Guest Editorial
Special Issue on Plasma Propulsion

THIS SPECIAL Issue is dedicated to the fundamentals of the physics and technology of plasma propulsion. The issue consists primarily of papers presented at major international forums such as the International Electric Propulsion Conference and the AIAA/ASME/SAE/ASEE Joint Propulsion Conference in recent years.

Plasma propulsion is a very rapidly growing area of plasma science and technology. Experiments, modeling, and computer simulations have contributed significantly to the understanding of the physics of plasma propulsion. The field of plasma propulsion includes a broad variety of thrusters to achieve high propellant exhaust velocity, thereby offering a large mass of savings for space vehicles as compared to chemical rockets. These thrusters are broadly categorized into three groups: electrothermal, electrostatic, and electromagnetic [1]. Many new plasma thrusters have been developed recently, including numerous successful attempts of scaling to higher and lower power applications [2]. In these thrusters, plasma conditions span from a collisionless nonequilibrium state to a collision-dominated equilibrium situation. In recent years, significant advances have been made in the development and application of both theoretical and experimental methods for studying thruster discharges, including plasma generation, propellant acceleration, electron and ion transport, and plasma-wall interactions. Many traditional and new plasma diagnostic tools and methods, including electrostatic and electromagnetic probes and sensors, and advanced spectroscopic methods were developed to characterize the harsh and complex environments of plasma propulsion systems. A variety of simulation techniques such as particle-in-cell (PIC), direct simulation Monte Carlo, fluid models, hybrid approaches, and multidimensional analyses are now commonly used for studying thruster discharges and predicting thruster performance and lifetime.

We are pleased to introduce this Special Issue, which addresses plasma science aspects in several key directions of modern plasma propulsion. This issue contains 25 papers that represent a substantial fraction of existing efforts, but obviously not the entire spectrum of basic and technological research on plasma propulsion. This Guest Editorial article highlights these contributions and overviews the state-of-the-art and relevant research efforts in a broader context. We structure this article according to natural divisions in the various plasma propulsion concepts.

A *Hall thruster* is one of the most efficient devices for space propulsion in which thrust is generated by ion acceleration in a quasi-neutral plasma. This feature results in a much higher thrust density than other types of ion thrusters. An electric field in the quasi-neutral part of the Hall thruster discharge is sustained across a magnetic field so that the electric field is orthogonal to the magnetic field. Detailed descriptions of Hall thruster physics and outstanding issues can be found elsewhere [3]–[6]. In this issue, several papers are devoted to Hall thruster physics.

High-frequency instabilities (> 1 MHz) are discussed in the paper by Lazurenko *et al.* [7]. The development of these high-frequency instabilities results in anomalous electron transport, and the corresponding transport coefficients are evaluated from the experimental data.

A shear-based hybrid model of the Hall thruster channel is described in the contribution by Scharfe *et al.* [8]. In this paper, an electron cross-field transport model based on instantaneous simulated plasma properties is incorporated into a radial–axial hybrid simulation of a Hall plasma thruster. A comparison between shear-based, experimental, and Bohm-type models for cross-field transport is presented. The major conclusion of this work is that, although the shear-based model is in some disagreement with experimental data, it better predicts measured plasma properties than the Bohm model. Ion current in Hall thrusters was investigated by Katz [9], and ion velocity measurements within the acceleration channel of a low-power Hall thruster is described in a paper by Hargus *et al.* [10]. An anodic plasma instability was considered by Kapulkin and Guelman [11]. The instability is due to the finite temperature of the electrons and nonuniformity of both the plasma and magnetic field. The anodic plasma instability exhibits characteristics consistent with the Rayleigh–Taylor instability and may be responsible for the enhanced transfer of electrons between the thruster ionization region and the anode.

Mazouffre *et al.* [12] measured the velocity distribution function of metastable Xe ions along the channel axis of a 5-kW-class Hall thruster using laser-induced fluorescence. They found that the ion velocity distribution function broadens across the region of a strong magnetic field, which is explained by the overlap of the ionization and acceleration regions. In addition, their finding confirms that most of the acceleration voltage is localized outside of the thruster channel but the fraction of the voltage inside the channel increases with discharge voltage.

The Hall thruster exhaust plume was studied by Cohen-Zur *et al.* [13] with an aim at understanding the effect of the pressure on plume divergence. The evolution of the electron temperature and the radial expansion of the plasma are

Digital Object Identifier 10.1109/TPS.2008.2005834

calculated self-consistently. They found that there is an optimal strength of the magnetic field where the plume divergence is minimized.

In recent years, a number of research groups have focused on the electron kinetics of Hall thruster plasma. Using a 2-D axial–azimuthal PIC model, Adam *et al.* [14] have demonstrated that plasma turbulence associated with the development of a high frequency short-wavelength azimuthal instability can be responsible for anomalous electron transport in a Hall thruster. Recent collective scattering experiments [15] have confirmed the existence of the azimuthal wave instability predicted by the PIC simulations. Also, the PIC simulations of Adam *et al.* show that anomalous transport can be predicted by PIC codes in a way that is consistent with experiments; even if secondary emission from the wall is not included in the model, they do not prove that secondary electron emission from the wall does not actually play a role in real thrusters. Therefore, the relative role of turbulence or secondary emission from the walls on electron transport across the magnetic field is still an open question. Several recent papers discuss the role of secondary electron emission. Ahedo and Parra [16] and Sydorenko *et al.* [17], [18] predicted that secondary electrons emitted from the opposite walls of the thruster channel could form counterstreaming beams that propagate through the collisionless plasma between these walls. Analytical studies and PIC simulations by Sydorenko *et al.* showed that the electron velocity distribution function in Hall thrusters is non-Maxwellian and anisotropic. Electrons are stratified into several groups depending on their origin and confinement. These kinetic effects lead to many new properties of plasma in a Hall thruster. In particular, PIC simulations predict that the beams of secondary electrons from the walls may significantly enhance the electron conductivity across the magnetic field but only weakly affects the insulating properties of the near-wall sheath. Such decoupling between the secondary electron emission effects on the electron energy losses and the electron cross-field transport is currently not captured by the existing fluid and hybrid models of Hall thrusters. Another prediction from these kinetic simulations is that the sheath near the electron-emitting surface may become unstable if it is characterized by negative electron conductivity. Taccogna *et al.* [19] developed a model of the plasma discharge in both the radial and azimuthal direction in order to capture self-consistently the evolution of the azimuthal disturbance and the secondary electron emission from the wall without use of *ad hoc* parameters for the axial transport mechanism. In order to lower the computational cost, they have reduced the periodicity length to 1/16 of the entire azimuthal domain. Azimuthal fluctuations with different wavenumbers and frequencies have been detected in agreement with experimental observations. One of the most evident types of fluctuations is characterized by a frequency of 2.8 MHz. The strong interaction with the walls, as opposed to the axial gradients, is the most plausible candidate to excite this instability. Indeed, the sheath potential drop is azimuthally modulated, as are the wall potential and the surface charge density. In fact, the combination of a reduced sheath (due to secondary electron emission) and a floating wall (from nonlinear coupling between the current collected and the wall potential) is the most important candidate to drive the azimuthal instability. An electron differential model for a two-stage Hall thruster hybrid code is described by Ahedo [20]. An electron trap experiment for studying electron mobility across the magnetic field is described by Fossum [21].

A long lifetime is a critical factor that drives a strong interest in the research and development of Hall thrusters with reduced plasma-wall interactions. This trend is particularly important for low-power applications for which the thrusters must be miniaturized to small scales. In this Special Issue, two papers are devoted to the miniaturized cylindrical Hall thruster (CHT) with a favorably large volume-to-surface area ratio. The principle of operation of this CHT is in many ways similar to that of a typical annular geometry Hall thruster, i.e., it is based on a closed $E \times B$ electron drift in a quasi-neutral plasma [22]. However, because the CHT uses a mirror and/or cusp-type magnetic field, both the forces on the unmagnetized ions and the means by which the electron drifts close are quite different, which leads to a profoundly different operation of the CHT as compared to conventional annular thrusters. The Special Issue paper by Smirnov *et al.* [23] suggests that electron emission from the cathode can affect both electron cross-field transport and ionization of propellant in the CHT. The paper of Garrigues *et al.* [24] compares results of hybrid simulations for the miniaturized CHT with experimental data and predicts the enhanced electron cross-field transport rates in the CHT as compared to annular thrusters.

Two challenges associated with Hall thruster technology are plume divergence and discharge channel erosion. The precise mechanisms causing the plume divergence are not clear, but they are believed to be associated with the combined effects of radial pressure gradients, magnetic field curvature, and nonuniform distribution of the ion production. What clearly remains a challenge is developing ways of narrowing the plasma plume. The Special Issue paper of Hofer *et al.* [25] demonstrates that a thruster configuration with an internally mounted cathode narrows the plume and increases plume symmetry in the near-field plume in comparison to traditional Hall thrusters with externally mounted cathodes. The authors attempted to explain this plume narrowing due to the reduction of radial pressure gradients in the thruster. More detailed experimental and theoretical studies are needed to understand this effect of the cathode placement. Shitrit [26] described factors that can lead to improvements of Hall thrusters.

Several papers are devoted to *RF-plasma thrusters*, including inductive and helicon thrusters. Key advantages of these electrodeless propulsion devices over their dc and pulsed plasma counterparts are a potentially longer lifetime and their ability to operate with a broader variety of gas propellants. Charles and Boswell describe new results for a helicon double-layer thruster [27]. They demonstrate a transition of the ion acceleration from the expansion to a more effective double layer regime in a xenon helicon source. Both the ion beam energy and the ion beam to downstream plasma flux ratio increase with the exhaust magnetic field strength. Chen shows that great savings in the size and weight of plasma helicon sources can be obtained by using specially designed permanent magnets (PMs) [28]. This PM helicon design, originally developed for plasma processing of large substrates, was extended for space propulsion. The design principles have been checked experimentally, showing that the predictions of the theory and computations are reliable. In another paper, Foster and Gillman studied and demonstrated a magnetically enhanced inductive discharge of a planar geometry that could be used as a plasma source for an ion thruster or as a stand-alone ambipolar thruster [29]. The addition of a ring-cusp magnetic field to this planar source is shown to improve the plasma confinement and reduce the ion production cost, which should improve thruster efficiency. A model of an RF-ion thruster was also presented by Goebel *et al.* [30]. A high-fidelity model of ion thruster grid erosion was discussed by Wirz *et al.* [31].

The vacuum arc thruster is an example of an ablative pulsed thruster device in which propellant is supplied by electrode erosion [32]. The operation of the vacuum arc thruster relies on the natural expansion of a hot arc plasma in vacuum. As a result of an ambipolar electric field in the expanded plasma, the ions are accelerated in the plasma jet to speeds up to 30 km/s. In this Special Issue, several papers dedicated to this interesting thruster concept are presented. Beilis [33] analyzed the operation of the vacuum arc discharge with a micrometer-sized gap. It was predicted that there is high coupling between the cathode and anode activities in this case. In addition, it was shown that the anode erosion rate exceeds the cathode erosion rate, thus suggesting a novel configuration for a plasma thruster. Rysanek and Burton [34] described measurements of the macroparticle charge generated by a vacuum arc thruster. This issue is extremely important for the assessment of vacuum arc thruster contamination. They found that macroparticle charge is positive in a case of a pulsed vacuum arc, which is much different from the previously predicted negative charge in the dc vacuum arc literature. Polk *et al.* [35] presented a theoretical analysis of vacuum arc thruster performance. Empirical data on the current density distribution, charge state, and velocity of ions were used to develop expressions for the expected thrust and specific impulse as a function of thruster geometry. They concluded that vacuum arc thrusters can be operated efficiently and provide great flexibility in specific impulse.

The use of plasma devices, including thrusters, charge neutralizers, and plasma contactors onboard satellites and spacecraft may create various integration issues. The Special Issue paper by Gabdullin *et al.* described interesting and important phenomena associated with the plasma environment surrounding the International Space Station [36]. The authors present the numerical analysis based on a self-similar fluid model and show how the plasma plume created by the plasma contactor unit interacts with the geomagnetic field to create conditions potentially hazardous to astronauts conducting space walks. Katz *et al.* presented a model that investigates the heating and ignition phenomena of inert-gas hollow cathodes [37].

Cassibry [38] considered two types of pulsed electromagnetic propulsion concepts: coaxial plasma accelerators and conical theta-pinch accelerators. Both concepts were compared parametrically. It was found that, while coaxial plasma accelerators are generally more efficient, under certain conditions, the conical theta pinch performance is higher. Polzin considered pulsed inductive plasma thrusters from the scaling and systems analysis perspective [39].

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