self-organization

State of the art: A number of EP devices exhibit self-organized behavior in the form of low-frequency (typically <100 kHz) coherent oscillations in plasma density and potential (c.f. Fig. 2). In HETs, these take the form of longitudinal "breathing" mode fluctuations in the direction of the applied electric field and rotational, "spoke mode" fluctuations propagating in the direction of the E × B drift.[7] The breathing mode is usually the most powerful in HETs and manifests itself in oscillations of the discharge current, often reaching amplitudes comparable to the mean discharge current itself. The spoke similarly has been shown to conduct as much as 50-70% of the discharge current.[7,8] In hollow cathodes, the electron source for most state of the art forms of EP, the onset of longitudinal, ionization-like oscillations in the plasma density and discharge current is well-known to pose a risk to the device's health and lifetime.[9]

Knowledge gaps and challenges: While self-organization in EP devices has been studied for some time and impressive progress has been made in the last decade —through self-consistent modeling[10] and detailed experimental validation[11]—it is commonly accepted in the community that there is still an inadequate understanding of the physical mechanisms involved in self-organization. There is a growing realization that in conditions relevant to the practical operation of these devices, these modes result from the interplay of several effects and so a complete picture of the physics remains elusive. Towards a better understanding of self-organization in HETs, hollow cathodes, and related plasma propulsion devices (e.g. Field Reversed Configuration (FRC) and helicon

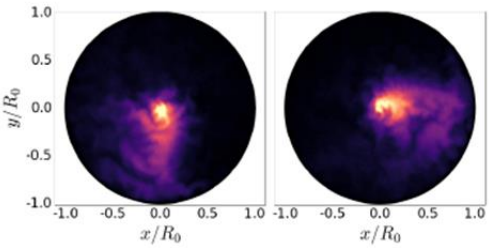

Figure 2: Particle-in-Cell simulations of electron density contours in a real scale E× B Penning system showing spoke rotation.[10]

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[6] Z. Brown and B. Jorns, *AIAA-2018-4423* (2018). Link

[7] C. L. Ellison, Y. Raitses and N. J. Fisch, *Phys. Plasmas* 19, 013503 (2012). Link

[8] M. S. McDonald and A. D. Gallimore, *IEEE Trans. Plasma Sci.* 39, 2952 (2011). Link

[9] D. Goebel, K. Jameson, I. Katz, and I. Mikellides, *Phys. Plasmas* 14, 103508 (2007) Link

[10] A. Powis. J. Carlsson, I. Kaganovich, Y. Raitses, and A. Smolyakov, *Phys. Plasmas* 25, 072110 (2018). Link

thrusters), the community needs to answer questions related to the role of gradients, electron kinetics, and the coupling between large- and small-scale plasma structures (energy cascade). Moreover, given that these devices are subject to known non-classical effects such as anomalous transport, there are open questions as to their role in self-organization.

Outlook: Future progress in understanding these questions will be driven by a combination of modern experimentation, theory, and simulations. The ultimate challenge and long-term goal would be a first-principles understanding of this self-organization and computational capabilities to self-consistently predict it.

Plasma material interactions

State of the art: The plasma-material interaction (PMI) is important for EP devices because it ties the electrical boundary condition of the plasma to the transport of mass, charge, and energy. These transport properties can impact overall device performance and efficiency. Prior work in the field has combined experiment and simulation to examine the impact of LTP environment on materials relevant to EP (ceramic insulators, permeable materials, and high temperature alloys). These studies have revealed a number of nuanced effects including the dependence of secondary electron emission on material geometry and temperature; [11] the dependence of surface sputtering on topography;[12] and the impact of non-thermalized and magnetized species on sheath formation.[13,14]

Knowledge gaps and challenges: The plasma device community requires the ability to predict the impact of material boundaries on bulk plasma properties and dynamic plasma behavior. Despite on-going work, however, PMI phenomena remain poorly understood in the plasma sheath near material boundaries. The ability to produce high fidelity, predictive simulations of PMI requires knowledge of the electron and ion energy distributions, microscopic properties of the surface material and how it responds to plasma flux, and the physics underlying the formation of sheaths in the presence of magnetic fields and strong thermal environments.

Outlook: Looking to the future, the community requires efforts to characterize the transport properties through plasma measurements in the sheath. Measurements of these properties should be performed in parallel with fully-kinetic (electrons and ions) simulations of the plasma sheath. Simultaneously, the community requires *in situ* characterization of the material surface to inform detailed simulations that capture evolving changes in the properties of the microstructure.

Developmental and testing challenges

State of the art: While state of the art EP systems operate at moderate power (~3-12.5 kW), there is growing demand for thrusters that can achiever substantially lower (< 100 W) and higher (> 100 kW) levels. Existing thruster architectures such as gridded ion and nested HETs have been demonstrated in the laboratory to be capable of high powers while maintaining high efficiencies (>60% of input power is used for thrust production).[15] However, erosion of electrodes and plasma-facing surfaces – a phenomenon that has thus far been manageable for present power levels and thruster lifetimes – can become increasingly problematic. Electrodeless thruster concepts[16] such as magnetic nozzles and Field Reversed Configuration thrusters[17] have been proposed that may reduce erosion to levels required for multi-year operation at high powers. The efficiencies of these concepts, however, currently are not competitive with state of the art EP. On the low power side,

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[11] S. Langendorf and M. Walker. *Phys. Plasmas* 22, 033515 (2015). Link

[12] G. Li, T. Matlock, D. Goebel, C. Dodson, C. Matthes, N. Ghoniem, and R. Wirz, *PSST* 26 (6) (2017). Link

[13] J. Lukas and M. Keidar, *IEPC-2015-282* (2015). Link

[14] A. Domínguez-Vázquez, F. Taccogna, E. Ahedo, *PSST* 27 (6) (2018). Link

[15] S. Hall et al, *IEPC-2017-228* (2017). Link

[16] S. Bathgate, M. Bilek, and D. Mckenzie, *PSST* 19 (8) (2017). Link

[17] J. Slough and D. Kirtley, *IEPC-2009-265* (2009).

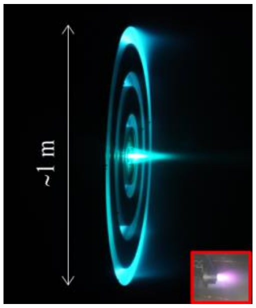

Figure 3: Extremes of power scaling with a 100 kW nested Hall thruster[15] and a 30 W cubesat system (inset).

(<100 W), there is an extremely high demand for propulsion systems that are compatible with the CubeSat architecture.[18] Yet, low-power concepts that rely on acceleration of plasma have been plagued by low performance.

Knowledge gaps and challenges: For high power concepts that leverage more mature technology (HETs and ion thrusters), there is a pressing need to understand and mitigate life-limiting mechanisms related to plasma-based erosion. For less mature concepts such as FRCs and magnetic nozzles, there are several knowledge gaps related to their fundamental operation, e.g. the inherent efficiency of inductive coupling and electron dynamics,[19] that must be resolved. Challenges also arise in the ground testing of thrusters related to so-called "facility effects." The propellant mass throughput at 100 kW overwhelms all but the most capable vacuum test facilities in the world. As a result, standard methods for the development of electric thrusters will occur only at significant cost. For low power plasma EP, the major challenge will be to understand and mitigate inherent surface-to-volume ratio losses that occur in down-scaling.

Outlook: For both high-power and low-power concepts, the mechanisms for acceleration must be understood before challenges with lifetime and performance can be addressed. There thus is a need for higher fidelity, experimentally-validated models of the formation and acceleration of their LTP plasma. With that said, particularly for high power concepts, the challenge of facility effects suggests a need for alternative methods for testing these high-power systems. Dedicated high-power user facilities are one option. In parallel, an improved understanding of thruster physics could enable alternative, cost-effective tests based on numerical models or accelerated wear tests.

Diagnostic Development

State of the art: Recent developments in EP plasma diagnostics have leveraged laser-based techniques that can offer highly spatially and temporally resolved measurements. Laser induced fluorescence (LIF) is a widely used diagnostic that can probe species-specific density and velocity distribution functions (VDFs).[20] An exciting new development aimed at studying low-frequency dynamic behavior in EP devices is provided by time-resolved (TR)-LIF approaches with resolution of ~10^{-6} s (Fig. 4).[21.22] While traditionally reserved for higher temperature and density systems, recent advances in laser Thomson scattering (LTS) have opened the door to more extensive use of this diagnostic in EP research. For more compact LTS setups, the use of volume Bragg gratings (in place of triple-pass monochromators) has been demonstrated. [23] Another recent advance, which may allow measurements at lower densities with improved time resolution, is based on cavity enhanced Thomson scattering (CETS) with a high-power (~10 kW) intra-cavity

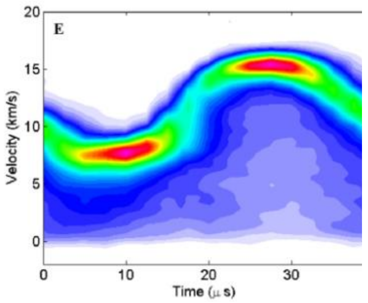

Fig. 4: Temporally resolved IVDF in plume of 400W HET[21]

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[18] Lemmer, Kristina. "Propulsion for cubesats." *Acta Astronautica* 134: 231-243 (2017). Link

[19] Little, J. M., and E. Y. Choueiri. *PRL* 117 (22). 2016. Link

[20] S. Mazouffre, *PSST* 22 (1) (2012). Link

[21] A. Fabris, C. Young, and M. Cappelli, *J. Appl. Phys*, 118 (23) 2015. Link

[22] C. Durot, A. Gallimore, and T. Smith, *Rev. Sci Inst.*, 85(1). 2014.

[23] B. Vincent, S. Tsikats, S. Mazouffre, T. Minea, and J. Fils, *PSST*, 2018. 27(5). Link

beam. [24] Finally, collective LTS also has been demonstrated on EP systems and used to measure density fluctuations.[25]

Knowledge gaps and challenges: While the sophistication of experimental techniques continues to progress, there are several critical aspects of EP operation that to date have not been experimentally accessible. These include non-invasive measurements of key properties of high frequency (> 1 MHz), mid-wavelength plasma oscillations (e.g. the relationship between density and potential fluctuations); the electron velocity distribution function (including electron drift); the neutral ground state of the working gas of these systems, xenon; non-invasive measurements of charge state; and impurity characterization of test facilities.

Outlook: Future diagnostic research is expected to apply emerging TR-LIF and LTS methods to EP systems and devices. Development of techniques with yet improved spatial resolution, and that can work well near surfaces, continues to be of interest. Other emerging areas include improvement of two-photon absorption LIF (TALIF) techniques for measurements of neutral xenon to examine facility effects (i.e., charge exchange reactions, impact on erosion etc.) and possible adoption of other novel diagnostics, such as laser collisional induced fluorescence and microwave scattering.

Modeling & Simulation

State of the art: Predictive computational modeling capabilities are a key component in advancing the technology of plasma-based EP devices, particularly when scaling thruster capabilities or attempting qualification through analysis. There are three main physics-based approaches employed to model plasma flows in EP devices: fluid;[26] particle;[10] and grid-based direct kinetic methods.[27] Hybrid models, where fluid and kinetic methods are used for different species, are also widely used.[28] Despite significant advances in the field in the past decade, modeling EP plasmas remains challenging due to the multi-physics and multi-scale nature of the discharge phenomena.

Knowledge gaps and challenges: While fluid models are inherently computationally less expensive with less noise, they have reduced capability in representing aspects of the kinetic-based processes, e.g. the onset of transport-driving turbulence, which are believed to play a role in many EP devices. The challenge for these models is to develop time-dependent, physics-based equations and closures that account for these kinetic effects. For kinetic models, which in principle have the highest fidelity, computational time is a major limitation. For example, current simulations are limited to a maximum of two-dimensional phenomena up to a few tens of micro-seconds using explicit particle methods. This is too short with insufficient dimensional fidelity to resolve or understand the interplay between collisionless phenomena (e.g. electron cyclotron drift instability) and three-dimensional collisional phenomena (e.g. plasma wall interactions and intermolecular collisions).

Outlook: The utilization of high-performance computing capabilities will be required to be able to create models of representative geometries on time-scales of interest. Developing standards for verification, validation, and benchmarking of these new and existing numerical codes will continue to be extremely important. Data-driven approaches[29] for plasma turbulence and anomalous electron transport are also promising potential paths. Using the experimental data collected by the community, reduced-order models and machine learning techniques may provide new insights into stochastic phenomena in plasma flows observed in EP devices.

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[25] S. Tsikata, C. Honore, and D. Gresillon, *Journal of Instrumentation*, 8 (2013). Link

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