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Perspectives, frontiers, and new horizons for plasma-based space electric propulsion

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ABSTRACT

There are a number of pressing problems mankind is facing today that could, at least in part, be resolved by space systems. These include capabilities for fast and far-reaching telecommunication, surveying of resources and climate, and sustaining global information networks, to name but a few. Not surprisingly, increasing efforts are now devoted to building a strong near-Earth satellite infrastructure, with plans to extend the sphere of active life to orbital space and, later, to the Moon and Mars if not further. The realization of these aspirations demands novel and more efficient means of propulsion. At present, it is not only the heavy launch systems that are fully reliant on thermodynamic principles for propulsion. Satellites and spacecraft still widely use gas-based thrusters or chemical engines as their primary means of propulsion. Nonetheless, similar to other transportation systems where the use of electrical platforms has expanded rapidly, space propulsion technologies are also experiencing a shift toward electric thrusters that do not feature the many limitations intrinsic to the thermodynamic systems. Most importantly, electric and plasma thrusters have a theoretical capacity to deliver virtually any impulse, the latter being ultimately limited by the speed of light. Rapid progress in the field driven by consolidated efforts from industry and academia has brought all-electric space systems closer to reality, yet there are still obstacles that need addressing before we can take full advantage of this promising family of propulsion technologies. In this paper, we briefly outline the most recent successes in the development of plasma-based space propulsion systems and present our view of future trends, opportunities, and challenges in this rapidly growing field.

I. INTRODUCTION

There is little doubt that the nanotechnological revolution has reached and in effect underpinned the tremendous progress in space technologies,[1] providing the much-needed technological framework to not only build extensive near-Earth satellite networks but also support ambitious aspirations for permanent lunar stations and eventual colonization of Mars.[2–4] As space assets become exceedingly smaller[5] and utilize more advanced electronics and sensors, the need for advanced space propulsion systems with the efficiency that matches that of other satellite systems is becoming increasingly evident. Not surprisingly, exploration of new physical principles for creating thrust in space[6,7] and advanced implementation of the existing thrust systems attract strong attention of the researchers.[8,9] Among the plethora of available and emerging space propulsion systems, the thrust platforms that utilize plasma[10–13] and ionized gas[14–16] to create reactive thrust are currently attracting the strongest attention due to many potential advantages of these devices,[17–19] particularly for their ability to deliver a very high specific impulse[20,21] and potentially long service life.[22,23]

However, further uptake of these systems is hindered by several challenges. First of all, there is an urgent need to further enhance the critically important operational parameters of these thrusters, such as their energy efficiency and capability to adjust specific impulse to the task at hand. This need holds true for all existing and emerging electric and plasma propulsion systems when used on any space asset—from a small satellite to a large spacecraft, including those destined for manned missions to the Moon and Mars. Indeed, the specific impulse of the electric propulsion system is, in most cases, a mission-dependent parameter. Other related parameters, such as thruster efficiency, are also critically important. For longer missions, the delivery of greater specific impulse requires a greater amount of energy for ion acceleration and thus an increased capacity with respect to energy storage and other systems. As a result, the specific impulse of an electric propulsion system will be determined by the complex optimization of the whole mission design.[24,25] It is worth noting that since the propulsion needs typically change during the course of the mission, there is strong interest in hybrid variable-specific-impulse electric propulsion platforms to deliver greater efficiency.[26,27]

Second, the service life of the existing plasma thrusters is still not sufficiently high, mainly due to very strong erosion of the electrodes and accelerating channel walls by the action of highly energetic ion, electron, and plasma fluxes impinging on the surface.[28,29] The heat, radiation, and other effects that are present in the energy-loaded plasma thrust systems may further contribute to the failure of materials that come into direct contact with plasmas. Finally, the limitations of the currently available plasma cathode systems still remain a critical block that significantly hinders the total efficiency and reliability of the entire space thrust system.

In this perspective, we will briefly outline the most recent successes in the plasma-based space propulsion systems and present our view on further trends, possibilities, and challenges facing these plasma systems. For the purpose of this discussion, the entire spectrum of the space electric propulsion platforms is subdivided into three main types, namely, the electrostatic, electromagnetic, and electrothermal systems. The electrostatic and electromagnetic thrusters exploit the electric and magnetic fields for the generation, acceleration, and expulsion of ionized propellant, and hence, the articles discussing these platforms are represented well in the *Physics of Plasmas* journal. In contrast, the electrothermal thrusters feature mainly a thermodynamic principle of acceleration via the electric current heating of the propellant, where the latter then expands and thermodynamically accelerates through the nozzle. When compared to the former two thruster types, the electrothermal thrusters demonstrate significantly lower specific impulse levels (see Fig. 3) and, as a consequence, are not a strong focus for the *Physics of Plasmas* journal. Hence, in this this article, we will mainly characterize the two main groups of thrusters, i.e., the electrostatic and electromagnetic systems, as well as cathodes that play an exceptionally important role in many various types of thrusters, such as Hall-type and gridded ion systems. We will first briefly characterize the major and most advanced types "of plasma- and electric discharge-based space propulsion platforms," show their level of development and challenges they are facing, and then set the ways for the future development of this field in Sec. II. Moreover, we will discuss two aspects of prime importance, namely, problems and challenges linked to "miniaturization" of various electric propulsion systems (Fig. 1) and advantages and opportunities provided by the application of novel materials in this field. Finally, in Sec. IV, we will set the longer-term goals and directions for this exciting field. We aim our Perspective article at the most general physics audience and students who may benefit from a comprehensive top-level view of the present-day state of the art in the plasma propulsion as a whole and see what opportunities, challenges and problems are there to be considered in the nearest future. For the more specialized expert audience, we will provide an extended (over 230 publications) list of the most recent specialized textbooks and papers on the topic.

The rest of this paper is organized as follows. In Sec. II, we will first briefly outline the major types of the electric propulsion

FIG. 1. A "planetary system" of electric propulsion thrusters. Four main types of electric propulsion systems are considered as the most promising candidates for various space applications. While Hall, ion, and pulsed thrusters have already been tested and currently found multiple applications as space propulsion systems, the magnetoplasmadynamic (MPD) thruster was only once tested in a real space flight in the framework of the EPEX (Electric Propulsion EXperiment) mission onboard of the Japanese Space Flyer Unit project.[24] Nevertheless, MPD thrusters are considered among the most promising propulsion systems for future missions related to the colonization of Mars and the Moon. Reprinted from Levchenko *et al.*, Appl. Phys. Rev. **5**, 011104 (2018). Copyright 2018 Author(s), licensed under a Creative Commons Attribution (CC BY) license.[8]

systems and their key characteristics; this section aims to introduce the field to the broader readership of the journal, including students and the not-expert audience. Then, in the subsequent subsections A, B, and C, we will analyze the challenges and opportunities specific to the electrostatic systems, electrodynamic systems, and cathode systems used for space electric propulsion thrusters. Next, Sec. III will deal with the modeling and simulation of the space electric propulsion systems, and, finally, Sec. IV will outline the directions for future development of the field, briefly touching on the emerging and prospective approaches.

A Hall thruster[30] uses a number of externally mounted magnetic coils or a single coil of a larger size surrounding the entire thruster. An internal magnetic coil may also be used. An incandescent cathode and anode are installed on the outside and inside of the acceleration channel, respectively. The acceleration channel itself can be made out of ceramic or a metal, with the latter configuration producing a thruster with an anode layer. The anode is typically perforated, with the holes used to supply the propellant, e.g., Xe, as shown in the figure. Upon application of an electric potential to the cathode relative to the anode, a closed Hall current is produced within the channel, being controlled by the intersection of magnetic and electric fields. A static electric field is used to accelerate ionized propellant, whereas the magnetized electrons of the circular Hall current diffuse in the direction of the anode. As Hall thrusters are electrostatic ion accelerators, thrust they produce can be described by considering the interaction of Hall current with the externally applied magnetic field. An ion thruster (depicted on the right) comprises a cylindrically shaped body housing a discharge unit, i.e., an incandescent hollow cathode, an anode, and a magnetic coil. Additional focusing magnetic coils are mounted on the outside of the body. A unit consisting of internal and external grids is used for extraction and acceleration, respectively. An additional cathode unit is mounted on the outside of the acceleration channel and is used to produce an electron flux to neutralize the ion exhaust as it exits the channel in order to prevent charge accumulation on the spacecraft. The propellant gas such as Xe is delivered into the hollow cathode, at which point it undergoes ionization in the magnetized discharge. The internal grid is then used to extract the ion flux, which is then accelerated by the second grid. This results in the ion flux exiting the thruster at high velocity.

II. SURVEY AND PERSPECTIVES: WHERE ARE WE WITH PLASMA PROPULSION?

First of all, we should briefly consider what makes plasma propulsion so promising. Newton's third law of motion postulates that in order to generate thrust in space, an object must expel mass to gain acceleration, with the force expressed as $F = \dot{m} \times V_{ex}$, where V_{ex} is the velocity with which mass is expelled relative to the object and $\dot{m}$ is the rate at which mass is consumed to produce the force (kilogram per second). At present, chemical rockets and electric propulsion thrusters are the most typical systems for space propulsion. Primarily used to deliver assets from Earth to space, chemical rockets are characterized by much greater thrust-to-mass ratio η reaching 2000 N kg^{-1}; however, the exhaust velocity of these systems is comparatively low, at $V_{ex} = 5000$ m s^{-1} even for the most efficient fuels. In contrast, systems that use electric propulsion can deliver a greater exhaust velocity approaching 10^5 m s^{-1} yet can only produce low levels of thrust. In these systems, ions are accelerated using electric fields, and there are no physical limitations to prevent further improvements in the value of V_{ex} (Fig. 2).

When compared to thermodynamic (chemical) rocket engines that come only in few modifications, plasma propulsion thrusters are represented by a large and diverse family of platforms, which could in principle produce thrust in space over a very wide range of power (from fractions of watts to megawatts) and specific impulse (from hundreds to tens of thousands of seconds), see Fig. 3 for a brief classification and visual representation of the devices within the power/impulse field. A more comprehensive picture and characteristics of various types of space electric propulsion systems could be found in the numerous recently published review papers.[6,8,9,17,18,31–36] Figure 4 shows the two very important classes of electrostatic systems, i.e., the Hall-type and gridded ion thrusters that use a DC potential to accelerate ions. These systems are currently considered among the most promising thrust platforms for the long-term missions and for space exploration within the Solar system and beyond its bounds. In addition to the thrusters themselves, "plasma cathodes" could be considered as a separate type of auxiliary but extremely important devices that are either used in conjunction with electrostatic thrusters or themselves could be utilized as ultrasmall thrusters. Electrostatic thrusters always incorporate a set of at least two (sometimes more) electrodes to create an accelerating DC electric field; the electrostatic thrusters may also include several electrodes to create a discharge between them or may be realized in the electrode-less configuration. An analysis of the current state of art of the electrostatic thrusters and the advanced techniques for their numerical analysis is presented below in Sec. II A.

There are a number of electrodynamic space thruster configurations that are currently being developed (Fig. 5). A typical system of this type operates by first ionizing the propellant and then accelerating the ionized species along the channel. A power energy source on board of a spacecraft is used to generate the electric and magnetic fields used for generation, control of movement, and acceleration of changes particles. Once ionized, the particles can be moved along the acceleration channel by the Lorentz force and expelled out. This force is the result of the current of the flowing plasma interacting with the externally applied magnetic field; the magnetic field may also be induced by the plasma's current. Notable examples of such devices include the actively researched helicon plasma thruster [HPT, Fig. 5(a)],

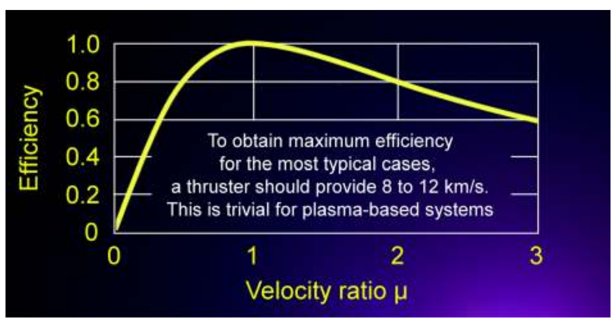

FIG. 2. Why do we need to adjust the exhaust velocity? In order to obtain the maximum efficiency for the most typical case of orbital velocity, the thruster should be able to provide 8–12 km/s. This is not easily achievable when using chemical thrusters yet a trivial challenge for any plasma-based system. Moreover, when the exhaust velocity V_e is very high, the energy efficiency drops off weaker than for the case when V_e is low, as seen from the graph.

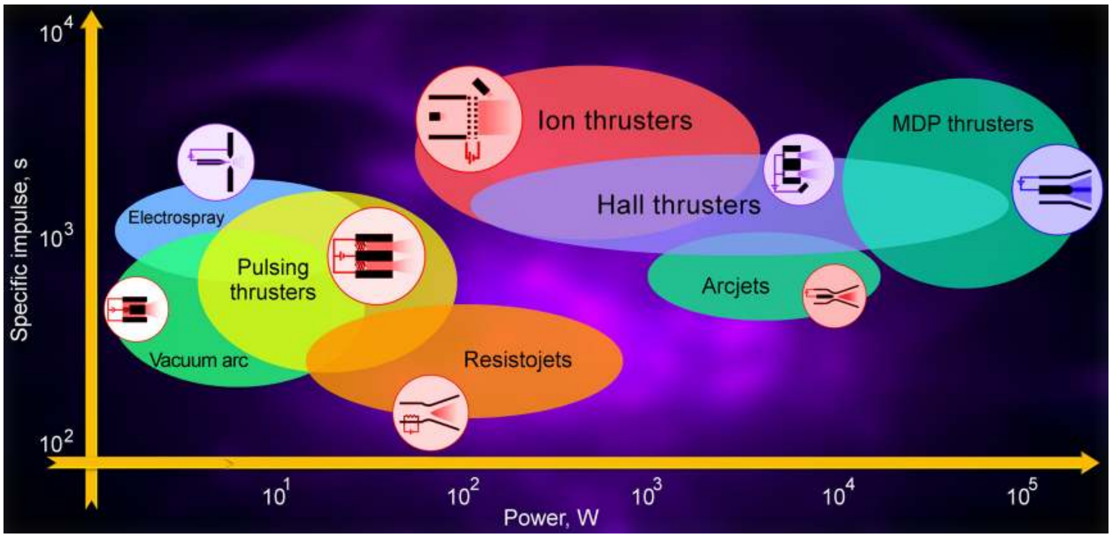

FIG. 3. Characteristic parameters of the major types of space electric propulsion thrusters in the power-specific impulse coordinates. The electric propulsion thrust systems span of five orders of magnitude in power and two orders of magnitude in the impulse. Such considerable diversity enables the use of this family of thrusters across very different missions, from the smallest Cubesat systems to large, powerful spacecraft designed for, e.g., manned flights to Mars. Insets illustrate the principal schematics of each device type.

magnetoplasmadynamic (MPD) thruster [Fig. 5(b)], and pulsing thruster [Fig. 5(c)]. Other examples include the Helicon Electrodeless Advanced Thruster (HEAT), which uses helicon plasma with high density; the plasma is produced using an RF antenna, with rotating magnetic field (RMF) coils operated in the open magnetic field configuration of the divergent field; these are used for the acceleration of plasma. The rotating magnetic field induces an azimuthal current $\boldsymbol{j}_\theta$, and the externally applied static radial magnetic field $\boldsymbol{B}_r$ results in the generation of an axial Lorentz force $\boldsymbol{f}_z$. If successfully realized, the HEAT-type thrusters will be the next step in propulsion technology. At present, however, the prototype devices typically suffer from low efficiency and require further exploration and

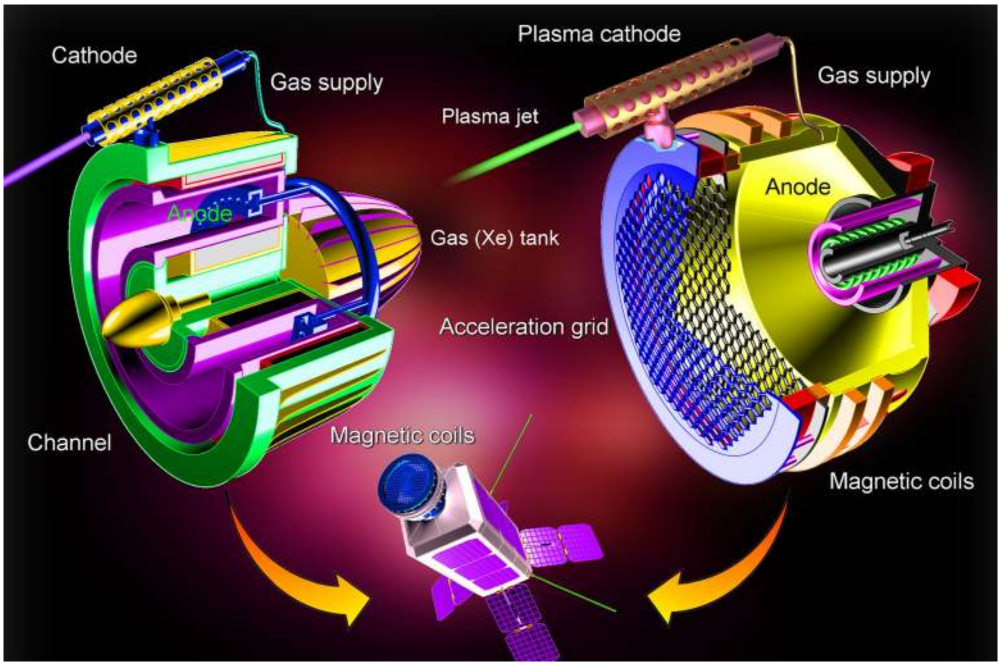

FIG. 4. Electrostatic systems: Hall (left) and gridded ion (right) thrusters, the two major candidates for powering future spacecraft.

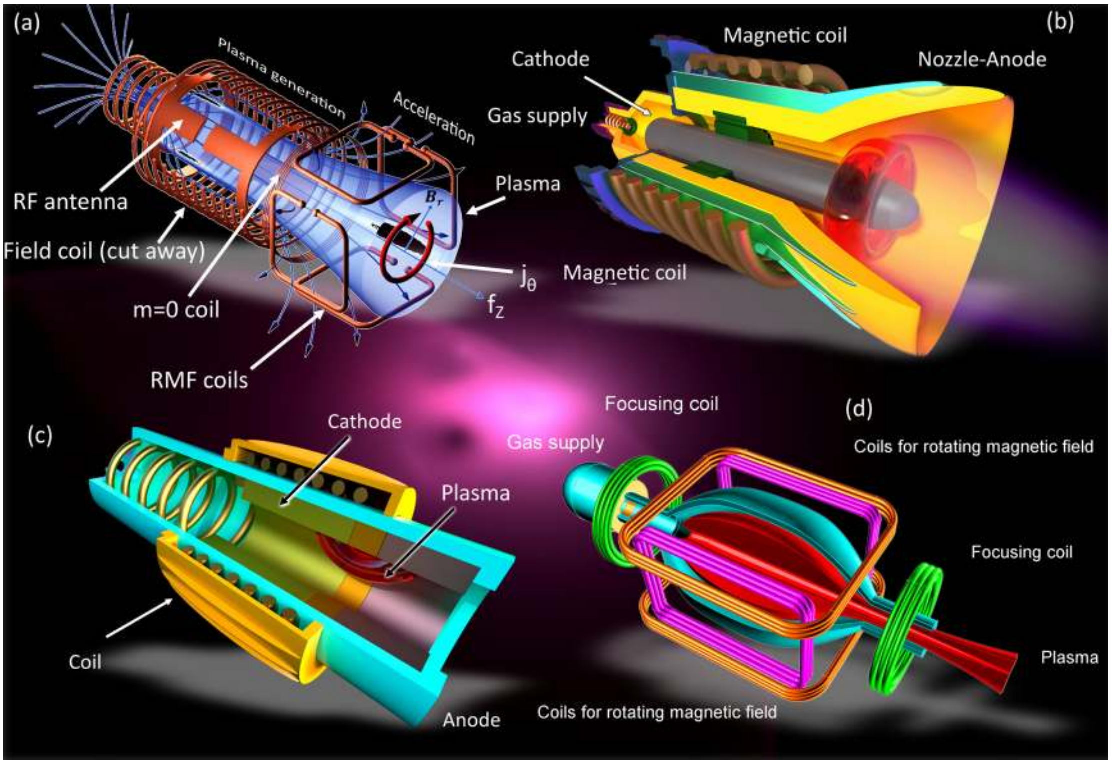

FIG. 5. Electrodynamic space thruster systems. (a) Schematic diagram of the Helicon Electrodeless Advanced Thruster (HEAT). Adapted from Ref. 31. (b) Magnetoplasmadynamic (MPD) thruster. (c) Pulsed plasma thruster. (d) Conceptual Rotamak-type design of a space thruster. (b) and (d) Adapted with permission from Appl. Phys. Rev. **5**, 011104 (2018). Copyright 2018 AIP Publishing.[8]

optimization.[37,38] More details about the characteristics of these devices are presented in Sec. II B.

A. Electrostatic systems: Challenges and opportunities

1. Hall thrusters and variants

Electrostatic thrusters used for space propulsion of satellites and interplanetary spacecraft include two major types, namely, Hall thrusters and gridded ion engines as shown in Fig. 4. Ion engines deliver a high exhaust velocity, but the thrust is limited due to space charge effects. Hall thrusters offer a larger thrust-to-power ratio with specific impulses above 1000 s.[18,39] In Hall thrusters, a DC plasma discharge is created inside an opened annular dielectric cavity, termed the channel, between an anode placed at the back of the channel and an external cathode. Magnetizing coils or permanent magnets wrapped around the channel produce a transverse magnetic field that confines the electrons without altering ion trajectories. The cathode generates energetic electrons needed both for maintaining the discharge and for plume neutralization. The propellant gas, typically xenon for the present generation of Hall thrusters, is supplied to the channel through either a perforated anode, as illustrated in Fig. 4, or a dedicated injection system decoupled from the anode. The cathode-to-anode potential drop is abrupt and located near the channel exit plane, a region where the electron transport across the magnetic field is low due to the high magnitude of the magnetic field.[40] The axial electric field combines with the radial magnetic field to generate a closed electron drift in the azimuthal direction, the so-called Hall current, which efficiently ionizes the propellant gas. Ions are subsequently accelerated outside the channel by the static electric field. Hall thrusters are thus essentially electrostatic ion accelerators.[18] Hall thrusters have been designed to operate across a very broad range of input power from 10 W up to 100 kW using xenon and krypton as propellant.[41] Current state-of-the-art thrusters generate a thrust level between 1 mN and 5 N, while the specific impulse remains between 1000 s and 2500 s, which is well above the maximum value that chemical engines offer.[42] Figure 6 shows an example of a recently developed low-power Hall thruster suited for microsatellite maneuvers.[43] This thruster produces 8 mN at 150 W with an anode efficiency above 30%. Figure 7 shows the evolution of the thrust and the specific impulse with the input power for small Hall thrusters. The general trend is the decrease in the performance metrics when the power, i.e., the size and storage capacity of the on-board power system, decreases. The anode efficiency follows the same tendency. This fact brings to light the difficulty in developing efficient miniature Hall thrusters.

- “Hall thrusters demonstrate high thrust-to-power ratios and high efficiencies over a broad power range, which make them very good candidates for various applications that encompass small and large satellites as well as Earth orbit missions and

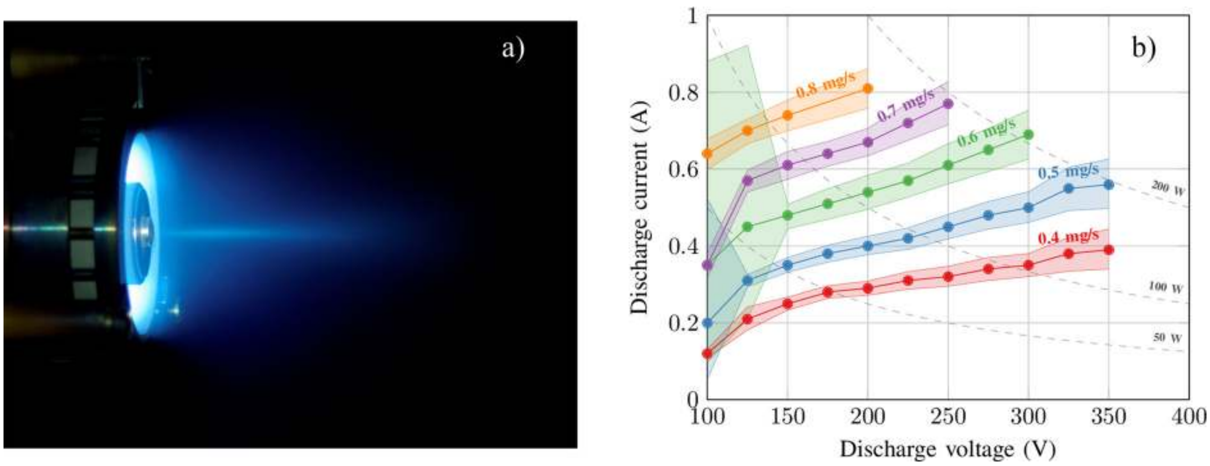

FIG. 6. A 100 W class permanent magnet Hall thruster ISCT100 developed in Orléans, France. (a) Photograph of the ISCT100 firing with xenon at a 100 W input power in the vacuum chamber. A well collimated plasma jet is observed. (b) Discharge current vs applied voltage plot. A low level of oscillation is achieved as shaded areas cover 90% of the discharge current oscillations. Reprinted with permission from S. Mazouffre and L. Grimaud, IEEE Trans. Plasma Sci. **46**, 330–337 (2018). Copyright 2018 IEEE.[43]

interplanetary missions. For example, Hall thrusters are the prime candidates for the upcoming Mars colonization missions, as reported recently by NASA."[41,42]

At present, many groups are actively working to improve the performance and expand the capabilities of Hall thrusters. In addition to increasing the overall efficiency and the thrust level, many studies also focus on extending the lifetime, widening the operational envelope, developing devices with dual-mode (high vs low specific impulse) functioning, and system simplification.

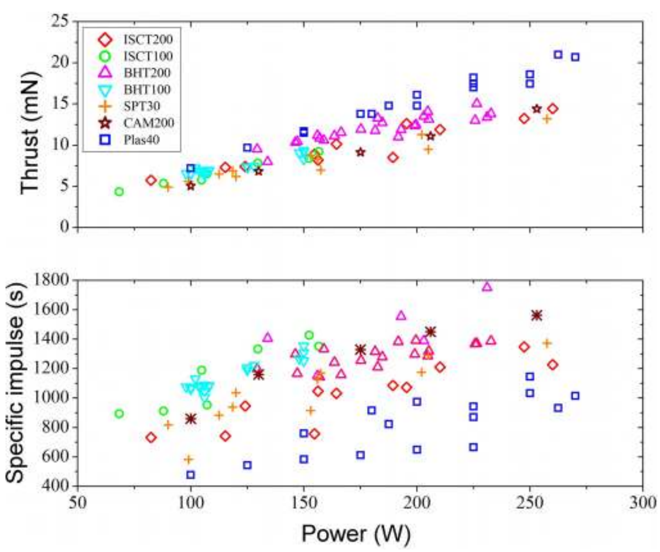

FIG. 7. Thrust and specific impulse against input power for several small Hall thrusters. The thrust, I_{sp}, and anode efficiency decrease when the power decreases.[62] The thrust-to-power ratio, however, remains relatively constant at around 65 mN/kW. Reprinted with permision from Mazouffre *et al.*, Proceedings of the 8th European Conference for Aeronautics and Space Sciences, Madrid, Spain, July 2019, Paper 214. Copyright 2019 Author(s), licensed under a Creative Commons Attribution 4.0 License.[63]

The development of the Hall thruster configuration known as "magnetic shielding" has resulted in a drastic improvement in the thruster lifetime range by decreasing the radial ion kinetic energy in the acceleration region.[18,44–48] Gains in the operational lifetime have been reported across a very broad range of power, with a slight decrease in efficiency at very low power. In addition, magnetically shielded thrusters can operate with conducting walls,[49–51] which provides a pathway to develop new architectures and explore new application possibilities. The wall-less configuration has the potential to provide a means for reducing the wear of the Hall thruster assembly along with proposing a simplified design, which can be manufactured at a reduced cost.[52–56]

Sophisticated magnetic field topologies and multistage configurations are among the possible approaches that are currently considered for the next generation of devices, see Fig. 8.[57–61] A two-stage Hall thruster with a helicon preionization stage has been proposed to enhance the ionization degree of plasma, therefore allowing device operation at high discharge voltages. To achieve this, the helicon stage is placed behind the channel, as shown in Fig. 8(a). Although the addition of radio frequency power allowed us to slightly increase the thrust, the global efficiency and the thrust-to-power of the device drastically decreased.[58] Similar results were obtained with a RF antenna wrapped around a Hall thruster channel.[59] A Hall thruster with two magnetic field peaks inside the channel and an intermediate electrode (IE) placed in the region of low field magnitude is another possible design. The so-called double stage Hall thruster, see Fig. 8(b), allows us to better separate the ionization and acceleration regions, which is necessary to enable dual-mode operation.[64,65] A similar technique has been proposed recently with permanent magnets and an electrode located in a zero field zone near the exit plane, see Fig. 8(c). The two-peak approach has not demonstrated a large increase in the operation envelope,[64] whereas the system is more complex and heavier than a conventional one. An innovative design named ID-HALL for the Inductive Double stage HALL thruster has recently been introduced to

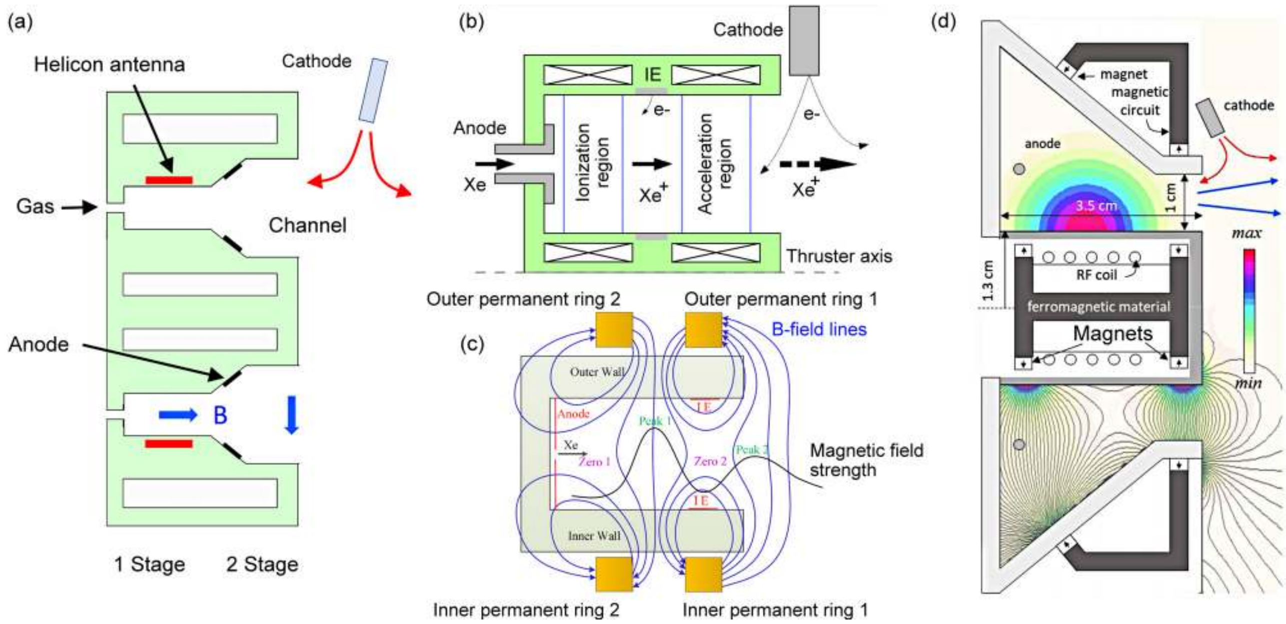

FIG. 8. Examples of strategies currently used to further improve device architecture and increase performance metrics of Hall thrusters. Several conceptual designs have been recently proposed. (a) Double stage Hall thruster with a helicon ionization stage. Reprinted with permission from Phys. Plasmas **25**, 093503 (2018). Copyright 2018 AIP Publishing.[11] (b) Schematic view of the double-stage Hall effect thruster with an intermediate electrode (IE) and a two magnetic field peak configuration. Reprinted with permission from Phys. Plasmas **14**, 113502 (2007). Copyright 2007 AIP Publishing.[64] (c) Drawing of a two magnetic peak Hall thruster using permanent magnets instead of coils. Reprinted with permission from Ding *et al.*, Eur. Phys. J. D **71**, 192 (2017). Copyright 2017 Springer-Verlag.[65] (d) The ID-Hall Double-Stage Hall Thruster. The inner cylinder and a RF antenna used to generate an inductively coupled discharge close to the acceleration channel. Contour plots represent the magnetic field intensity distribution (bottom) along with magnetic field lines and (top) the ideal spatial distribution of the power absorbed per electron. Reprinted with the permission from Phys. Plasmas **25**, 093503 (2018). Copyright 2018 AIP Publishing.[11]

efficiently guide ions produced in the first stage into the acceleration zone.[11] The ID-HALL architecture is depicted in Fig. 8(d). The ionization stage is a RF inductively coupled discharge of which the antenna is placed inside the inner part of the thruster. Magnets combined with a specific magnetic circuit create a magnetic barrier at the channel exit plane, a B-field free region where the plasma is created and a cusp-like structure is formed to limit the losses at walls. ID-HALL is optimized to generate ions in the vicinity of the acceleration region. Preliminary experiments show an efficient operation of the inductively coupled plasma source with a large plasma density upstream the channel and extraction of an ion current when the device operates in a two-stage configuration with a DC voltage applied between the anode and the external cathode.[11]

A promising and effective approach to reach high-power operation and large thrust generation is the nested-channel Hall thruster.[60,61] The principle is to combine Hall thrusters that vary in sizes and power levels into a multichannel thruster, as can be seen in Fig. 9. Nesting the discharge channels lowers the mass and size of this high-power system. In addition, the nested channel configuration widens the operating envelope and enables throttling through the selection of available channels. Thus far, the nested channel technology has been successfully tested with two and three channels, producing thrusters capable of operating at over 100 kW of power. Currently, a two-channel magnetically shielded thruster is under development to demonstrate that operating life-prolonging technologies can be successfully applied to high-power devices. This work is of prime

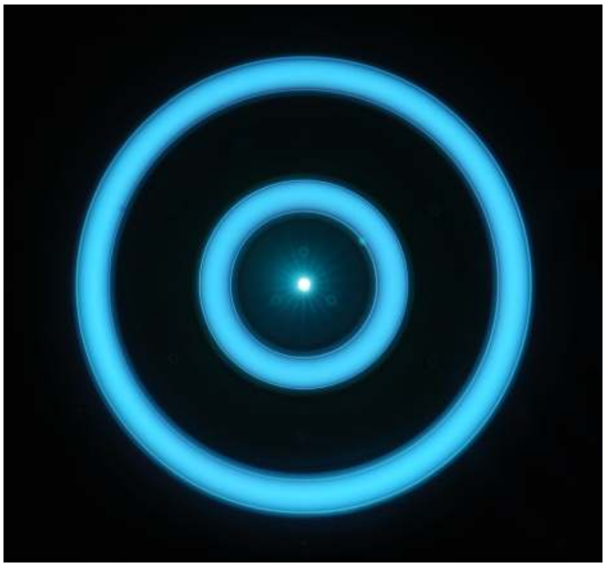

FIG. 9. A 10 kW class X2 two-channel nested Hall thruster with its centered-mounted cathode firing with xenon at full power in the dual channel configuration. Reproduced with the permission from J. Appl. Phys. **123**, 133303 (2018). Copyright 2018 AIP Publishing.[60]

importance as long-life high power Hall thrusters would be a cost-effective technology for near-Earth and deep space applications.

2. Ion engines

In ion engines with the electron bombardment ionization, a cylindrically shaped body houses the discharge unit. The typical unit consists of a thermionic hollow cathode, an anode, and internally mounted permanent magnets to confine the discharge plasma. Externally mounted magnetic coils may be used to confine the plasma in Kaufman ion thrusters. An acceleration grid unit contains internal and external grids used for extraction and acceleration, respectively. An additional cathode is mounted on the outer body of the thruster (Figs. 3 and 9). The propellant, most often Xe, is delivered to the hollow cathode, where ionization takes place within a magnetized discharge. Once it is extracted and accelerated by the respective grids, the ion flux is expelled from the thruster at a high speed. The role of the electron flux produced by the externally mounted cathode is to counteract the electric charging by the ion flux, thus preventing charge accumulation on the spacecraft. It is worth mentioning that in both types of thrusters discussed so far, the plasma is generated and sustained by electron-neutral collisions. Evidently, plasma can be sustained using other methods, for example, by using radio frequency- and microwave-driven ionization, with both methods employed in electric propulsion.

There are many advantages to using gridded ion thrusters, including a very high specific impulse and high thrust efficiency. Not surprisingly, the ion thrusters are among the most promising candidates for automated missions requiring very high fuel efficiency, such as visiting outer planets and asteroids.[66] However, along with the aforementioned advantages, there are a number of drawbacks. These include lower ionization efficiencies as compared to that of Hall thrusters. To overcome this, the radio frequency ionization stages could be used as an alternative promising technology to bring the gridded ion thrusters to the orbit of commercial exploitation. Moreover, the use of iodine instead of the widely used xenon for gridded ion thrusters may provide a promising pathway to reduce the cost of the long space flights; however, it is worth noting that iodine is a corrosive substance and the related degradation must be considered carefully to ensure sufficiently long lifetime of this technology for any given mission. The interested readers may refer to numerous recent publications to review the current state-of-the-art of various types of the modern gridded ion thrusters.[67–72]

- Owing to their very high intrinsic specific impulse and other advantages, gridded ion thrusters have been historically among the most intensely researched space thrust platforms. However, the Hall effect thrusters and other emerging thruster concepts are currently attracting most of the researchers' attention. The use of multistaged radio frequency driven thrusters and alternative propellants such as iodine may present the most promising directions for further development of efficient gridded ion thrusters, particularly for missions that require very high specific impulse at low thrust levels.[73]

B. Electrodynamic systems

There are a number of benefits to using magnetoplasmadynamic (MPD) thrusters. These include attractive thrust density approaching $100\,\mathrm{mN\,cm^{-2}}$, high power (approximately megawatt), lower voltage, a simple device design, and the possibility of using several propellants, including a variety of gases and metallic solids. This makes this form of propulsion highly promising for long-distance missions, such as for deep space exploration, due to a favorable combination of high efficiency reaching 60% and thrust and impulse reaching tens of Newtons and 10^4 s, respectively.[74,75] In this device, the interaction between the current flowing through the plasma and a magnetic field produces the Lorentz force needed for plasma acceleration. The magnetic field can be generated using externally mounted coils or arise from the plasma's own current. It should be noted that there are several concepts of the MPD systems; e.g., the "applied field molecular dynamics (MD)" utilizes the externally installed and powered coils to generate a magnetic field, whereas the "self-field MPD" uses the magnetic field produced by the discharge current flowing between the main cathode and anode. Importantly, MPD thrusters demonstrate higher efficiency in the self-field mode, which features an even simpler design and power supply system due to the absence of external magnetic coils. Capable of producing significant (tens of Newton) thrusts at the megawatt power level, these thrusters are considered among primary candidates for the future missions related to the Mars and Moon colonization, where significant cargo masses would need to be delivered quickly and with the optimal mass-to-cost ratio. They could be also very promising for missions related to the exploration of remote planets, i.e., those missions that currently require many years of flight. However, generating megawatt-level powers in space would require much more advanced nuclear power systems.[74,76]

Unlike pulsed plasma thrusters (PPTs) that are able to generate the high specific impulse at low power, MPD thrusters are not ideal for use in small satellites. Indeed, the former are well suited for attitude and orientation control, and low-thrust maneuvers by small space assets. PPTs that use ablation of solid propellants have the added benefit of design simplicity and high specific impulse.[77,78] These devices take advantage of the inherent properties of plasmas to generate thrust and gain considerably high velocity with very low fuel consumption.[79]

1. Helicon plasma thrusters

Helicon plasma thrusters have emerged as one of the most promising systems that are currently undergoing active exploration. Helicon plasma sources (Fig. 10) generate plasmas by using radio frequency radiation. They generate plasmas of high density ($\sim 10^{13}\,\mathrm{cm^{-3}}$) and can sustain a wide range of external operating parameters. For this reason, many different helicon sources of different geometrical scales have been designed and their ability to control plasmas described.[80–82] As the most types of electric propulsion thrusters mentioned in this article, helicon plasma thrusters feature very complex physics[83–86] but hold great promise for space thruster applications.[87] Experts anticipate rapid evolution of high-density helicon plasma sources, for a number of advantages that they offer when compared to other sources, particularly with respect to the ease of high-density plasmas over a wide range of external parameters. Nevertheless, more research efforts are needed to translate various concepts devised thus far into practical devices to underpin the development of a wide range of future innovative technologies across many fields, including fields of fundamental science.[88–91]

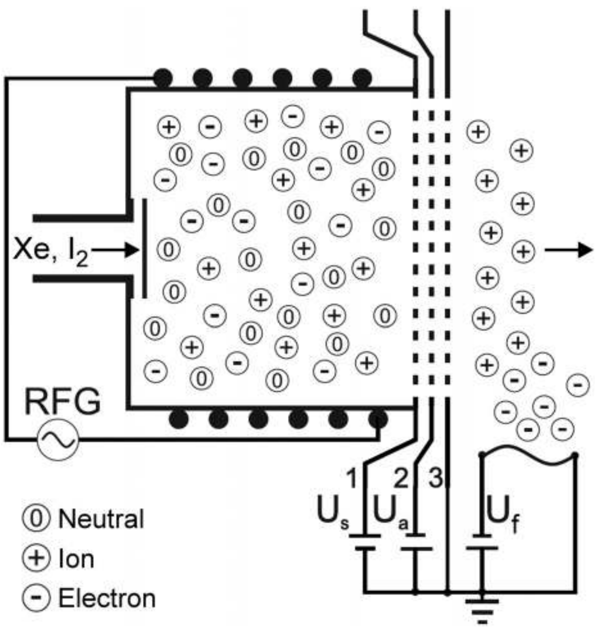

FIG. 10. Schematics of the radio frequency ion thruster including the electric interconnection of extraction grids and thermionic neutralizer. U_s is the screen grid (1) and U_a is the acceleration grid (2) voltage, respectively. The deceleration grid is on ground potential. Electrons for neutralization are provided by a tungsten filament (U_f is the filament heating voltage). Reprinted with permission from Holeste *et al.*, Eur. Phys. J. D **72**, 1–7 (2018). Copyright 2018 Springer-Verlag.[73]

2. Gradually expanded Rotamak (GER)-type devices

Before helicon plasma thrusters can take their place in the suite of widely used propulsion devices, a number of challenges would need to be resolved. These include the erosion of the dielectric wall of the plasma-confining tube (notably, half of the total thruster power can be lost in the form of radial particle transport to the walls[92–94]), comparatively low rate of propellant ionization, instability associated with the use of high-power plasmas, to name but a few. These challenges hinder the advancement of the currently available magnetoplasmadynamic thrusters. The development of a spherical plasma source has provided a pathway for the realization of a "gradually expanded Rotamak" system (GER, Fig. 11) as a potential candidate for space propulsion. With further development, the GER-type devices could enable the production of azimuthal plasma currents, and thus to accelerate species within the plasma, e.g., electrons, ions, and neutral species, through an axial body force. Other advantages of GER-type thrusters are the elimination of preionization stages, neutralizers, and high voltage grids and electrodes typically required for the efficient performance of ion and Hall thrusters. Of most significance is the possibility of scaling operational power regimes, reducing plasma-wall interaction and oblation. These features will likely make GERs a thruster of choice for long haul missions in Low Earth Orbit (LEO), geostationary orbits, and deep space exploration. Rotamak was originally developed (e.g., by Flinders University in the 1960s) as a more compact alternative to a tokamak, since it lacks an inner column[95] and uses a spherical discharge vessel. The external sources are configured to enable a "field reversed configuration" as well as other current drive schemes.[96] A prototype GER propulsion device was recently developed by the Space and Propulsion Center (SPC) at the National Institute of Education, Nanyang Technological University, Singapore. Early results of its use for space

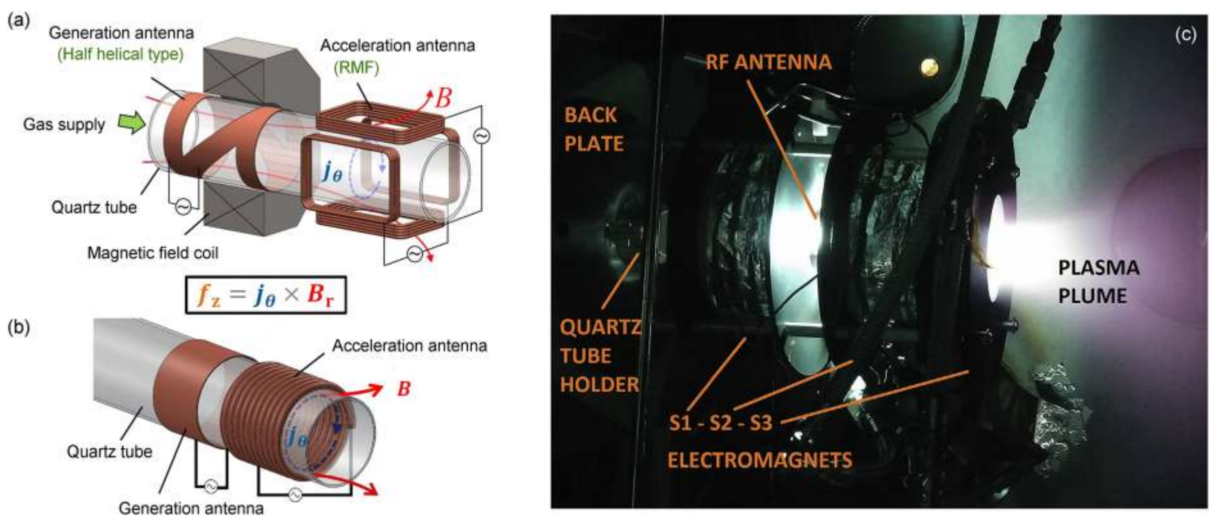

FIG. 11. (a) and (b) Schematics of the helicon plasma systems operating in the "rotating magnetic field" (RMF) mode, which has been originally utilized in the nuclear fusion field (a), and in the $m = 0$ "half-cycle acceleration mode" (here, m is an azimuthal mode number). The basic mechanism is to induce an azimuthal current j_θ in the divergent magnetic field to produce the $j_\theta \times B_r$ axial Lorentz force, where B_r is the static radial magnetic field. Reprinted with permission from Plasma Phys. Controlled Fusion **61**, 014017 (2019). Copyright 2019 IOP.[80] (c) Helicon plasma thruster firing in the 500–1000 W radio frequency power range, at 13.56 MHz with xenon in the vacuum chamber. Importantly, in the helicon thrusters, the plasma flow could be efficiently controlled.[90] Reprinted with permission from Vacuum **149**, 69 (2018). Copyright 2018 Elsevier.[88]

propulsion are encouraging, confirming its potential for the eventual development into a pure electromagnetic thruster that could sustain high density, noninductive plasmas. A pair of parallel RF coils can be used to sustain these plasmas, with the coils located outside of a spherical confinement vessel. Additional coils are located orthogonally to the former RF coils to provide a poloidal magnetic field by the DC pulses. The poloidal field confines and densifies the plasma in the middle of the vessel. It is possible to modify the device configuration and geometry to build a fully electromagnetic thruster, with the acceleration and the thrust sustained by an axial force in the absence of any neutralizes and grids, typical of conventional electric propulsion platforms. Larger thrusts per unit of the propellant spent could be generated, the latter being a requirement for longer-haul missions.

3. Arc thrusters

Pulsed and ablative systems are examples of thrust systems that share similar physical mechanisms and very small size (up to several millimeters), which makes them well suited for small satellites.[97–99] "Microcathode arc thrusters" (μ-CAT, Fig. 12) are also actively investigated, with examples including microthrusters employing a Ring Electrode, a Coaxial Electrode, and an Alternating Electrode developed by the George Washington University's Micropropulsion and Nanotechnology Laboratory (MpNL) since 2009. These configurations differ with respect to their performance and operational characteristics, namely, thrust and working life. On average, μ-CAT available at present features a thrust-to-power ratio and efficiency of approximately 20 μN/W and 15%, respectively. A major limitation of this device is that ~10% of the discharge current contributes to the ion current, and thus to thrust, with ~90% of the discharge current conducted by electrons spent on anode heating.[8,100,101]

Overall, at the present stage of development and understanding of the basic plasma physic mechanisms of the electrodynamic space thrusters, we can see the following opportunities and advantages presented by electrodynamic plasma thrusters when compared to electrostatic and electrothermal propulsion devices:

- ability to produce considerable thrust densities, since particle acceleration is not restricted by the positive space charge in the acceleration channel or by grid electrical screening;
- absence of the requirement for a neutralizer since the ponderomotive force is capable of accelerating all plasma species along the direction of the plume;
- ability to switch the thruster between optimum specific impulse and greater thrust while maintaining constant power enabled by the inherent multistaged nature of the electrodeless plasma thruster, which allows for independent optimization;
- minimal electrode degradation and absence of plasma contamination for the helicon and Rotamak devices enabled by the use of a combination of nonuniform high frequency field and a static magnetic field to generate the ponderomotive force, which means that the plasma does not come into direct contact with electrodes and no grids are used for species acceleration and extraction.

C. Hollow cathode systems for space electric propulsion thrusters

Hollow cathodes are used in the Hall effect and ion thrusters to provide electrons for the propellant ionization and the neutralization of the ion beam. The cathode affects the overall performance and lifetime of the thruster unit. The cathode propellant consumption, along with a possible additional power required to ensure its operation, has a direct impact on the thrust efficiency. The cathode position is an important aspect to be studied, since it affects the thruster performance characteristics and the cathode erosion. As such, important goals for the cathode development include the reduction of propellant consumption, improvement of the thermal design to lower the heat losses from the hot parts, and the increase in the cathode service life. Below, we will briefly discuss the recent advances and current trends in the development of hollow cathodes, starting from an outline of the basic physical phenomena involved in the operation of hollow plasma cathodes. We will then discuss some of the achievements in the modeling and simulation of plasma cathodes and describe the design and performance of low and high current hollow cathodes, respectively.

1. Physical phenomena in cathodes

The general schematic of a traditional hollow cathode is shown in Fig. 13.[39] The cathode uses a refractory metal tube to support the

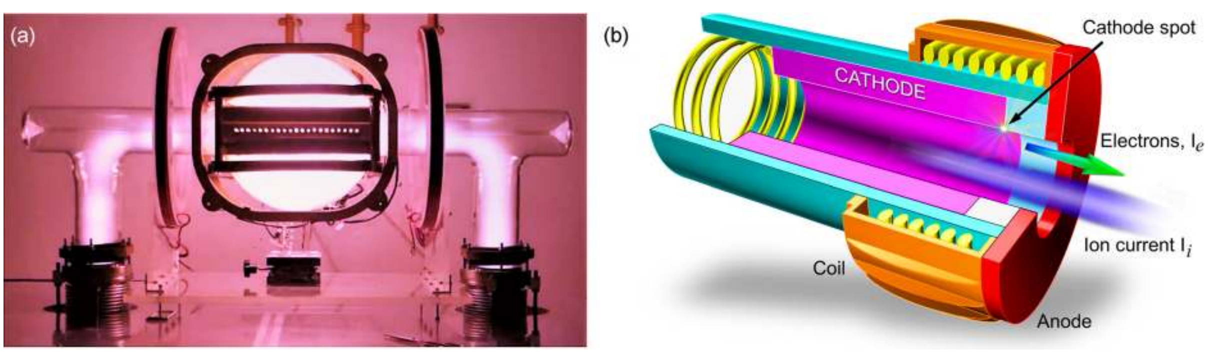

FIG. 12. (a) Lab prototype of the Rotamak system, now under exploration as a novel elctric propulsion system at the Space and Propulsion Center (SPC) at the National Institute of Education, Nanyang Technological University, Singapore. (b) Schematics of the proposed concept of the microcathode arc thruster with high thrust (μ-CAT-HT). Such a thruster can feature a thrust-to-power ratio of about 20 μN/W, with the efficiency of up to 15%. Plasma is also accelerated by the Lorentz forces. Reprinted with permission Levchenko *et al.*, Appl. Phys. Rev. **5**, 011104 (2018). Copyright 2018 Author(s), licensed under a Creative Commons Attribution (CC BY) license.[8]

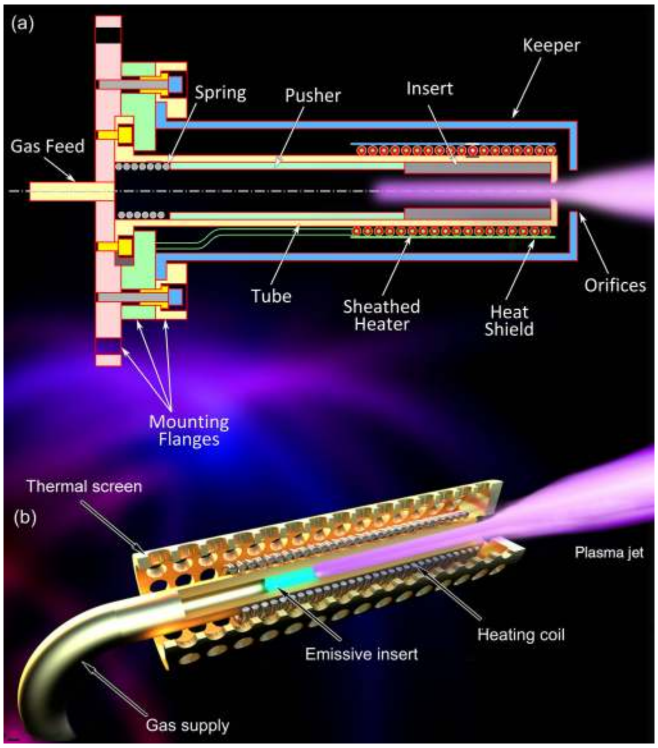

FIG. 13. A typical configuration of a hollow cathode showing its main components.[39] The insets made of a material with a low work function ensures an efficient emission of electrons. A heater is used to maintain the high temperature needed for electron emission and also reduces the total heat flux from an outer surface of the cathode (an additional thermal screen can also be used to further enhance the device efficiency). Reprinted with permission from Levchenko *et al.*, Nat. Commun. **9**, 879 (2018). Copyright 2018 Author(s), licensed under a Creative Commons Attribution 4.0 License.[139]

thermionic insert (or emitter). The insert is kept in its position by a pusher and spring arrangement and is pushed against a refractory metal end plate with a chamfered orifice. Historically, two types of inserts have been used in hollow cathodes: barium-oxide impregnated tungsten dispenser inserts and lanthanum hexaboride (LaB_6).[102] Barium-oxide inserts have a low work function (about 2.1 eV), but a maximum continuous current density of 20 A/cm^2 at a temperature of about 1200 °C. The LaB_6 insert is a well-known thermionic insert that has been used in low power flight Hall thrusters built in the Soviet Union and later in the Russian Federation since the 1970s.[103] LaB_6 inserts have a higher work function (2.67 eV) when compared to BaO dispenser cathodes and therefore operate at a temperature just exceeding 1600 °C to generate approximately 10 A/cm^2 emission current density. LaB_6 also has low evaporation rates and is insensitive to poisoning from the impurities in the propellant gas.

A heater can be included in the cathode assembly to warm the insert up to the thermionic emission temperatures prior to ignition. High current cathodes feature a high temperature coaxial sheathed heater, which is wound around the cathode to deliver sufficient heating to start the discharge. Alternative heater solutions in use or under development are described in the recently published comprehensive reviews on the cathodes for electric propulsion systems.[32] A heat shield comprising layers of thin refractory metal foil encases the heater coil to provide for greater heating efficiency. This arrangement is surrounded by an isolated "keeper" electrode, the purpose of which is to assist in igniting the discharge and also to provide protection to the orifice plate against the energetic ion bombardment from the cathode plume. The selection of material for the keeper electrode is aimed to minimize sputtering, with graphite keepers often chosen for present high current cathodes.

In recent years, extensive theoretical research on a variety of hollow cathode phenomena has been conducted. The research focused mainly on several specific physical processes: the neutral flow dynamics in the cathode interior,[104,105] electron transport and anomalous resistivity,[106–111] and spot and plume mode physics.[112,113] Particular attention was given to the theoretical and experimental investigation of cathode instabilities, in both the cathode interior and cathode plume region.[114–116] The ultimate goal of the aforementioned studies was to broaden the understanding of cathode-related physics, as well as to formulate relationships between the various cathode parameters. These relationships would enable the design of more power- and propellant-efficient cathodes.

Confronting the aforementioned theoretical challenges would advance the cathode effectiveness in the near future and provide researchers with the ability to adequately design and test hollow cathodes.

First, deeper understanding of cathode plume physics would enable proper testing of cathodes in diode mode configurations (against an anode structure instead of with a thruster). Further understanding of the cathode plume physics can dictate the required experimental setup, i.e., anode geometry, cathode-anode distance, additional peripheral mass flow rate, background pressure, etc.

Second, an improved theoretical understanding of the cathode/keeper orifice physics would lead to possible mitigation of orifice wear that would potentially extend cathode life and enable operation at a wide range of discharge currents, specifically high current levels.

Third, theoretical understanding of the interaction between the plasma flow and the interior cathode structure would allow for the development of novel cathode configurations. For example, the physics of "open-end emitter, orificed keeper" configurations, commonly used in heaterless hollow cathodes (HHCs), would reveal the optimal geometry for the efficient emitter heating while minimizing ion density and energy in the vicinity of the keeper orifice, thus reducing orifice erosion.

Finally, it is natural that further theoretical research of cathode-related physics would unfold a myriad of new possibilities, currently unconceived, ultimately leading to new and improved cathode configurations, designs, and cathode operation schemes.

2. Low current hollow cathodes

The low current cathodes find their principal use in nano- and microsatellites deployed for varied purposes: scientific research, Earth observation, astronomy, as well as technological, educational, and military applications. As previously noted, advances in microelectronics and miniaturized systems provided the practical means to lower the operating power of electric thrusters, with the goal of addressing the micro/mini propulsion market.[8] The related activities aim at the development of propulsion subsystems characterized by low cost, low power consumption, low mass, high thrust controllability, and manufacturing capability. The latter aspect is particularly important for constellations of satellites, which will mainly use electric propulsion for end-of-life de-orbiting. Another aspect under continuous investigation is the possibility to operate the electric thrusters with alternative propellants; in particular, iodine is a valid candidate to be used in low-power applications.[117]

The traditional hollow cathode architecture (Fig. 14) based on lanthanum hexaboride or barium-oxide tungsten impregnated inserts has been adopted by various research institutions and industries.[118–123] However, other promising insert materials, such as the electride C12A7e-, are under investigation for the low current class of hollow cathodes.[124,125] The traditional hollow cathode design presents a single point of failure, namely, the heater. The heater is generally made of a refractory wire (tantalum or tungsten alloy) and is electrically insulated from the cathode tube by means of ceramic components. Alternatively, a potted heater is included in the cathode assembly. The mineral insulated cables used to heat the high-current hollow cathodes could also be used for the low current cathodes, provided the cable dimensions are efficiently scaled down to fit the smaller geometrical envelope.[32]

To overcome the reliability and manufacturing issues related to the heater, the Heaterless Hollow Cathode (HHC) architecture was devised that does not require external heating to bring the electron insert to its operation temperature. Instead of using external heating, as with conventional cathodes, HHCs are heated via plasma heating. When the temperature of the electron insert is sufficiently high, the HHC works in a similar way to any other conventional hollow cathode operating, under steady state conditions. HHCs are suitable primarily for low-current hollow cathodes, since the heaterless ignition may induce a high thermal stress on the insert when reaching relatively high discharge current levels.[126–128]

In recent years, the interest in HHCs for low current hollow cathodes has been growing.[129–134] The quick ignition time, low power demand during the ignition phase, and the potentially longer lifetime have made these cathodes an attractive option for low power ion and Hall thrusters. To date, the HHC technology has overcome two technological challenges: the ignition voltage has been reduced to merely several hundred volts[123] and the transition to operational temperature of the insert is with minimal damage to the cathode, thus allowing for thousands of ignitions.[134] Further, it was shown that low-power HHCs can operate adequately with different insert materials such as the electride C12A7e-,[130,131] BaO-impregnated tungsten,[133–135] and LaB_6.[132,133]

Nevertheless, the current state of HHC technology development still needs to overcome two leading challenges:

(1) Cathode conditioning: after the exposure to ambient air, the insert must be conditioned, which is gradually heated to emit impurities.[136] However, since HHCs are heated using plasma that is formed within the cathode cavity, a dedicated rigorous and methodological research is needed to identify the appropriate cathode conditioning schemes. The research should focus on correlating the keeper (or anode) current, insert temperatures, and the required time to achieve the cathode conditioning for each current level;
(2) The sensitivity of breakdown voltage to temperature: it has been demonstrated that in the cylindrical geometry, the decrease in the temperature leads to an increase in breakdown voltage.[137] A device the use of which can lead to the reduction of HHC temperatures prior to ignition has been proposed and physically realized.[138] However, the outcomes of the test of the sensitivity of cathode ignition to cathode temperature have not yet been communicated to the research community. To properly qualify an HHC for in-space missions, its sensitivity to low temperatures, primarily the required ignition voltage, should be studied experimentally.

New frontiers of the low current cathode development are likely to include new designs, new concepts, and new advanced materials, and the combination of thereof. For example, ultrananoporous inserts are under study to reach a longer cathode lifetime, through a larger surface area per volume unit, also increasing the efficiency due to the smaller required heated volume.[139] Carbon nanotubes possess a potential for cold, propellant-free cathodes, whereas nanoscale metamaterials capable of reversal heat transmission could help reduce heat losses.[140]

Concerning the mass production of hollow cathodes, advanced manufacturing techniques (e.g., additive manufacturing) could play an important role, especially with ongoing simplification of the cathode design and manufacturing flow; mass production is necessary to meet the current and future needs of ambitious satellite constellations.[32]

3. High current hollow cathodes

Hollow cathodes used in the present day ion thrusters and Hall thrusters are capable of producing discharge currents of up to about

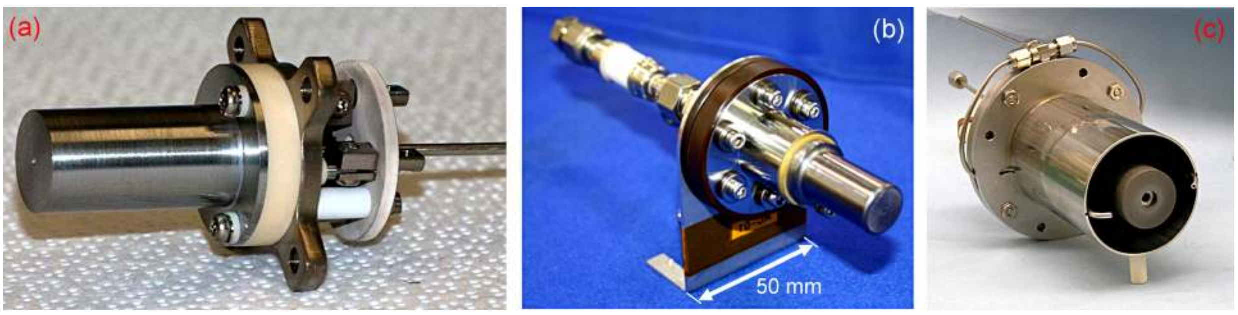

FIG. 14. (a) SITAEL's HC1 cathode and (b) Rafael's RHHC (Rafael Heaterless Hollow Cathode) cathode. (c) The X3 cathode assembly with external gas injectors required for operation over 200 A of discharge current. (a) and (c) Reprinted with permission from Lev *et al.*, Rev. Mod. Plasma Phys. **3**, 6 (2019). Copyright 2019 Springer-Nature.[32] (b) Reprinted with permission from Lev *et al.*, IEEE Trans. Plasma Sci. **46**, 311 (2018). Copyright 2018 IEEE.[126]

25 A. The next generation of Hall thrusters are designed to operate in the 5–20 kW range and thus require discharge currents of less than 50 A. The design of high current hollow cathodes dated back to the 1970's, when they were developed to neutralize the beam from ion sources intended for injection heating in fusion applications.[141] These cathodes routinely in the range of 50 to over 500 A of discharge current, which, for the purpose of this discussion, can be considered as "high current" hollow cathodes. There are five major issues that dominate the design of high current hollow cathodes:

1. Insert design, in terms of current density and evaporation;
2. Effective emission length;
3. Orifice plate design;
4. Heater design;
5. Suppression of erosion phenomena.

Theoretical modeling and numerical simulations prove to be effective tools to design hollow cathodes, besides providing explanations of experimental results in terms of performance and lifetime, as described in Sec. III.

At temperatures over 1100 °C, BaO dispenser cathodes have significant evaporation rates and tend to form tungstates. Both of these factors limit their life in high current applications where power deposition from cathode self-heating is significant. A preferable insert material for high current hollow cathodes is LaB_6: the higher temperature operation and the higher emissivity of LaB_6 (compared to BaO-W inserts) mean that the insert radiates effectively and overheating is not a significant issue.

The plasma density profile along the axial direction in the insert region is an important characteristic of high current hollow cathodes, since it defines the plasma contact area and thus the insert temperature profile. The axial uniformity in plasma density affects the uniformity in both the insert temperature and the evaporation rate. In addition, if the plasma density is excessively low close to the insert upstream end, the thermionic emission of electrons can be limited by space-charge effects, thus lowering the current provided by the insert. Operation at higher discharge current and higher gas flow rates often required by higher power thrusters tends to constrict the plasma in the downstream portion of the insert, limiting the effective emission length. The only solution is to enlarge the cathode diameter, selecting larger insert and orifice diameters, to operate the cathode in the nominal 1-Torr pressure range.[39]

The maximum allowed current of a hollow cathode is often limited by the orifice plate, since the orifice dimensions drive the current density of the electrons drained from the insert, ultimately affecting the growth of instabilities and energetic ion production in the cathode plume. The orifice size also determines the pressure inside the cathode for a given gas flow;[142] as described previously, this would impact the plasma contact area, the required insert temperature to produce the discharge current, and therefore the insert life. Finally, orifice plate heating is significant in high current hollow cathodes,[143] and larger orifice plates are required to radiate the power away. High current hollow cathodes have large radiation and conduction areas and so require high power (200–400 W), high temperature (>1400 °C) coaxial sheathed heaters or filament heaters wound in an insulating mandrel around the cathode tube. Conventional BaO-W dispenser hollow cathodes use coaxial sheathed tantalum heaters with a MgO powdered insulation capable of nominally withstanding up to about 100 W of power. High current LaB_6 hollow cathodes typically use a tantalum sheathed-heater that incorporates high-temperature alumina-powder insulation.[143] Alternative heaters based on refractory metal filaments in ceramic mandrels or thin film heaters on ceramic substrates are under development for this application.[144]

Operation of hollow cathodes at high discharge currents tends to generate ionization instabilities or current-driven turbulent ion acoustic instabilities in the near cathode plume.[111] These result in the energetic ion generation that erodes the cathode and keeper orifice plate and limits the cathode life. These modes are avoided in lower current hollow cathodes by means of a particular selection of the cathode orifice diameter and the mass flow rate, at a fixed discharge current. However, the same solution is not sufficient in the case of high current hollow cathodes, where exceptional means are needed to suppress or damp the instabilities. The injection of additional neutral gas in the near plume of the cathode has been found to successfully damp the ionization and ion acoustic instabilities. An increase in the cathode mass flow rate to damp the instabilities is not a recommended solution since, as described above, the higher internal pressure constrains the plasma in the downstream portion of the insert, lowering the contact area thus affecting the lifetime. Nevertheless, a propellant source similar to the cathode mass flow rate can be added externally to the cathode or into the plume through the cathode to keeper gap to damp the instabilities. The 2.1-cm-dia. X3 cathode was provided with an additional gas feed external to the cathode orifice plate for all the operating points from 200 A to 330 A of discharge current. Figure 14(c) shows the X3 cathode with the external gas injectors. High current hollow cathodes that are capable of producing 50 to 300 A of discharge current are available now for development as propulsion cathodes. Achieving higher current with long life will require larger diameter inserts to provide more area for electron emission, larger insert IDs for sufficient penetration of the plasma density upstream for complete contact area with the insert, thicker inserts for longer life, larger cathode orifice plates to radiate the power away, higher power heater designs, and optimized external gas injection schemes.

Hollow cathodes in the range 50–300 A are now under development for electric propulsion applications.[145,146] Higher current levels with extended lifetime will be achieved selecting inserts with larger Inside Diameters (IDs), to increase the emission surface and to enhance the plasma penetration in the upstream direction for a total contact with the insert, increased insert thicknesses to extend the lifetime, larger orifice plates to improve the power radiation, more powerful heater designs, and solutions to externally inject additional gas in the near plume. Despite many of the advantages of LaB6, namely high current capability with long lifetime (tens of thousands of hours), low sensitivity to contaminants, and the possibility to sustain the heating due to high current operation, new materials with low work function and evaporation rate are under study. The theoretical study of cathode operation, thermal behavior, and plasma plume instabilities deserves to be pursued to achieve fully predictive capabilities of the design codes.

III. MODELING AND SIMULATION: CHALLENGES AND FRONTIERS

A. Modeling approaches

Numerical modeling and simulations are very powerful tools; their use can drastically reduce the time and resources needed to design, test, and optimize space propulsion thrusters. Moreover, modeling and numerical simulations have become even more important for miniaturized plasma thrusters, since the reduction of the scale of the device inevitably results in increasing difficulty and invasiveness of the direct measurement approaches. In addition, with recent advances in in the high-performance computer (HPC) technology, the high-fidelity of reproduction and rapid execution time of numerical models are improving quickly. As a proof of the importance of numerical modeling in the electric propulsion community, a dedicated project named LANDMARK[148] (Low temperAture magNetizeD plasMA benchmaRKs) has been developed in the last two years. The project aims to (1) provide an open forum for evaluating methods used to describe plasma transport in nonfusion magnetized plasmas (e.g., ion sources, Hall thrusters (HTs), magnetrons, cusped-field thrusters, etc.); (2) define benchmark test cases for full-kinetic, fluid, and hybrid methods; (3) address physics issues linked to the questions of anomalous transport across magnetic field, instabilities, plasma-wall interactions, and their possible effects on particle and energy transport; (4) facilitate international collaboration and promote mutual understanding among researchers.

B. Kinetic techniques

The full kinetic description has often been applied to HT configurations. Since electron thermalization and isotropization rates are quite low in HTs, kinetic approaches are more suitable to represent the important deviations of electron distribution functions from the Maxwellian one. Furthermore, kinetic approaches are of *ab initio* type and do not require any empirical adjustable parameter to fit the experimental current. Among the different kinetic techniques, the Particle-in-Cell-Monte Carlo Collision (PIC-MCC)[149] model in the electrostatic approximation is the one that is most commonly used. It consists of a mixed Lagrangian-Eulerian (particle-mesh) solution of the coupled Boltzmann-Poisson equations. By means of the Klimontovich-Dupree representation of distribution functions, electron and ion Boltzmann equations reduce to the solution of equations of motion for macroparticles (clouds of real particles representing small regions of the phase space). Figure 15 illustrates the typical PIC-MCC cycle. The charge density is deposited on a spatial mesh (the size of which must be smaller than the Debye length, step 3) where the electric potential is solved (step 4) and from where the electric field is interpolated back to the macroparticle locations (step 5). After pushing the virtual particle (step 1) and before restarting the PIC cycle again, a MCC[150] module (step 2) is called to process volumetric (i.e., electron-neutral, ion-neutral, and Coulomb collisions) or surface events (i.e., secondary electron emission,[151] ion sputtering,[152] etc.). PIC-MCC is a very powerful numerical tool that allows for a very accurate and extremely detailed analysis of plasma and discharge parameters. However, there are important constraints associated with PIC-MCC methods. In the explicit version where the electric field is supposed to be constant during one time step, the integration time step must be less than the inverse of the plasma frequency. The grid spacing must also be limited to make sure that one particle does not move over more than one grid interval during the time step. Another constraint is that the number of particles per cell of the simulation must be large enough to avoid statistical errors and numerical heating.

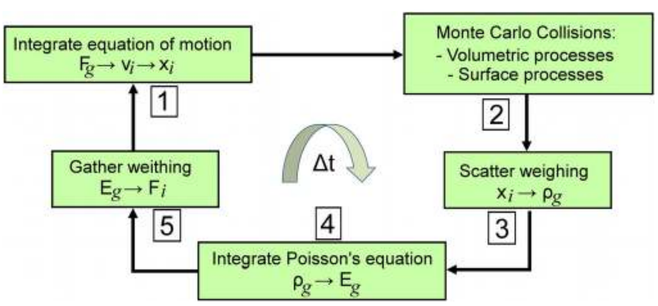

FIG. 15. Diagram showing one integration time steps in a PIC MCC simulation. Adapted with permission from J. Appl. Phys. **121**, 011101 (2017). Copyright 2017 AIP Publishing.[147]

The most important features of the HT PIC-MCC models are as follows:

(i) Solution of the Poisson equation for the self-consistent electric field. It allows resolving the deviation from the quasi-neutrality in the plasma-wall transition regions.
(ii) Detailed description of the electron-wall interactions.[153] With a high surface-to-volume ratio, plasma-wall interactions play an important role, not only as a source of energy loss but also as an active source of particle and energy terms.
(iii) Ability to reveal microinstabilities and self-organized structures typical of E×B partly magnetized low temperature plasma devices, such as electron E × B drift,[154,155] spoke,[156] sheath,[157] and two-stream[158] instabilities. Detailed description of methods, advanced numerical algorithms, and high-performance computing techniques applied to PIC-MCC models can be found in the recent review publications.[159,160]

Figure 16 shows examples of self-organized structures detected by the PIC-MCC models. In Fig. 16(a), the temporal evolution of the azimuthal profiles of electron density is reported. It is evident that the electron E × B drift instability is characterized by a nonlinear evolution toward longer wavelengths by an inverse energy cascade. Figure 16(b) reports the $m = 1$ spoke instability rotating with a velocity of 6.5 km/s. Both phenomena lead to similar high-frequency electric field oscillations characterized by a wavelength of mm-scale, frequency of few megahertz, and amplitudes of the order of 100 V/cm that have also been experimentally observed[161] and are considered as very effective in inducing the anomalous electron cross field transport.[163,164]

The primary challenge concerning PIC-MCC codes is being able to describe HTs through a full three-dimensional representation. It may be possible to address this challenge by increasing their scalability up to 10^5 processors using optimized Poisson equation solvers, implementing particle sorting techniques, and taking advantage of the particle domain decomposition on the modern supercomputer architecture [the central processing unit (CPU)/graphic processing unit (GPU) combination].

- Kinetic PIC methods are extremely powerful and convenient tools to significantly cut off the time and resources need for optimization of plasma thrusters; further development of this technique is in high demand.

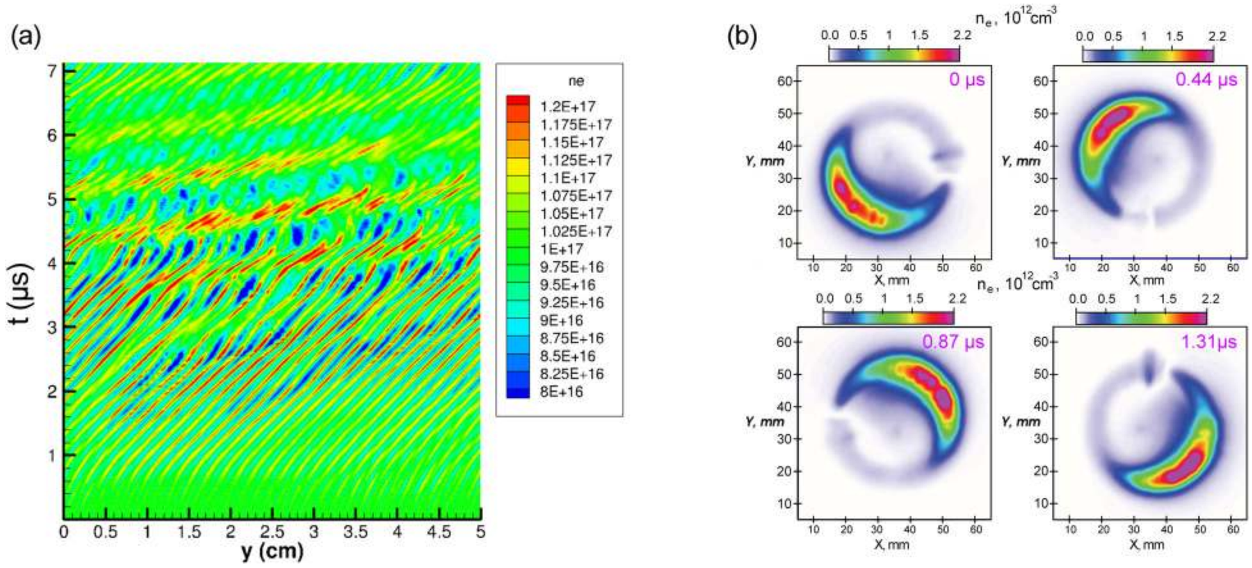

FIG. 16. (a) Temporal evolution of the electron density profile along the E × B direction y in the acceleration region of HT. (b) Evolution of the plasma density 3 mm above the anode during the spoke cycle. Reprinted with permission from Matyash *et al.*, Proceedings of the 36th International Electric Propulsion Conference, Vienna, Austria, September 15–20 (2019), Paper No. IEPC-2019–437 (2019). Copyright 2019 ERPS.[162]

- Kinetic numerical modeling is efficient for investigating self-organized structures and microinstabilities typical of E × B partly magnetized low temperature plasma devices.

C. Direct simulation Monte Carlo (DSMC) and atomistic simulation techniques

The Direct Simulation Monte Carlo (DSMC) method is actually a class of kinetic methods, which uses probabilistic (Monte Carlo) simulation to solve the Boltzmann equation (Fig. 17). As a random particle-based method, DSMC can be used to solve dilute gas flow problems. Originally developed by Bird more the 50 years ago, DSMC has evolved into becoming one of the most frequently used approaches for simulating the flows of gas within the so-called nonequilibrium Knudsen number regime.[165] In this approach, each individual particle embodies a significant number of gas species (i.e., real atoms or molecules). This notably reduces the computational power needed to execute the simulation when compared to molecular dynamics (MD) and other fully deterministic approaches. These individual particles are allowed to move freely in space, characterized by their individual velocity and the local time step. The particles can engage into interactions with other particles, as well as with the margins that confine the system. The collisions between the particles are considered stochastically after all individual particle movements have occurred. In doing so, as it progresses, the simulation reflects the physical processes that take place in a real gas instead of trying to resolve Newton's equations of motion for a large set of individual atoms/molecules, as is the case in fully deterministic MD methods.[166]

There are a wide variety of collision phenomena that can be described by means of the DSMC method. These include the exchange of momentum, charge, and internal energy between the colliding particles, as well as chemical reactions that make take place when particles interact. The properties of individual particles are time averaged to obtain the average characteristics of the gas flow, including its density, velocity, and pressure. It is possible to stimulate unsteady flows by considering the average properties over discrete periods of time or by applying ensemble averaging.[167] This method is particularly suitable for simulating hybrid particle-fluid systems, where electrons impacting on the heavy particles are defined as a fluid, and the particles represent the heavy species.[168,169] Specifically, when using the DSMC technique, the principal elastic and charge exchange collisions can be included in the model, thus ensuring the sufficient level of accuracy. In the No-Time-Counter method typical for DSMC,[170] the selection and rejections of the pairs of individual particles for collisions within cells are performed statistically. It is possible to assign distinct macroparticle weightings to individual heavy species. Since this method is very powerful for modeling and studying phenomena in very rarefied gases, it could be used, e.g., for investigating the interaction of plasma jets with the background gases.[171,172] Using this technique, it has been demonstrated that the characteristics of the jet of plasma are highly affected by the nature of the background. Since these parameters are of importance for propulsor incorporation into the spacecraft, experimental parameters obtained in the vacuum tank environment should be analyzed with a degree of caution.[170,173] Not surprisingly, this method is also promising for studying the interactions of electric thruster-produced ions with spacecraft. Indeed, this problem features very rarefied ion fluxes that are hard to model but which could, at a long time runs of several years required for interplanetary travels, cause severe damage to the structure of spacecraft and instruments installed on board of these space assets.[164]

Atomistic simulation techniques are mainly used to simulate the plasma-material interactions, which is very important for predicting material wear and sputtering and for modeling service life of the thrusters, the components of which are subject to strong ion, electron, and heat fluxes, e.g., accelerating grids of ion thrusters[174] and walls of

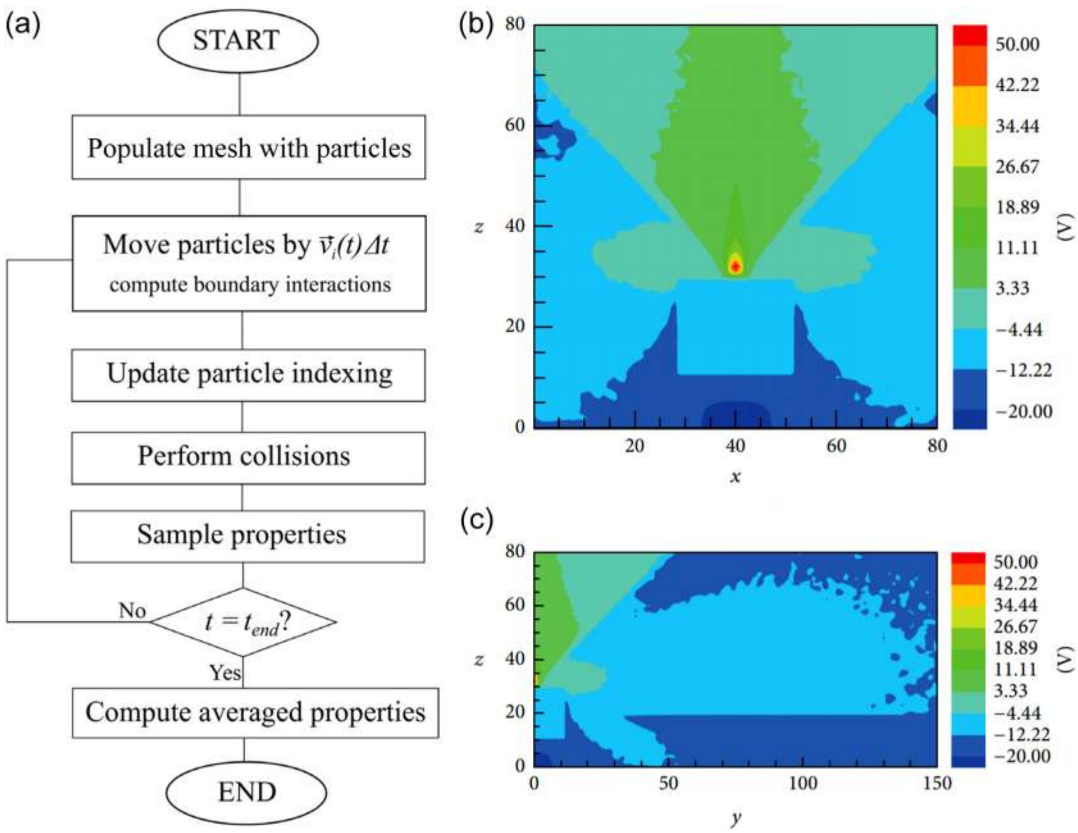

FIG. 17. (a) Flow chart of a basic DSMC time-integration scheme. Reprinted with permission from White *et al.*, Comput. Phys. Commun. **224**, 223 (2018). Copyright 2018 Author(s), licensed under a Creative Commons CC BY license.[166] (b) and (c) Plasma potential distributions obtained by the three-dimensional IFE-PIC-MCC code with the DSMC technique applied to model neutral atoms for the numerical simulations of SMART-1 spacecraft that had traveled to the Moon using a PPS-1350 Hall thruster.[163] Reprinted with permission from Shan *et al.*, Math. Probl. Eng. **2015**, 418493. Copyright 2018 Author(s), licensed under a Creative Commons Attribution License.[164] These studies have revealed that the maximum disturbance normal force can reach 1% of the main thrust produced by the thruster. While this value is small, it may be important for special astronomical missions requiring very high attitude accuracy for the spacecraft.

acceleration channel in Hall thrusters.[175,176] Moreover, special configurations of the magnetic field and other parameters in the acceleration channel of Hall thrusters could be organized to significantly prolong the deposition area in the channel, where redeposition of the sputtered material occurs, and hence, atomistic simulations would be required to model the growth of surface structures under the effect of plasma[177,178] and to ensure healing and self-regeneration of the surfaces.[139,179] Evidently, selection of such parameters is not a trivial task, and sophisticated atomic scale simulations could be a powerful tool to ensure long service life of the thrusters through the careful modeling of the materials-plasma interactions. While a detailed discussion of the atomic simulations is outside of the scope of this article, it is worth emphasizing their current and future importance for the design and optimization of future advanced thrusters. In general, the atomic scale simulations can be broadly categorized as those based on quantum mechanisms, i.e., those based on the wave function and density function and those based on classical principles. The latter type can itself be divided into reactive and nonreactive models. In the former, the simulation allows for the chemicals bonds to form and break. Further details about specific applications of atomic simulations for modeling sputtering and growth in plasma can be found elsewhere, with a view to implement this technique for the further advancement of electric propulsion systems.[180,181]

D. Fluid approach

Fluid-based models are valid when the distributions of particles are close to equilibrium, i.e., the pressure is high enough for the charged particles to collide between themselves rather than with the walls, as is the case in the electromagnetic engines and thermionic cathodes (see Sec. II C for challenges in the latter category). Plasma properties are described through density, mean velocity, and mean energy that are the solution of a system of macroscopic fluid equations. In electromagnetic thrusters, fluid equations are coupled with Maxwell's equations[182,183] to self-consistently determine the induced electric and magnetic fields profiles.[184–186] The magneto-hydrodynamic code MACH developed by the US Air Force research laboratory has successfully been used to model the operation of a self-field MPD thruster in a real thruster geometry. Figure 18 shows the typical results of the MACH code in its 2D axisymmetric version. The results show an incomplete ionization of the hydrogen propellant and that the mass expansion in the vicinity of the anode contributes to the thrust.[187] The

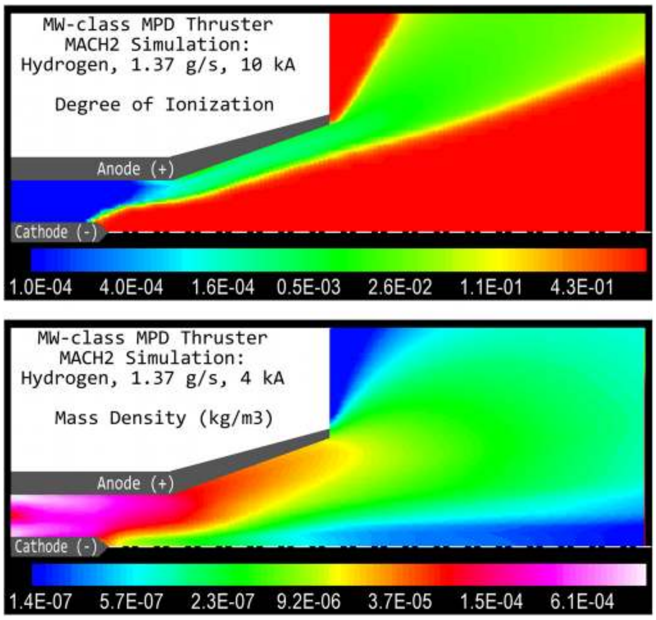

FIG. 18. MACH 2 two-dimensional distributions for a 10 kA MPD thruster, (top) average degree of ionization, and (bottom) mass density. Reprinted with permission from P. G. Mikellides, Proceedings of the 27th International Electric Propulsion Conference, Pasadena, CA, October 2001, Paper No. IEPC-2001–124. Copyright 2001 IEPC.[187]

complexity of electrodynamic thrusters in terms of dynamics of instabilities in 3D highlights the considerable challenges fluid modeling must overcome in the coming years.

E. Fluid-hybrid technique

In a fluid-hybrid approach, the system of macroscopic fluid equations for ions has been replaced with a kinetic description, where the ion energy distribution is self-consistently calculated. In electrostatic thrusters, the ion energy distribution varies in time and space and corresponds to a peaked distribution far from equilibrium. These properties have to be self-consistently determined. In that way, a hybrid approach is often preferred over other methods. In ion thrusters, the modeling efforts are mainly related to ion optics and its consequences for grid erosion. In most instances, the fluid transport of electrons is simplified through a Boltzmann relation with a given electron temperature that makes electrons immediately respond to the electric potential variations. Poisson's equation is solved to calculate the electric field profile due to the space charge face to grid apertures.[188–190] Figure 19 illustrates a comparison of the effect of charge exchange collisions on grid erosion for an ion thruster working with xenon and krypton propellants. 3D Commercial software can now be used to properly define the best design for the grid system according to the thruster operation, with current challenges revolving around the availability of basic data of ion sputtering for different grid materials.

As HTs are not space-charge limited and since the self-induced magnetic field can be ignored, the self-consistent electric field is deduced from the electron fluid transport assuming the quasineutral hypothesis. Sheath properties (including the effects of secondary electron emission and sputtering) are analytically described.[191] Hybrid approaches have been highly successful in describing the HT operation with the prediction of so-called breathing mode and transit time oscillations, as illustrated in Fig. 20.

To enable further progress in the fluid and hybrid modeling of HTs, a number of challenges need to be overcome. The first challenge concerns present capability to propose efficient numerical schemes able to capture the effect of nondiagonal terms in the tensor of transport coefficients to be able to model a large variety of magnetic field configurations.[192,193] The second and main challenge concerns the inclusion of mechanisms responsible for anomalous transport through electron-wave interactions (high frequency-small scales and low frequency-large scales), as illustrated in Fig. 20, and its implementation via wave-interaction equations[154,194,195] or analytical laws derived from numerous experimental campaigns.[196]

Finally, whatever is the type of the electric propulsion system being considered, the study of interactions between the plume and the satellites and the induced spacecraft charging is of considerable importance. A hybrid approach assuming a Boltzmann equilibrium for unmagnetized electrons is often the preferred method. Three-dimensional large scale tools like the open-source SPIS software[197,198] are able to contain all of the satellite geometry but with the simplified boundary conditions for charged particle properties coming from the thrusters. The coupling between refined models of electric propulsion systems and larger scale plume-interaction tools, validated with measurements, is crucial for the electric propulsion community.[199,200]

IV. FRONTIERS AND OUTLOOK

A. What does the future hold for electric and plasma propulsion technology?

Given the current trends described in the reports coming out from academic and industry stakeholders, three directions of high priority can be identified: miniaturization, uptake of the advanced and self-healing materials, and search for new device paradigms to widen the niche of possible applications for plasma space propulsion.

1. Miniaturization

Our built environment is in the process of overwhelming miniaturization. Handy, ultraminiaturized, multifunctional electronic devices are among a wide range of inventions that are now penetrating every facet of our life and revolutionizing how we deliver and consume products and services.[201] There is no doubt that miniaturization of space assets is also steaming ahead, bringing along obvious advantages of lower cost and advanced functionality, efficiency, and lifetime. Most probably, miniaturization alone would likely to remain a key trend and a major driver for the advancement of future spacecraft. Miniaturization provides additional space—and the space is limited even in space! This is particularly true for near-Earth orbits where debris can be encountered more frequently than operational satellites. Moreover, miniaturization in combination with the use of small and ultrasmall satellites "en masse" means new capabilities—which is the key aspect of current space technologies.

Miniaturization means reduced cost and hence much greater affordability and easier access to space for those who need some special functions but cannot spend millions to purchase the entire launch. Examples include small scientific labs, private companies, and universities. Most importantly, small satellites could form networked

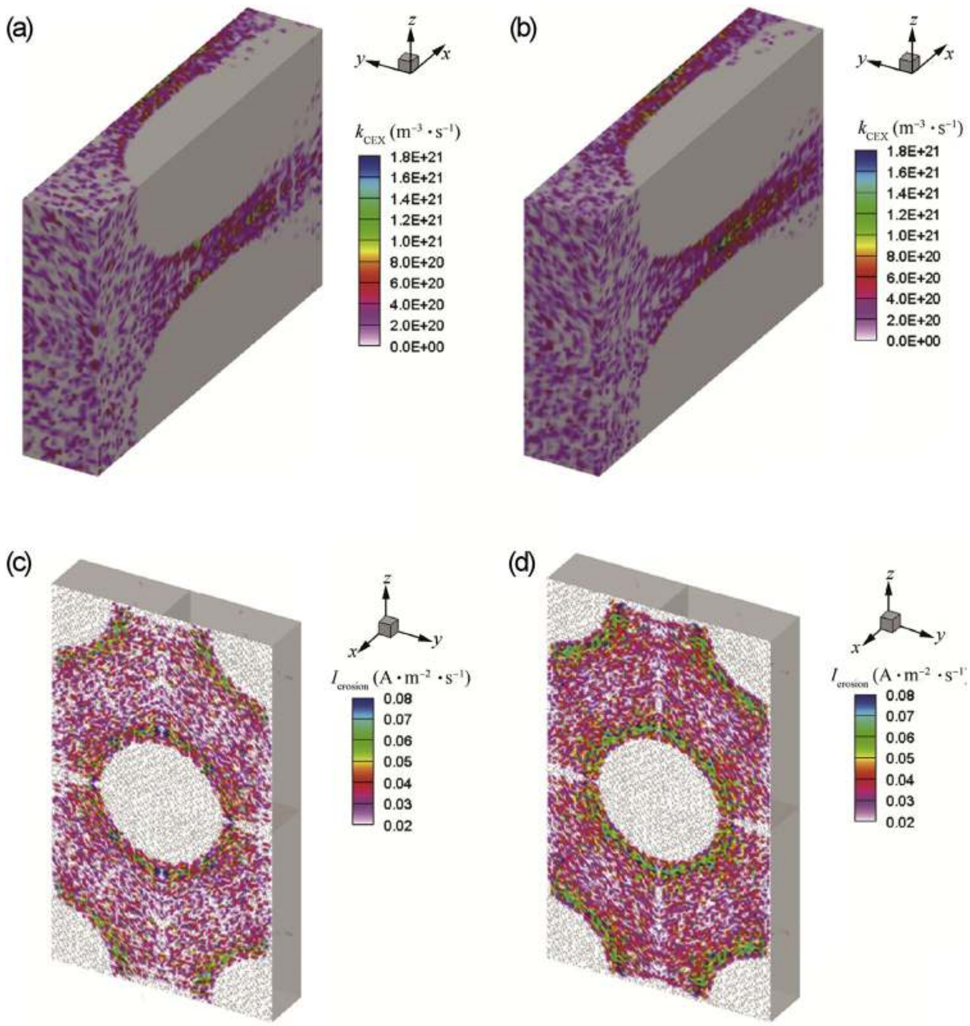

FIG. 19. Distribution of the charge exchange collision rate and its influence on current density on the accelerator grid. (a) and (b) charge exchange (CEX) collision rate of Kr and Xe ion thrusters, respectively. (c) and (d) Current density on the accelerator grid of Kr and Xe ion thrusters by CEX ion impact. Reprinted with permission from Chen *et al.*, Chin. J. Aeronaut. **31**, 719–726 (2018). Copyright 2018 Author(s), licensed under a Creative Commons CC BY-NC-ND license.[189]

distributed systems, i.e., dynamically changing, adaptive constellations for the mission-oriented coordinated formation flights of a large number of mini-satellites that feature expressive capabilities not readily available when using several satellites with the total mass similar to that of the net mass of the constellation. New opportunities offered by these interconnected networks include the widest-possible coverage of survey and information pickup; and larger, of the constellation size, observation bases with the relevant resolution and ability to collect and coherently process the information inside the constellation. These features may open new horizons for the efficient, robust space exploration.[5] This holds true not only for the near Earth exploration and connectivity. Small yet organized groups of small satellites at the orbits of the Moon and Mars could be quite realistic and a much cheaper alternative to large, heavy universal probes that require heavy launch vehicles to reach remote planets. Recent studies suggest that deep-space Cubesats are nearing reality.[202]

However, significant stumbling blocks still hinder the deployment of organized mini-satellites, albeit launching them in hundreds at a time is nowadays a routine practice (e.g., 104 satellites were deployed by the Polar Satellite Launch Vehicle C37 mission on February 15, 2017).[203] Yet, many of these assets can be described as passive spacecraft in that they have the capacity to change orientation but not to conduct active maneuvers. Whereas, for organized coordinated flight, spacecraft fitted with highly efficient, reliable thrust systems that can maintain active work and coherent maneuvering of small satellites within the formation. On the other hand, at the power level of hundred and even tens watts as required for typical Cubesats of one to ten U form-factor, the efficiency of small thrusters is unacceptably low, sometimes below 10%. Such low efficiency implies the need for considerable quantities of propellant and electric power to be carried on board, often at the expense of payload, and, consequently, a reduced orbital service life.

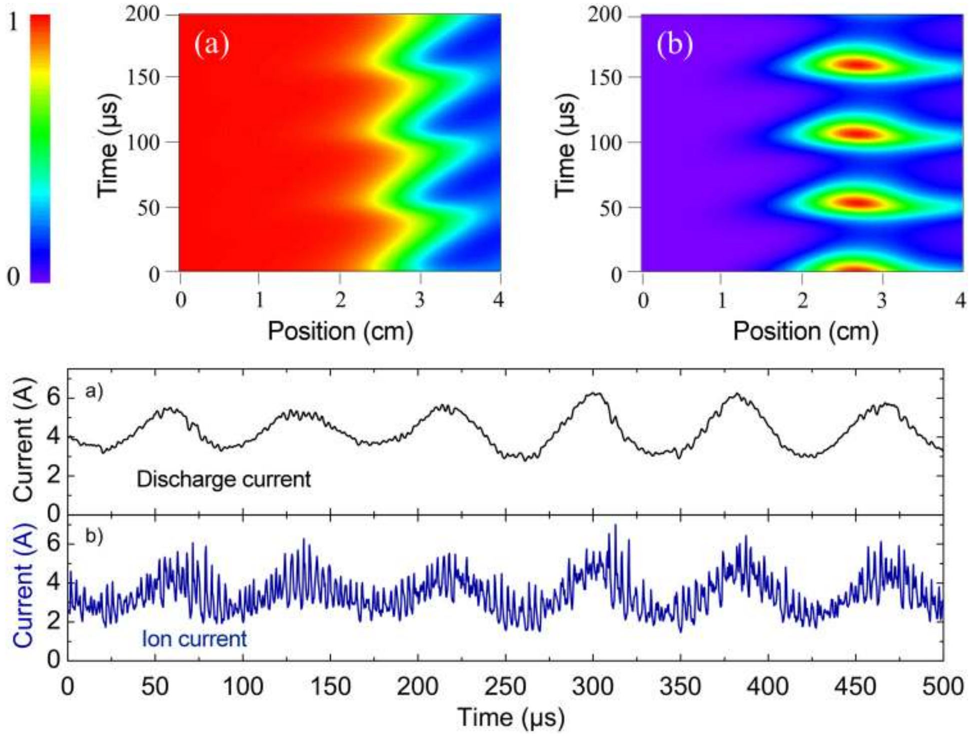

FIG. 20. (Top) Results from the 1D axial hybrid model. (a) Neutral density (maximum 1.6×10^{19} m^{-3}) and (b) plasma density (maximum 1.6×10^{18} m^{-3}). Reprinted with permission from Darnon *et al.*, IEEE Trans. Plasma Sci. 27, 98 (1999). Copyright 1999 IEEE.[199] (Bottom) Results from the 2D (axial-radial) hybrid model. Discharge and ion currents as a function of time show the breathing model oscillations at a frequency of 20 kHz with superimposed ion transit time oscillations at 200 kHz. Reprinted with the permission from Phys. Plasmas **10**, 4886 (2004). Copyright 2004 AIP Publishing.[200]

B. How can we advance miniaturization of space propulsion systems?

Systems that rely on cold gas and hydrazine show suboptimal performance with respect to specific impulses when their dimensions are reduced to produce tens of watts. This is quite expected from the physics point of view due to considerable hydraulic losses in the accelerating channels and nozzles as a result of high surface-to-volume ratios in radically scaled down systems. While efforts have been made to enhance the specific impulse by employing electric heating, the resulting hybrid thrusters did not feature significantly improved efficiency. Moreover, they were cumbersome and demanded the use of both electrical energy and chemical fuels, the latter often being harmful and corrosive. Although they were used in several missions, such systems did not find a niche in the space technology.

Therefore, the current trend is "all-electric space thrust platforms," the development of which is currently being driven by many prominent industry players, e.g., by Airbus with its Eutelsat 172B launched on 2 June 2017.[204] These systems are very flexible and diverse; their amazing assortment and versatility are the most prominent signature of the electric thrust platforms. To date, a wide range of electric thrusters has been developed and tested in labs and directly in space. Several device types could be highlighted as the major trends in the field:

- Hall thrusters that rely on a closed electron drift and deliver high thrust-to-power ratios and large thrust densities;
- ion thrusters that accelerate ions through a high electric potential applied between two metal grids and deliver low thrust density but very high specific impulse;
- magnetoplasmadynamic thrusters that accelerate plasma as a whole medium by means of an electric discharge between two electrodes;
- electrodeless systems with rotating and complex-shape magnetic fields, such as Rotamaks, helicon thrusters, and similar systems;
- electrospray thrusters of different structures, and
- printable cathode arc thrusters.

Every one of the aforementioned devices requires a special approach to overcome the specific stumbling blocks that presently limit their scale down and thus to achieve miniaturization. Several major trends and approaches to achieve said miniaturization have already been proposed.

1. Hall thrusters

Hall thrusters are now considered as a very promising propulsion means for medium and large satellites and space probes. Thus, considerable efforts are dedicated to their miniaturization toward sizes compatible with Cubesats. An interesting and promising step toward this goal is the invention and testing of the "cylindrical Hall thrusters" featuring a simplified geometry without the central cylindrical part. This configuration decreases the efficiency of the device, yet it opens wide prospects for miniaturization by providing a way to build a tiny acceleration channel with a very small diameter. Underpinned by the pioneering works at the Princeton Plasma Propulsion Laboratory, these thrusters have gained a wide recognition and may be soon adapted to Cubesats.[205–207]

Hall thrusters developed and tested at the Space Propulsion Center in Singapore (SPCS) combine a number of innovations, including novel materials with exceptional properties for acceleration channels, flexible permanent magnet-based magnetic circuits, and an innovative cathode design. These technological innovations allowed the development of a 10 W Hall thruster, a world record. Such a device could typically be installed on 6U Cubesats.[208]

Another potential way to improve the efficiency of small Hall thrusters is by using the so-called wall-less configuration where the plasma discharge is shifted outside the channel, therefore drastically reducing losses at the walls; it also makes the device very simple and hence more reliable.[52–56] Although these preliminary reports are encouraging and show stable operation and low wear of the device, ionization remains to be increased, e.g., by shaping the magnetic field, and the ion beam divergence angle has to be reduced to increase performance metrics.

2. Ion thrusters

Ion thrusters are promising electric propulsion systems that are currently being considered as promising candidate thrusters for active maneuvers, orbit keeping, and gaining impulse for the interplanetary missions. In these devices, the ion flux is accelerated by the DC potential applied to the grids, delivering very high specific impulse. However, unlike Hall thrusters, the ion thrusters are characterized by lower thrust density attributed to the electric space charge in the discharge chamber. This limits their suitability for miniaturization. It may be possible to compensate for, the low value of the thrust density by applying greater accelerating voltage to the grids. Yet, this may be challenging to realize in the miniaturized systems due to increased likelihood of electric breakdowns owing to small gaps between the powered electrodes, and thin insulators. It is possible that with the development of sophisticated miniaturized semiconductor systems in may e possible to sustain safe generation of high voltages on board of Cubesats. For this reason, miniaturization of ion thrusters requires advances in materials science and engineering, just as much as progress in plasma physics and technology. Current efforts to design the miniaturized ion thrusters include, e.g., the article in *Journal of Spacecraft and Rockets*.[209] Busek Co. Inc., a private propulsion company, has recently reported the radio frequency ion thruster of 1 cm size with the power of about 10 W, designed specifically to address the needs of Cubesats.[210]

3. Magnetoplasmadynamic thrusters

Magnetoplasmadynamic thrusters accelerate the ionized propellant as the entire medium. As such, their thrust density is sufficiently high to render these devices suitable to be used in microthrust configurations. Pulsed thrusters have a range of applications in small satellites and Cubesats of various sizes, including the smallest ones. In a microcathode form-factor, they can be used in Cubesats of 1 U form-factor and smaller, mainly for precise attitude control.[211,212] Yet, it is important to note relatively low power efficiency of these devices when compared to Hall and ion thrusters, primarily because of high energy losses due to metal evaporation and ionization in nonequilibrium plasmas and nonstation discharge transition processes. From this perspective, they may not be ideal for missions that demand significant delta-v changes, such as orbit rising and interplanet transitions, but provide a good fit for precise attitude control and positioning. These operations require high accuracy for small satellites built for the highly organized formation flights. A greater level of miniaturization is vitally required to fulfill the growing requirements to the accuracy of attitude control in large satellite networks. These pressing demands have stimulated the development of a new generation of pulsing thrusters based on the flat (material form-factor) "printed arc thrusters."

4. Printaed cathode arc thrusters

Printable cathode arc thrusters are propulsion devices that rely on a pulsed or DC discharge between the two electrodes. The species to be ionized arise as a result of electrode erosion. Once ionized, the species are accelerated and expelled at high speed. Unlike conventional pulsed thrusters that have a 3D geometry, printed thrusters comprise two or more flat concentric electrodes. The electrodes are printed using a metallic ink on a dielectic wafer, which is typically a thin flexible polymer sheet. These thrusters can be made exceedingly small, with a typical diameter of a few millimeters and thickness of fractions of millimeters. They can be produced cheaply, as they have a simple configuration. Of most significance, however, is their ability to produce extremely small thrust impulses for the extra-precise attitude control of the smallest but still active satellites (e.g., picosatellites of less than 1 kg). Further progress in the area of printable thrusters would come from optimization of their geometry to improve the efficiency of material ionization, and acceleration is still underexplored in flat discharges. Another area from which advances are likely to come is in the discovery of novel materials capable of efficiently supplying an easily ionisable propellant to the acceleration zone and, simultaneously, able to withstand the harsh open-space conditions (cycling heating-cooling, ionized radiation, etc.) without the disruption of the thin structure and material exfoliation. The group led by Professor M. Kim from the University of Southampton, UK, had recently produced a printed cathode arc thruster of about 5 cm size.[8]

5. Electrodeless systems with rotating and complex-shape magnetic fields

Electrodeless systems with rotating and complex-shape magnetic fields do not involve an exchange of current between the plasma and conductive electrodes, thus excluding power and material losses that arise as a result of material heating, erosion, and energy spent on work function. Although in principle highly efficient, electrodeless systems are at the very early stages of miniaturization, with their advancement hindered by the exceptionally complex physics of the processes that underpin these systems. However, significant progress has already been achieved by several teams working on helicon thrusters (i.e., the group led by Professor S. Shinohara at the Tokyo University of Agriculture and Technology, see their article in *Physics of Plasmas*),[213] Rotamak-type systems designed by SPCS, Singapore (see their video article in the *Journal of Visualized Experiments*),[214] and radio frequency electrothermal thrusters (the "Pocket Rocket," designed by the Space Plasma Power and Propulsion Group at the Australian National University, see the article in *Plasma Sources Science and Technology*).[215] At present, it is not clear whether these and similar systems will eventually be scaled down to a Cubesat scale or whether they will only ever occupy a niche reserved for the medium and high power thrusters.

6. Electrospray thrusters

Electrospray thrusters occupy a niche between the flat printed systems that generate ultralow thrust pulses and micropulsed thrusters. Electrostatic voltage is applied to electrospray emitters to accelerate liquid propellant, the latter exiting from a channel with a small diameter. Compared to other miniaturized device configurations, electrospray thrusters can be viewed as a relative mature technology that is inherently miniature. Scaling these devices down further would most probably be driven by the use of complex nanostructures as the needles. Where currently electrospray systems employ porous tungsten, future microfabricated emitter tips can be made of silicon. The possibility multiplexing electrospray microthrusters makes this technology attractive for the use of Cubesats and other small space assets. In addition to silicon technology, other advanced complex metamaterials coupled with optimized device geometry may further enhance thruster efficiency and reduce its size. The thrusters of this type have already been used in the Laser Interferometer Space Antenna (LISA Pathfinder) project, see the article in *Acta Astronautica*.[216]

The aforementioned examples provide but a brief snapshot of the current efforts by many research and engineering teams to miniaturize various space assets to meet the growing expectations of the space industry and, in doing so, respond to a number of global challenges. Global information access, distributed orbital networks, and exploration of extraterrestrial bodies for gathering vital information and founding a solid base for their approaching colonization would be among the prime benefits of the efficient low-scale thrust systems.

C. Advanced space materials

Superrational distances, billions of light years of dark spiritless space and billions of years of existence—this is our Universe. Is interplanetary space travel just a dream, or have we finally reached a stage where we have the capacity to develop technologies sufficiently advanced to allow colonization of Mars, or at the very least, extend exploration of remote planets? There are no repair shops, no fueling, and charging stations along the way, and, for unmanned probes, the flight path and spacecraft configuration are controlled by the automatic equipment and remote control systems, without any crew present on board. To survive for long time under severe conditions in open space and on surfaces of other planets, space assets should ideally be self-healing and highly adaptable. In most instances, these features are impossible to attain within the framework of traditional materials and design paradigms. To ensure real progress in exploring the near-Earth and remote space and to realistically approach the existing plans for Mars and Moon colonization,[3,4] novel dynamic, self-healing materials should be designed to realize the next generation of spacecraft and bring about a new generation of humans as a multiplanetary species.[2] Specifically, the ability of novel advanced space materials to actively self-heal and self-assemble would be considered as one of the most important technological frontiers.

1. Is a self-healing plasma thruster possible?

However, when examining self-healing features and abilities of the materials used in spacecraft design, we should first of all consider the intended use and design of a specific system onboard of spacecraft. Indeed, while the design elements of the spacecraft bus and frame panels suffer mainly from internal cracks and similar damage due to degradation of the bulk material, other subsystems such as power units and control electronics would suffer from quite different effects, such as thermal degradation, electrical breakdowns, and electric current-induced diffusion. The critical elements of the electric propulsion thrusters of interest here are mainly degraded and sputtered by the effect of plasma fluxes and very strong heat loads. These effects have been shown to cause extensive material evaporation from the surfaces. In other words, in thrusters, the bulk of material damage can be classified as surface-localized damage. To effectively combat and halt these processes, novel materials should feature self-healing surfaces and, moreover, external processes should be organized in the thrusters to ensure restoration of surfaces damaged by plasma and ion fluxes. Two different approaches may be proposed for this aim, namely, restoration of the surface structure and integrity by exploiting strong electric fields at the damaged surface and redeposition onto the damaged surfaces from plasma that is generated by the thruster itself.[217,218] It goes without saying that plasma is capable of producing a widest spectrum of particles with sizes ranging from nanometers through millimeters, i.e., quite suitable for various materials and repair scenarios. Selective deposition of the repairing material onto the damaged surface could be in principle organized by taking advantage of the electric field at the plasma-surface interfaces; the irregular pattern of the electric field could promote selective deposition onto the damaged surface in such a way as to fill the damaged features, thus rebuilding the surface and restoring an even topography of the design elements. Conceptual experiments have already demonstrated the possibility of such a strategy for plasma-induced reorganization at surfaces.[219–221] Moreover, electric-field induced self-organization and ordering on the surfaces can also stimulate the processes of self-healing and restoration by promoting re-distribution of material on the surface.[222–224]

D. New paradigms and hybrid concepts

1. Laser-plasma systems

Apart from the "classical" plasma-based propulsion systems outlined above, other concepts could be considered in the nearest future, and among them, the "laser-plasma systems" may be of key importance (Fig. 21). It is possible to design thrust systems that take advantage of photonic propulsion to propel spacecraft in space. These can employ laser radiation generated by a power station based on the ground, on a space base, or on board. The light can then be used to drive the acceleration of a propellant, which can be a solid or a liquid.[225,226] A microthruster that uses light to ablate a solid target is currently being developed.[227] There are several benefits to using light for propellant acceleration. One of the major advantages lies in the ability to physically disconnect the spacecraft and power generation unit. Not only would this result in a lighter and more compact spacecraft, but since the power source would not have to be accelerated with the spacecraft, higher efficiency may be realized. Furthermore, power generation methods that involve large or heavy infrastructure or may

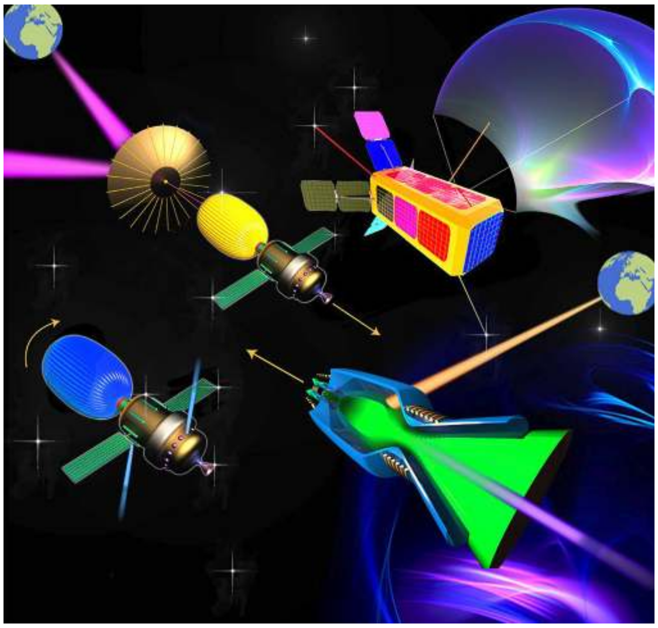

FIG. 21. Artistic presentation of several types of photonic space thrust platforms, where laser beams may be used to power plasma-based thrusters. An externally generated laser beam with a significantly higher power density than that of sunlight could be converted to electric energy and used to accelerate working fluid and produce thrust via plasma acceleration. Reprinted with permission from Levchenko *et al.*, Nat. Photonics. **12**, 649 (2018). Copyright 2018, Springer-Nature.[6]

present danger for the crew, e.g., a nuclear reactor, may be used. The efficiency of the propellant would deliver the desired specific impulse.

It may be possible to operate such ablation-type photonic thrust systems in transverse and coaxial modes. In the former, the laser beam reaches the target from the side[228] via a transparent window, whereas in the latter, the incident flux of photons will be coaxial to the resultant reactive jet.[229] Where the transverse mode may provide for greater flexibility with respect to thrust vector control, the specific impulse can be effectively controlled by altering power density at the surface of the solid target, e.g., through changing the pulse duration and focal radius. It may in principle be possible to realize devices with a propellant exhaust velocity of up to 50 000 $\mathrm{m\,s^{-1}}$, given that it is possible to achieve an ion temperature of 10 000 K in a laser focus. The plasma that is created under the latter conditions would produce an electric field that will further increase the exhaust velocity. Of particular importance is the thrust-to-weight ratio that can be significantly greater for photonic devices that use ground- or space-based sources of power when compared to conventional electric propulsion platforms that carry their primary power source on board of a spacecraft.[230] Lightcraft is the early realization of a photonic-powered object that demonstrates stable flight sustained by the light from a ground-based laser.[225,231] Although Lightcraft employs shock waves produced in air to achieve propulsion, the interactions between laser light and matter are critical to the transfer of energy from the Earth to this system.

Electromagnetic systems feature a number of notable advantages when compared to conventional systems currently used for space propulsion. For this reason, it is imperative that we continue to pursue the realization of highly efficient electromagnetic modes of propulsion and continuous advancement and optimization of space propulsion systems that are already serviceable.

In particular, the magnetically shielded Hall thrusters were proposed for life extension and possible operation at higher voltages and in the dual-mode configurations capable of providing low and high specific impulses; the high power thrusters may be realized in the nested-channel configuration. The gridded ion thrusters may be equipped with radio frequency preionization stages to ensure higher efficiency and power.

Among others, the PEGASES (plasma propulsion with electronegative gases) concept is of significant interest. In this system, the gridded ion thruster accelerates alternately positively and negatively charged ions to provide thrust by accelerating both positive and negative ions from the same source. This eliminates the need for additional neutralizers (cathodes).[232]

The field-emission electric propulsion (FEEP) is especially important for Cubesats due to their ultraminiaturized form-factor. Yet, at present, they provide very low thrust, so the search for increasing the thrust level for larger satellites is the most actual challenge here. Moreover, the interaction between the metal propellant of FEEP thrusters and the satellites, especially at high power and higher mass flow rates, is a problem that remains to be solved.

The electrospray (ionic liquid) thrusters are interesting for their long lifespan, utilization of liquid propellant, and possibility to cover sides of satellites if made as thin thrusters. However, they feature low current density that should be increased to make the electrospray systems more applicable.

Hollow cathodes intended for space propulsion applications have been developed to operate in various propellants while producing discharge currents from a fraction of an ampere to over 300 A. Modeling of hollow cathodes has progressed from simple zero-dimensional particle and energy balance models to full 2D plasma fluid codes that include neutral dynamics, thermionic emission, electron flow and anomalous resistivity, discharge instabilities, and life predictions. The technology of hollow cathodes has also progressed, as shown by new heater and heaterless designs, new thermionic emitter developments, and active instability suppression techniques that produce cathodes with $>$10 kh life. Work in these areas continues.

There is still considerable research and development in hollow cathode physics going forward. Theoretical and experimental investigations of the instabilities generated in the near cathode plume region are continuing in order to predict the onset of plume mode and energetic ion generation that lead to sputter-induce life limitations. Techniques to fully mitigate these issues are still needed, especially at very high discharge currents over 100 A in order to provide the life required for deep space missions. Further research is needed that incorporates fully consistent thermal models with the plasma modeling to broaden the understanding of cathode-related physics to enable the design of more power-efficient cathodes that require less propellant gas to operate and provide lifetimes approaching 100 kh.

One more interesting application is the use of plasma thrusters for Spacecraft-plasma-debris removal (Fig. 22).[233] As government agencies and private sector continue to deploy an increasingly large number of space assets into Earth orbits, the question of space junk and debris removal becomes fundamental to the continuous exploitation of these orbits. Deceleration may be used to deorbit the debris

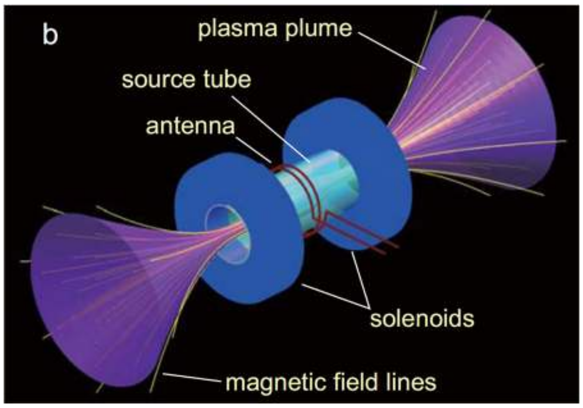

FIG. 22. An open exit magnetic nozzle RF plasma thruster forms a single electric propulsion device where control of the momentum flux imparted onto the debris is obtained via the control of the plasma momentum fluxes ejected at each open exit using variable external parameters (solenoid currents and propellant gas flow rates). Reprinted with permission from Takahashi *et al.*, Sci. Rep. **8**, 14417 (2018). Copyright 2018 Author(s), licensed under a Creative Commons CC-BY License.

and facilitate their entry into the atmosphere. However, once the space asset runs out of fuel, finding an external means of applying the decelerating force is not trivial. One possible option is to use another satellite capable of producing a sufficiently powerful plasma beam that it can direct at the debris to decelerate it, and another plasma beam that it can use to ensure a safe distance is maintained between itself and the debris. For this purpose, a magnetic nozzle plasma thruster may be well suited, as it can support bi-directional ejection via two open exits. Laboratory tests using a space simulation facilities have provided early confirmation that this propulsion platform can indeed exert a deceleration force on the debris (approximated by a target plate) while maintaining zero net force on the thruster. Importantly, these forces can be independently controlled by modifying the external electrical parameters, confirming the possibility of switching between acceleration/deceleration modes in a single propulsion device.[234]

2. Hybrid systems

Hybrid systems incorporating several different schematic solutions may be also a very promising alternative to the existing classical platforms.[235] There are many options on how the already known and tested systems can be combined into novel platform to enhance their characteristics and capabilities; here, we outline several examples that may inform further investigations in this field. One of the most promising approaches could possibly combine the two major classes of electric propulsion systems, namely, electrostatic and electromagnetic platforms. Indeed, a series of the most recent works has demonstrated great potential of such hybrid systems. Figure 23(a) shows the hybrid system that has been successfully tested at the Department of Aerospace Engineering, Nagoya University.[236] The electrostatic-magnetic hybrid system includes a central-cathode electrostatic thruster (CC-EST) with a centrally located hollow cathode and a ring anode that form an electrostatic system; along with this, a diverging magnetic field has been applied to this system with the help of externally located coils or permanent magnetic system. Further, developments of this system (CC-EST-1 and CC-EST02) have also been reported, proving the viability of hybrid technologies incorporating hollow cathodes and various external acceleration subsystems, both of the electrostatic and electrodynamic character.[26,235] In hybrid systems incorporating electrostatic acceleration stages, an important feature is

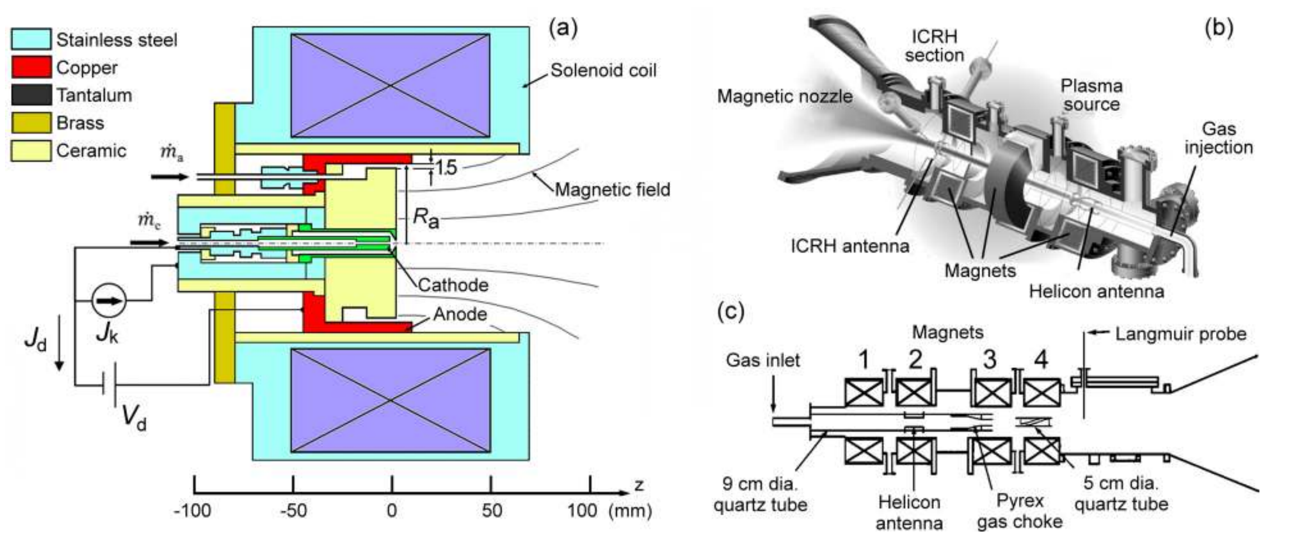

FIG. 23. Where do the frontiers lie? Hybrid and novel advanced concepts. (a) Electrostatic-magnetic-hybrid thrust generation in central–cathode electrostatic thruster (CC-EST). Reprinted wih permission from Sasoh *et al.*, AIP Adv. **7**, 065204 (2017). Copyright 2017 Author(s), licensed under a Creative Commons CC-BY License.[236] (b) Layout of VASIMR system. Reprinted with permission from Arefiev *et al.*, Phys. Plasmas **11**, 2942 (2004). Copyright 2004 AIP Publishing.[237] (c) Schematics of the magnetoplasma thruster prototype of variable Specific Impulse Magnetoplasma Rocket (VASIMR). Reprinted with permission from Phys. Plasmas **11**, 5125 (2004). Copyright 2004 AIP Publishing.[238] The hybrid technologies incorporating hollow cathodes and various external acceleration subsystems, both of electrostatic and electrodynamic character, could be capable of significant broadening the functional diversity of the space electric propulsion systems.

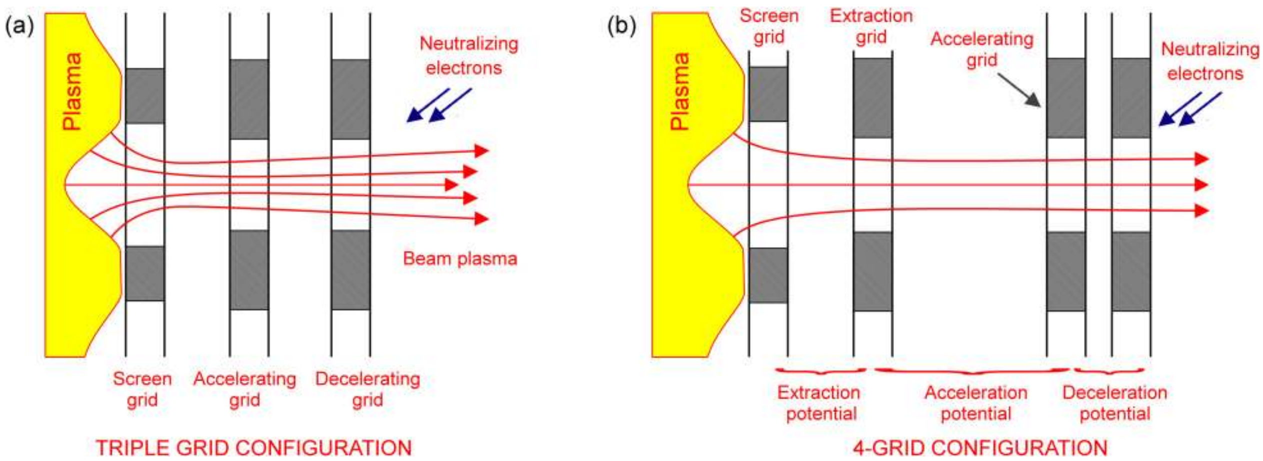

FIG. 24. Perspective concepts for the gridded ion thrusters: (a) triple grid and (b) four-grid configurations. The most advanced 4-grid system significantly reduces the grid sputtering and allows for up to 80 kV acceleration potential, which results in much higher thrust density.

additional electromagnetic acceleration character; a unique combination of both electrostatic and electromagnetic acceleration mechanisms would be capable of significantly broadening the functional diversity of the space electric propulsion systems.

Another example of a prospective hybrid system is a Variable Specific Impulse Magnetoplasma Rocket (VASIMR) platform that has not been tested in space so far but demonstrates quite promising characteristics in lab tests and theoretical studies [Figs. 23(b) and 23(c)]. This system employs three major components, namely, a helicon plasma source, an ion cyclotron-resonance heating section, and a magnetic nozzle. This system is particularly promising now, when the need in thrusters for fast, convenient Earth-Mars flights has appeared. Indeed, the VASIMR concept has been proposed for interplanetary missions, due to its unique capabilities of operating at different specific impulses, to power the cruise phase of the flight when high impulse and lower thrust are required, and maneuvering phases near the planets when higher thrust levels are needed. Moreover, the VASIMR system is also very promising in terms of long operation life, since it uses the radio frequency radiation to ionize and accelerate the propellant. Being an intrinsically electrode-less system, VASIMR does not incorporate any electrodes to sustain gas ionization and plasma acceleration, and so its operational lifetime is not limited by erosion of any critical parts. While first proposed in the early 1980s, this concept is still at the relatively early stages of development, due to the two main reasons: absence of efficient power sources of the required (relatively high) power level and absence of the realistic missions to drive. Now, when the Mars and Moon colonization is at the top of the agenda, further development and practical realization of the hybrid system such as VASIMR are expected to be at the frontiers of the space electric propulsion systems.

3. Complex optical systems for ion thrusters

Along with other types, gridded ion thrusters still attract significant interest, especially for the missions that require very high specific impulse. However, the intrinsic problem of the gridded ion thrusters, the low ion flux (and hence thrust) surface density, still needs to be addressed. The complex multigrid system is one of the recently emerged promising techniques that could in principle drastically enhance the surface thrust density without compromising their specific impulse and grid sputtering-determined service life.[17,239]

While the traditional gridded ion systems comprise usually two grids that extract and focus the ion flux from plasma and accelerate it, in the three-gridded system [Fig. 24(a)], the third grid is a decelerating grid. As a result, much higher potential may be applied to the second (accelerating) grid "to ensure much higher current and hence thrust density Newton per meter square." The third (decelerating) grid is used to decelerate the ion flux and thus not to operate on too high specific impulse, which is an optimized mission-dependent parameter.[25] In this system, the first (screen) grid ensured better collimation of the extracted ion flux and thus significantly reduces the sputtering of the acceleration grot, which is the principal life-limiting factor in ion thrusters.[174] To further enhance the process, decrease the gird sputtering, and mainly, to enhance the thrust surface density, a novel 4-grid system has recently been proposed and successfully tested [Fig. 24(b)].[239]

The four-grid ion thrusters are in fact a dual-stage system where the processes of ion flux extraction and acceleration are decoupled, in contrast to the traditional three-grid systems where flux extraction and acceleration proceed simultaneously, with the maximum ion potential limited to about 5 kV. In the four-grid ion thrusters, the first stage efficiently extracts ions from the plasma by using the two front grids, while a longer second stage formed by the 3rd and 4th grids accelerates ions to much higher potentials reaching 80 kV.

In summary, the recent successes in the development of plasma-based space propulsion systems discussed in this article suggest that this family of propulsion platforms is bound to play an important, perhaps even crucial, role in the advancement of our capabilities in space exploration, exploitation, and, eventually, colonization of other celestial bodies.

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