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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. They 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. This demands novel and more efficient means of propulsion. At present not only heavy launch systems are still based on thermodynamic principles but satellites and spacecraft still rely on gas-based thrusters or chemical engines to move. Similarly to other transportation systems where electrical platforms expand rapidly, space propulsion technologies are also experiencing a shift towards electric thrusters which do not feature limitations intrinsic to thermodynamic systems. Most important, electric and plasma thrusters promise virtually any impulse ultimately limited by the light speed. Not surprisingly, consolidated efforts in this field could be seen, and all-electric space systems are becoming closer to reality. In this paper we briefly outline the most recent successes in the development of plasma-based space propulsion systems, and present our view on future trends, possibilities and challenges.

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I. INTRODUCTION

A strong need for advanced space propulsion systems is becoming increasingly evident. Space assets are becoming exceedingly smaller,[1] and utilize more advanced electronics and sensors. There is little doubt that the nanotechnological revolution has reached the space[2] and has already raised dreams about permanent lunar stations and colonization of Mars.[3,4,5] 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 other space propulsion systems, the thrust platforms that utilize plasma[10-13] and ionized gas[14,15,16] to create reactive thrust are currently attracting the strongest attention due to many potential advantages of these devices,[17,18,19] mainly owing to very high specific impulse[20,21] and potentially long service life.[22,23]

However, further uptake of these systems is challenged by several problems. First of all, further enhancement of the specific impulse is urgently required to ensure wide application of the electric and plasma propulsion systems for various spacecraft – from small satellites to large spacecraft, including manned systems for the Moon and Mars colonization.

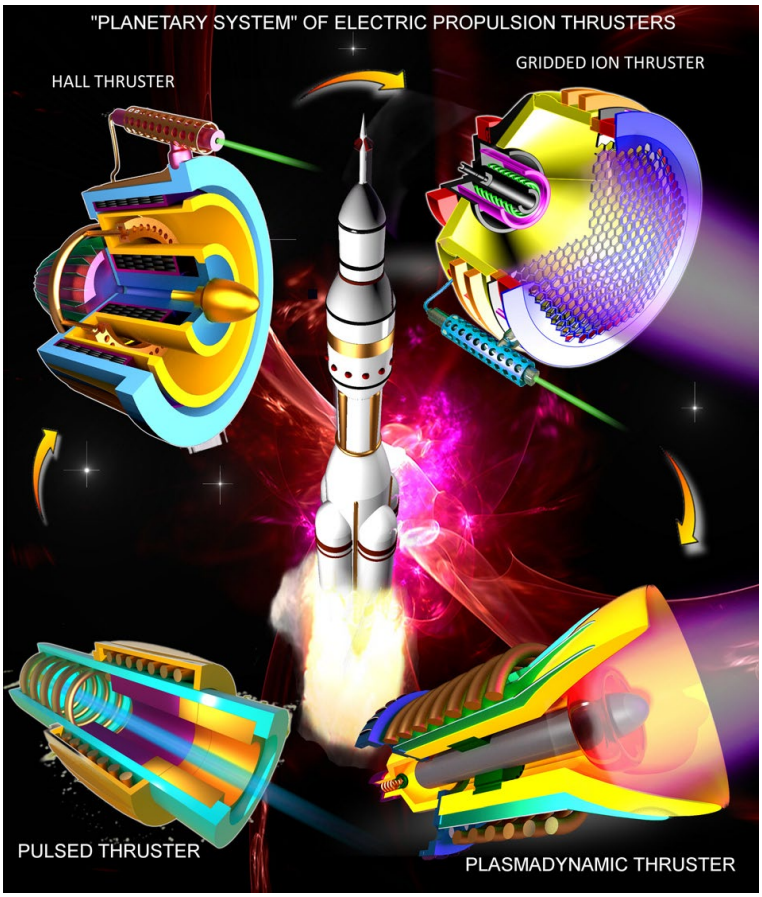

FIG. 1. A "Planetary system of electric propulsion thrusters"—four main types of electric propulsion systems currently tested and used on small satellites and Cubesats (credit: *Appl. Phys. Rev.* 2018, the Authors).

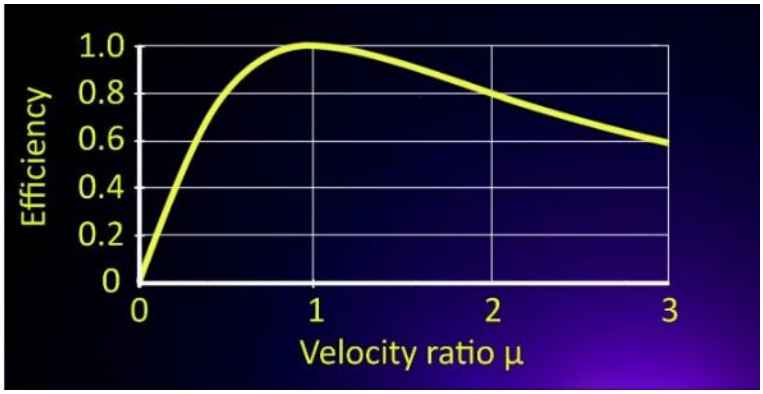

FIG. 2. Why do we need to adjust the exhaust velocity? In order to obtain the maximum efficiency for the most typical case of orbital velocity, the thruster should be able to provide 8 to 12 km/s. This is unachievable for chemical thrusters but quite trivial for any plasma-based system. Moreover, when the exhaust velocity V_e exceeds V, the energy efficiency drops off much weaker than in the case of V_e that is too low. Indeed, when $V_e = V/2$, the efficiency is 0.8, while for the case of $V_e = 3/2V$, the efficiency is 0.9.

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Second, service life of the existing plasma thrusters is still not sufficient, due to very strong heat, radiation, and other effects in the energy-loaded plasma thrust systems. Finally, plasma cathode systems still remain a critical point that significantly limits the total efficiency and reliability of the whole space thrust systems. In this Perspective, we briefly outline the most recent success in the plasma-based space propulsion systems, and present our view on further trends, possibilities and challenges facing these plasma systems.

In this Perspective article, 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 the Perspectives section. Specifically, we will characterize the two main groups of thrusters, i.e. the electrostatic and electromagnetic systems, as well as cathodes which play an exceptionally important role in many various types of thrusters, such as Hall-type and gridded ion systems. Moreover, we will discuss two aspects of prime importance, namely problems and challenges linked to *miniaturization* of various electric propulsion systems (**Figure 1**), and advantages and opportunities provided by the application of novel materials in this field. Finally, in a short outlook, 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 that need to get a comprehensive view of the present-day state of the art in the plasma propulsion as a whole, and see the clear opportunities, challenges and problems to be solved in the nearest future. For the more specialized expert audience, we will provide an extended (about 190 publications) list of the most recent specialized textbooks and papers.

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

First of all, why plasma propulsion? Newton's third law of motion postulates that in order to generate thrust in space, an object must expel mass to gain accelerated, with the force expressed as $F = m \times V_{ex}$, where V_{ex} is the velocity with which mass is expelled relative to the object and m is the rate at which mass is consumed to produce the force ($kg \times s^{-1}$). Within the bounds of classical physics, we do not consider systems that violate the law of momentum conservation. Examples of these systems include the so-called electromagnetic propulsion, where electromagnetic forces are used within a closed cavity. At present, there are three typical modes of space propulsion. Used to deliver assets from Earth to space, chemical rockets are characterized by much greater thrust-to-mass ratio η reaching 2,000 $N \times kg^{-1}$; however, the exhaust velocity of these systems is comparatively low, at $V_{ex} = 5{,}000\ m \times s^{-1}$ even for the most efficient fuels. In contrast, systems that use electric propulsion have greater exhaust velocity approaching $10^5\ m \times s^{-1}$ yet can only produce low level of thrust. In these systems, ions are accelerated using electric fields, and there are no physical limitations to hinder further improvements in the value of V_{ex} (**Figure 2**).

In contrast to thermodynamic (chemical) rocket engines which come in just a few modifications, plasma propulsion thrusters are represented by a quite large, diversified family which could be subdivided into the two major classes, namely the *electrostatic* thrusters (**Figure 3**) that use a DC potential to accelerate ions, and *electrodynamic* thrusters that utilize ponderomotive forces to accelerate plasma as a whole. In additional to these two classes, *plasma cathodes* could be considered as a separate type of auxiliary but extremely important devices that are either used with electrostatic thrusters, or even could be utilized as ultra-small 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 the section **2A**.

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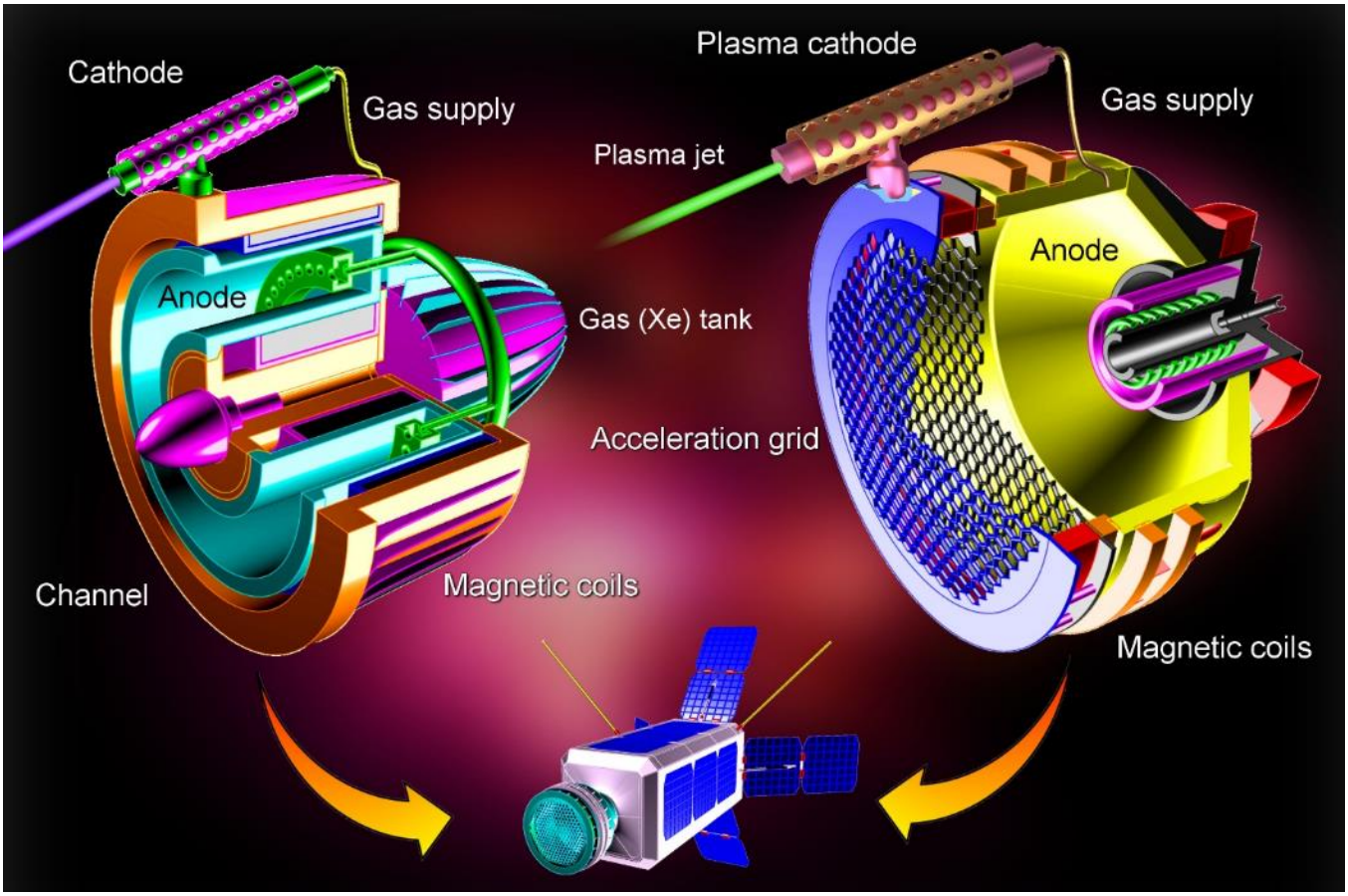

FIG. 3. **Electrostatic systems: Hall (left) and gridded ion (right) thrusters, the two major candidates for powering future spacecraft**. A Hall thruster[24] uses a number of externally mounted magnetic coils or a single coil of a larger size surrounding the entire thruster. An internal magnetic coil 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 giving a thruster with 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 an internal and external meshes are used for extraction 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 mesh is then used to extract the ion flux, which is then accelerated by the second mesh. This results in the ion flux exiting the thruster at high velocity.

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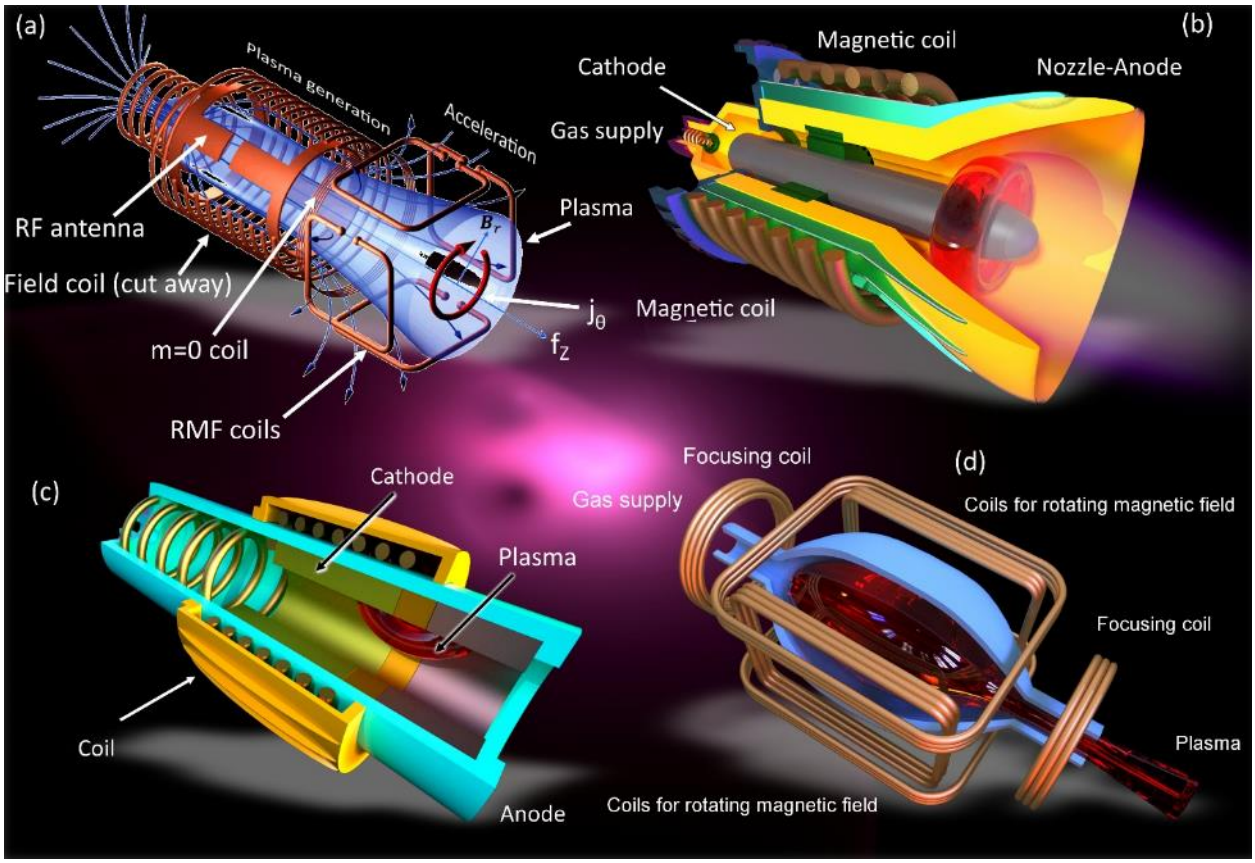

FIG. 4. Electrodynamic space thruster systems. (a) Schematic diagram of the Helicon Electrodeless Advanced Thruster (HEAT). Adapted from Ref. [25]. (b) Magnetoplasmadynamic (MPD) thruster. (c) Pulsed plasma thruster. (d) Conceptual Rotamak-type design of a space thruster.

There are a number of electrodynamic space thruster configurations that are currently being developed (**Figure 4**). A typical engine of this type operates by first ionizing the propellant, and then accelerating the ionized species along the channel. A power source on board of 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, **Figure 4a**), magnetoplasmadynamic (MPD) thruster (**Figure 4b**), and pulsing thruster (**Figure 4c**). 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 used for acceleration of plasma.[26,27] 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 of approximately 10-20%. More details about the characteristics of these devices are presented in the section **2B**.

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A. Electrostatic systems – challenges and opportunities

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 **Figure 3**. 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.[18,82] 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 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 HT generation, is supplied in the channel through either a perforated anode, as illustrated in **Figure 3,** or a dedicated injection system decouple from the anode. The cathode-to-anode potential drop is abrupt and located near the channel exit plane, a region where the electron resistivity is high due to the high magnetic field magnitude. 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.[18,82] Hall thrusters have been operated with xenon and krypton as propellant in a very broad range of input power from 10 W up to 100 kW. Current state-of-the-art thrusters generate a thrust level between 1 mN and 5 N while the specific impulse stays between 1000 s and 2500 s, which is well above the maximum value chemical engine offer. **Figure 5** shows an example of recently developed low-power Hall thruster suited for micro-satellite maneuvers.[46] This thruster produces 8 mN at 150 W with an anode efficiency above 30 %. **Figure 6** shows the evolution of the thrust and the specific impulse with the input power for several small Hall thrusters. The general trend seen in Figure 6 is the decrease of the performance metrics when the power, i.e. the size, goes down. The anode efficiency follows the same tendency.[49] 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 interplanetary missions. For example, Hall thrusters are the prime candidates for the upcoming Mars colonization missions, as reported recently by NASA.*[28,29]

Numerous works are presently aiming at improving performances and capabilities of Hall thrusters. Not only the overall efficiency and the thrust level are of relevance but many studies are in addition focusing on lifetime extension, operational envelope widening, dual-mode (high versus low specific impulse) functioning and system simplification.

The development of the Hall thruster configuration termed "magnetic shielding" has led to a drastic improvement in thruster lifetime range by decreasing the radial ion kinetic energy in the acceleration region.[18,30 - 34,43,49] Gain in operational lifetime has been noticed in 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,[35,36,37,49] which opens the way to new architectures and new possibilities. Likewise, the wall-less configuration may potentially provide a means for reducing the wear of the Hall thruster assembly along with proposing a simplified design, hence a reduced cost.[38 - 42]

Sophisticated magnetic field topologies and multi-stage configurations are possible approaches under investigation for the next generation of devices, see **Figure 7**.[43] A two- stage Hall thruster with a helicon pre-ionization stage has been proposed to enhance the ionization degree therefore allowing operation at high discharge voltages. Basically the helicon stage was placed behind the channel as shown in **Figure 7a**. Although addition of radiofrequency power allowed to slightly increase the thrust, the global efficiency and the thrust-to-power drastically decreased[44]. Similar results were obtained with a RF antenna wrapped around a Hall thruster channel.[45] A Hall thruster with two magnetic field peaks inside the channel and an intermediate electrode placed in the region of low field magnitude, the so-called double stage HT, see **Figure 7b**, allowed to better separate the ionization and acceleration regions, which is necessary to enable dual-mode operation.[51] A similar technique has been proposed recently with permanent magnets and an electrode located in a zero field zone near the exit plane, see **Figure 7c**. Although simple, the two-peak approach has not demonstrated a large increase in the operation envelope[50] whereas the system is more complex and heavier than a conventional one. An innovative design named ID-HALL for Inductive Double stage HALL thruster has recently been introduced to efficiently guide ions produced in the first stage into the acceleration zone.[11] The ID-HALL architecture is depicted in **Figure 7d**. The ionization stage is a RF inductively coupled discharge of which the antenna is placed inside the inner part of

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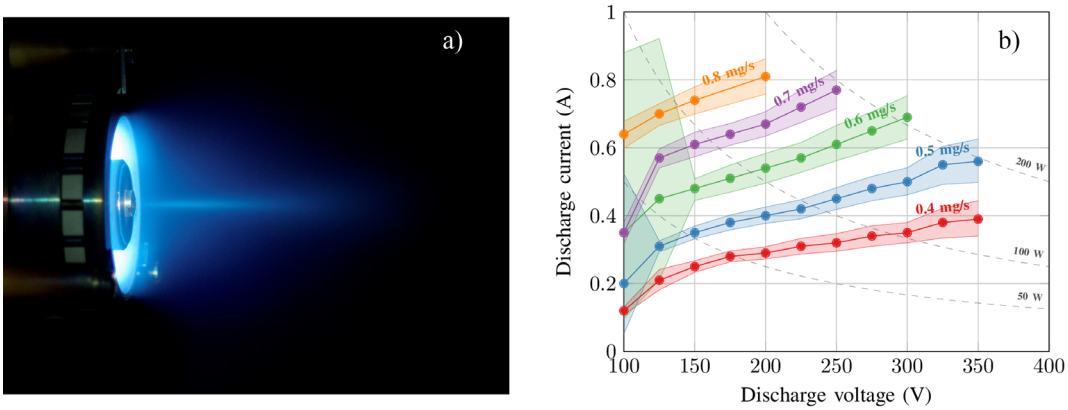

FIG. 5. 100 W class permanent magnet Hall thruster ISCT100 developed in Orléans, France. a) Photograph of the. ISCT100 firing with xenon at 100 W input power in the NExET vacuum chamber. A well collimated plasma jet is observed. b) Discharge current versus applied voltage plot. A low level of oscillation is achieved as shaded areas cover 90% of the discharge current oscillations.. Reprinted with permission from *IEEE Trans. Plasma Sci.* **46**, 330-337 (2018)[46]. Copyright 2018, IEEE.

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 to limit losses at walls. ID-HALL is optimized to generate ions in the vicinity of the acceleration region. Preliminary experiments show 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.[47,48] The principle is to combine HTs of various sizes and power levels to form a multichannel thruster, as can be seen in FIG. 8. Nesting discharge channels reduces the thruster mass and size of a high-power system. Additionally, the nested channel configuration broadens the operating envelope and facilitates throttling through the selection of available channels. To date, the nested channel technology has been successfully tested with two and three channels and it yields thrusters able to operate at over 100 kW of power. Currently a two-channel magnetically shielded thruster is under development to demonstrate life-prolonging technologies can be successfully applied to high-power devices. This work is of prime importance as long-life high power Hall thrusters would be a cost-effective technology for near- Earth and deep space applications.

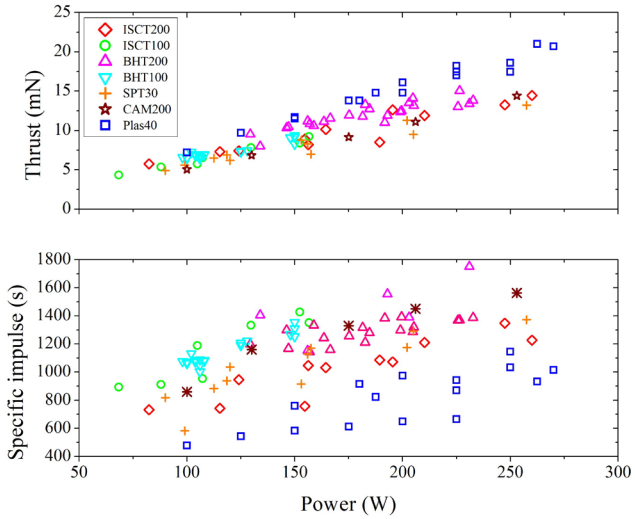

FIG. 6. Thrust and specific impulse against input power for several small Hall thrusters. The thrust, the Isp and the anode efficiency decrease when the power decreases[49]. The thrust-to-power ratio however stays relatively constant around 65 mN/kW.

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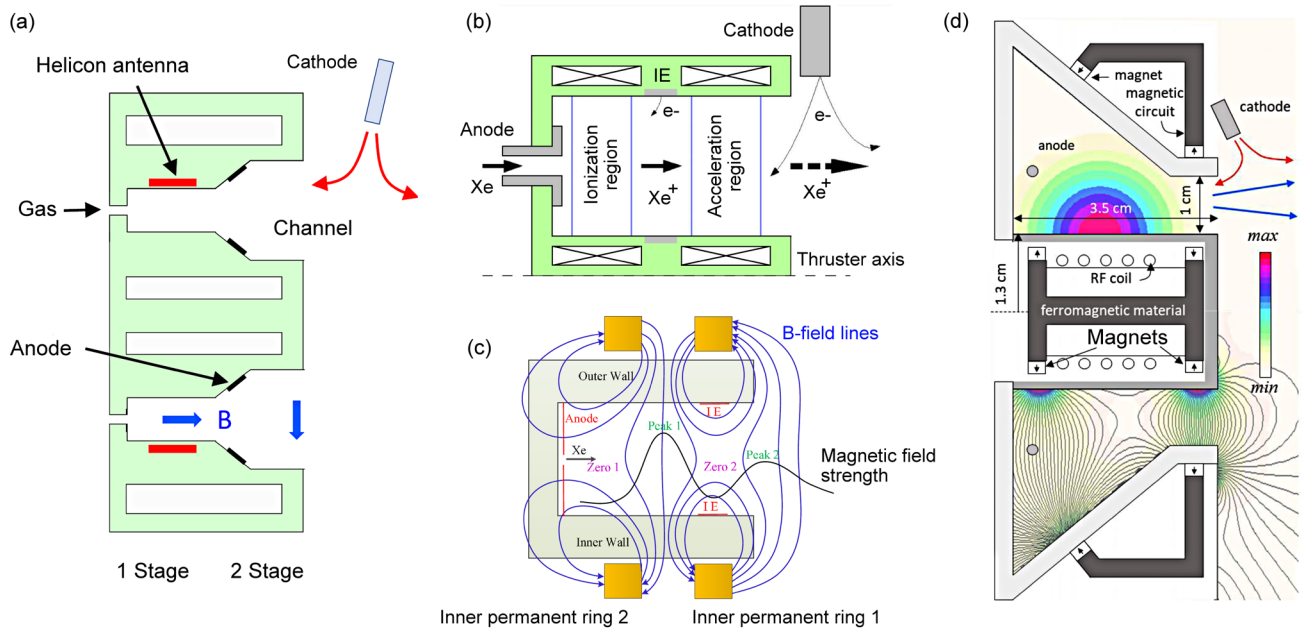

FIG. 7. What are the ways to further improve Hall thrusters and increase their performance metrics? Several conceptual designs have been recently proposed. (a) Double stage Hall thruster with a helicon ionization stage. Reprinted with permission from *Phys. Plasmas* **25**, 093503(2018).[11] (b) Schematic view of the double-stage Hall effect thruster with an intermediate electrode (IE) and a two magnetic field peak configuration. Reprinted with permission from *Eur. Phys. J. D* **71**, 192 (2017).[50] (c) Drawing of a two magnetic peak Hall thruster using permanent magnets instead of coils. Reprinted with permission from *Eur. Phys. J. D* **71**, 192 (2017).[51] (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 permission from *Phys. Plasmas* **25**, 093503(2018).[11]

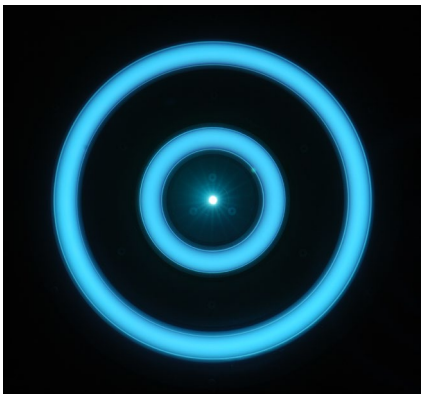

FIG. 8: 10 kW class X2 two-channel nested Hall thruster with its centered-mounted cathode firing with xenon at full power in dual channel configuration. Image courtesy of Ray Liang, reproduced with permission.

Ion engines. In an electron bombardment ion engine, a cylindrically-shaped body houses a discharge unit. The unit consists an incandescent hollow cathode, an anode, and an internally-mounted magnetic coil. Externally-mounted magnetic coils are used for focusing. An acceleration mesh unit contains an internal and external meshes used for extraction and acceleration, respectively. An additional cathode is mounted on the outer body of the thruster (**Figures 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 meshes, the ion flux is expelled from the thruster at high speed. The role of the electron flux produced by the externally-mounted cathode is to counteract the electric charging by the ion flux with the aim to prevent 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 examples by using radiofrequency- and microwave-driven ionization, with both methods employed in electric propulsion.

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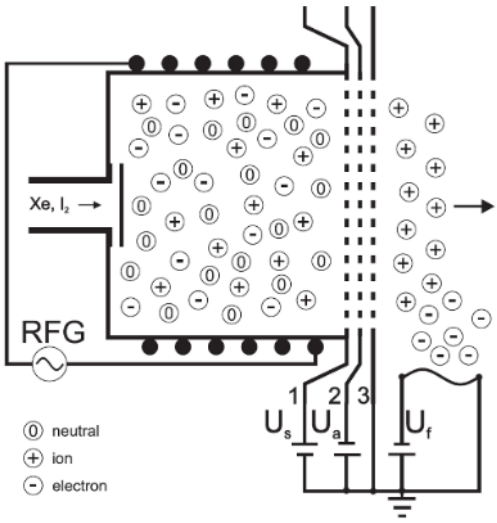

FIG. 9. Schematics of the radio frequency ion thruster including the electric interconnection of extraction grids and thermionic neutralizer. U_s is the screen grid (1) and U_a the acceleration grid (2) voltage, respectively. The deceleration grid is on ground potential. Electrons for neutralization are provides by a tungsten filament (U_f is filament heating voltage). Reprinted with permission from Eur. Phys. J. D 72, 1-7 (2018).[52]

Along with many advantages of gridded ion thrusters such as very high specific impulse, some drawbacks can be pointed out. These include lower ionization efficiencies as compared to that of Hall thrusters. To overcome this, the radiofrequency ionization stages also could be specified as a promising technology to bring the gridded ion thrusters to the orbit of commercial exploitation. Moreover, the use of iodine instead of widely used Xenon for gridded ion thrusters may be very promising to reduce the cost of the long space flights; however, iodine is a corrosive substance. The readers may refer to numerous recent publications to review the recent progress with various types of the modern gridded ion thrusters.[53 - 58]

✓ *Gridded ion thrusters, due to very high intrinsic specific impulse and other advantages, will be among the most intensely researched space thrust platforms; the use of multi-staged radio-frequency driven thrusters and alternative propellants such as iodine may be pointed out as the most promising directions for further studies.*[52,59]

B. Electrodynamic systems

There are a number of benefits to using magnetoplasmadynamic (MPD) thrusters. These include attractive thrust density approaching 100 mN×cm^{-2}, high power (~MW), lower voltage, a simple device design and the possibility of using several propellants, including gases and metallic solids. This makes this form of propulsion highly promising for long-distance missions, such as for deep space exploration, due a favorable combination of high efficiency (up to 70%), and thrust and impulse reaching tens of newtons and 10^4 s, respectively. 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. Unlike pulsed plasma thrusters (PPTs) that are able to generate high specific impulse at low-power, MPD thrusters are not ideal for the 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.[60,61] These devices take advantage of the inherent properties of plasmas to generate thrust and gain considerably high velocity with very low fuel consumption.[62]

Helicon plasma thrusters is one of the most promising systems that is currently undergoing active exploration. Helicon plasma sources (**Figure 10**) generate plasmas by using radio frequency radiation. They generate plasmas of high density (~10^{13} 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.[63,64,65] They feature very complex physics[66 - 69,] but hold high promise for space thruster applications[70]. We expect the explosive evolution of high-density helicon plasma sources, which have many advantages compared to other sources from the viewpoints of easy handling of high-density plasmas over a wide range of external parameters. Various ideas developed thus far should be converted into practical devices for future innovative technologies in diverse fields as well as for contribution to basic fields of science.[71 - 74]

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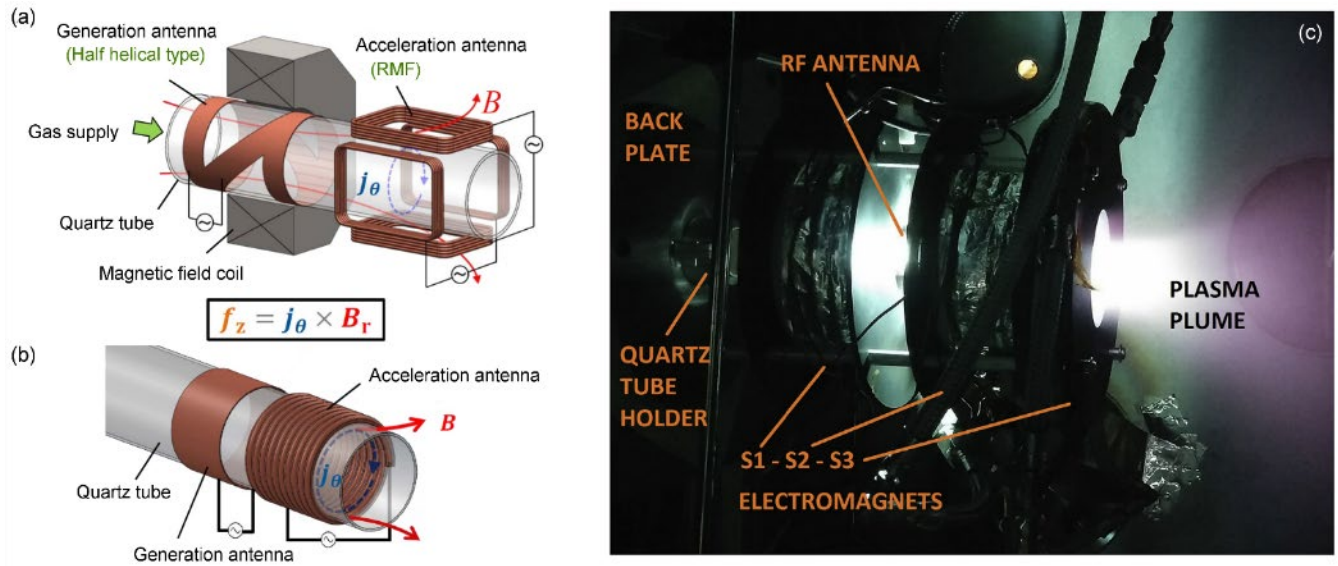

FIG. 10. (a,b) Schematics of the Helicon plasma systems operating in the *rotating magnetic field* (RMF) mode, which has been originally utilized in the nuclear fusion field (a), and in the *m = 0 half-cycle acceleration mode* (here *m* is an azimuthal mode number). The basic mechanism is to induce an 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. Control. Fusion* **61**, 014017 (2019). Copyright 2019, IOP. (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, plasma flow could be efficiently controlled in the helicon thrusters.[73] Reprinted with permission from *Vacuum* **149**, 69 (2018). Copyright 2018, Elsevier.

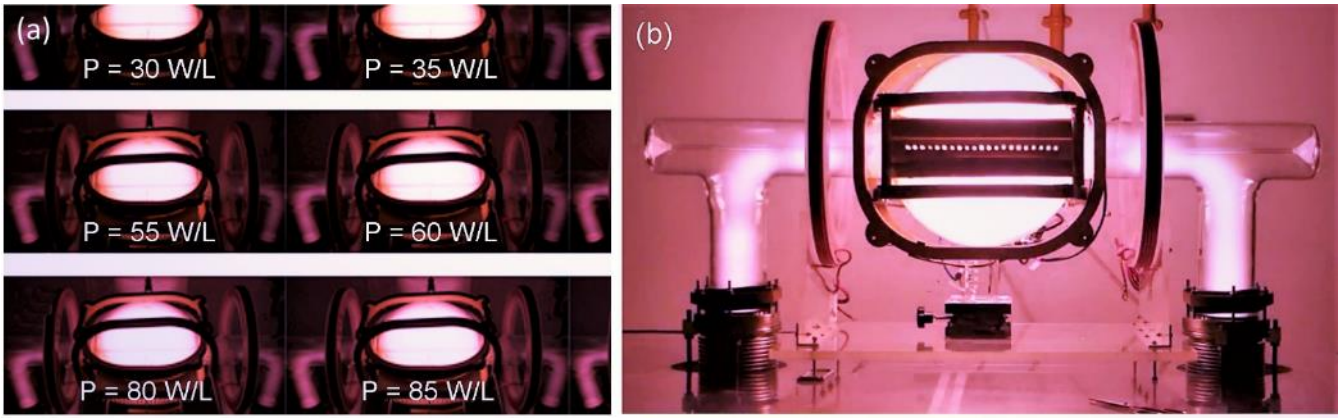

FIG. 11. The experimental results when thrusters are powered by (a) one RF power supply; (b) two RF power supplies. (c-e) Dependence of optical emission intensity on applied RF power as captured by high resolution photography.

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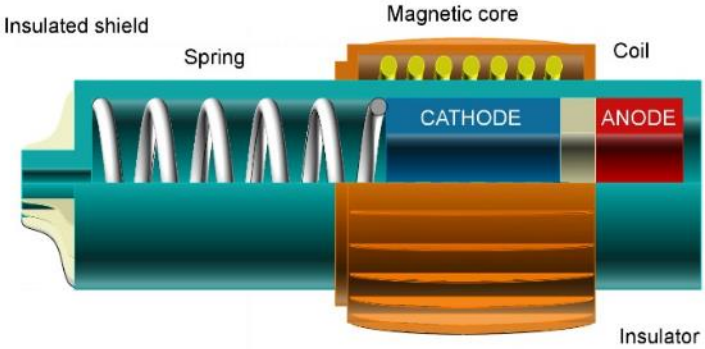

FIG. 12. Schematics of the proposed concept of micro-cathode arc thruster with high thrust (μ-CAT-HT). Such a thruster can feature a thrust-to-power ratio of about 20 μN/W, with the efficiency of up to 15%. Plasma is also accelerated by the Lorentz forces.

Before they can take their place in the suit of widely used propulsion devices, helicon plasma thrusters need to resolve a number of challenges. These include the current-related erosion of the cathode, 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 (GER, **Figure 11**) system as a potential candidate for space propulsion. With further development, the GER-type devices could enable the production of azimuthal plasma currents. The latter could be used to drive indiscriminate acceleration of species within the plasma, e.g. electrons, ions and neutral species, through an axial body force.

Other advantages of GER-type thrusters include the elimination of the requirement for pre-ionization stages, as well as the need for neutralizers and high voltage extraction and acceleration grids typically required for the efficient performance of conventional ion and Hall thrusters. Of most significance is the possibility of scaling operational power regimes, reducing plasma-wall interactions, and obviating the need for moving components. These features will make GERs as a thruster of choice for long haul missions in LEO and geostationary orbit, and for deep space exploration. Of the available options, a Rotamak device developed by Flinders University in the 1960s presents an attractive alternative. Rotamak was originally developed as a more compact alternative to a tokamak, since is lacks an inner column, which is also more efficient due to higher fuel density.[75]

Rotamak uses a spherical discharge vessel. The external sources are configured so as to enable a "field reversed configuration" as well as other current drive schemes.[76] The gradually expanded Rotamak (GER) device based on a Rotamak was developed by the Space and Propulsion Centre (SPC) at the National Institute of Education, Nanyang Technological University, Singapore. Preliminary studies on its use for space propulsion are encouraging, confirming its potential for the development into a pure electromagnetic thruster that could sustain high density, non-inductive plasmas. Specifically, the device produced dense plasmas in a spherical vessel. A pair of parallel RF coils can be used to sustain these plasmas. These coils are located outside of the confinement vessel. An additional pair of coils is located orthogonally to the former RF coils. Their role is to provide a poloidal magnetic field, which is generated by the use of a DC pulse. The poloidal field leads to plasma confinement and densification in the middle of the discharge vessel. It is possible to modify device configuration and geometry to realize a fully electromagnetic thruster, where acceleration and thus the thrust is sustained by an axial body force in the absence of neutralizes and grids typical of conventional electric propulsors. Importantly, larger thrust values per unit propellant could be generated, a requirement for longer haul missions.

Arc thrusters, pulsed and ablative systems are examples of thrust systems that share similar physical mechanisms and very small size (up to several mm), which makes them well suited for application on small satellites.[77,78,79] **Micro-cathode arc thrusters** (μ-CAT, **Figure 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 feature 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.[8,80,81]

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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 Hall parameters or 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 multi-staged 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 non-uniform 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.*

2C. Hollow cathode systems for space electric propulsion thrusters

Hollow cathodes are used in 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 are a reduction of propellant consumption, an improvement of the thermal design to lower the heat losses from the hot parts, and an increase of the cathode service life. Below we briefly discuss the recent advances and future perspectives in hollow cathodes, starting from an outline of the basic physical phenomena involved in the operation of hollow plasma cathodes, discuss some achievements in the modeling and simulation of plasma cathodes, and describe the low and high current hollow cathodes, respectively.

Physical Phenomena in Cathodes. The general schematic of a traditional hollow cathode is shown in **Figure 13**.[82] The cathode uses a refractory metal tube to support the thermionic insert (or emitter). The insert is held in place by a pusher and spring arrangement, and pushed against a refractory metal end plate with a chamfered orifice. Historically, two type of inserts have been used in hollow cathodes: barium-oxide impregnated tungsten dispenser inserts, and lanthanum hexaboride (LaB_6).[83] 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. LaB_6 is a well-known thermionic insert used in low power flight Hall thrusters from Russia since the 1970's.[84] LaB_6 has a higher work function (2.67 eV) than BaO dispenser cathodes, and therefore operates at temperature of just over 1600˚C to produce about 10 A/cm^2 emission current density. LaB_6 also has low evaporation rates and is insensitive to poisoning from impurities in the propellant gas.

A heater can be included in the cathode assembly, to warm the insert up to thermionic emission temperatures prior to ignition. High current cathodes feature a high temperature coaxial sheathed heater, coiled around the cathode to provide sufficient heating to start the discharge. Alternative heater solutions in use or under development are described in Sections 0 and 0. A heat shield consisting of layers of thin refractory metal foil are used around the heater coil to improve the heating efficiency. This arrangement is surrounded by an isolated "keeper" electrode that is used to help ignite the discharge and also to protect the orifice plate from energetic ion bombardment from the cathode plume. The keeper material is chosen to minimize sputtering, and graphite keepers are commonly used in present high current cathodes.

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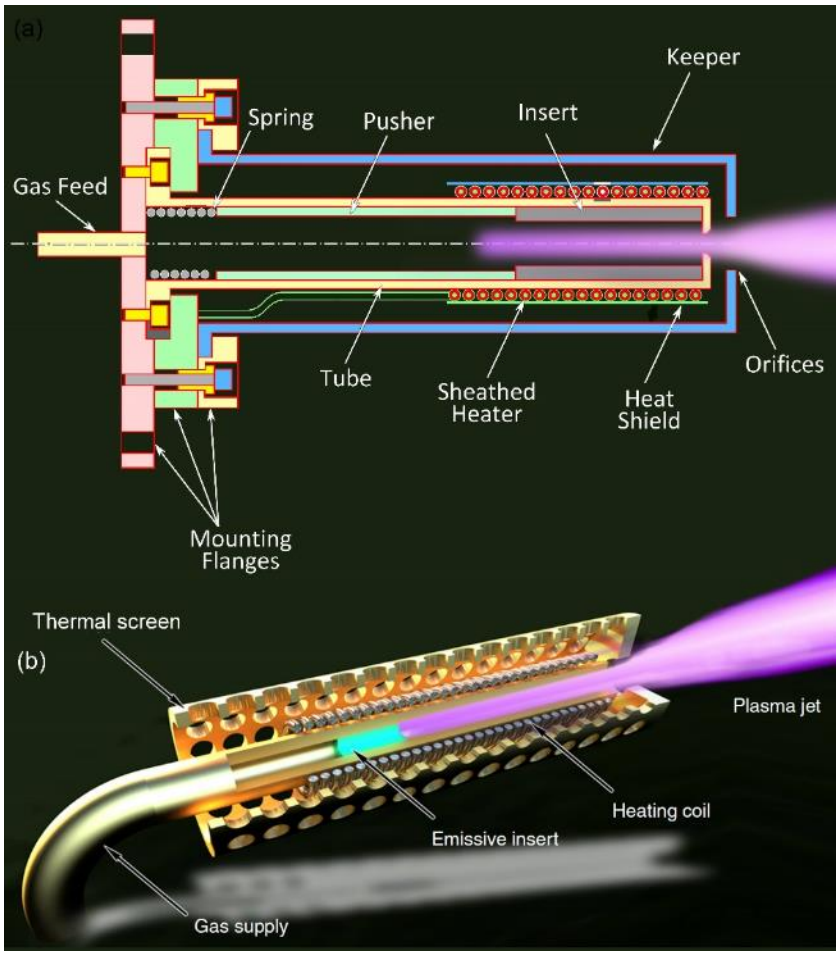

FIG. 13. A typical configuration of a hollow cathode showing its main components. The insets made of a material with ow work function ensures efficient emission of electrons. A heater is used to maintain high temperature needed for electron emission, and also reduces the total heat flux from an outer surface of the cathode (an additional thermal screen can also be used to enhance the efficiency). Reprinted with permission from *Nat. Commun.* **9**, 879 (2018). Copyright 2018, Authors.

In recent years, extensive theoretical research of 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,[85,86] electron transport and anomalous resistivity,[87 - 92] spot and plume mode physics.[93,94] Particular attention was given to the theoretical and experimental investigation of cathode instabilities, both in the cathode interior and cathode plume region.[95,96,97] The ultimate goal of the aforementioned studies is to broaden the understanding of cathode-related physics, as well as to formulate relations between the various cathode parameters; relations that would enable the design of more power- and propellant-efficient cathodes.

Several specific goals can be accomplished in the near future, thanks to the currently confronted theoretical challenges mentioned above. Once accomplished, these goals would advance the cathode effectiveness and the ability to adequately design and test hollow cathodes.

Firstly, the 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 cathode plume physics can dictate the required experimental setup, i.e. anode geometry, cathode-anode distance, additional peripheral mass flow rate, background pressure etc.

Secondly, an improved theoretical understanding of 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.

Thirdly, 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, would reveal the optimal geometry for efficient emitter heating while minimizing ion density and energy in the vicinity of the keeper orifice, thus reducing orifice erosion.

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Lastly, it is but 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.

Low Current Hollow Cathodes. The Low current cathodes find their principal use in nano- and micro-satellites deployed for varied purposes: scientific research, Earth Observation, astronomy, as well as technological, educational, and military applications. Advances in microelectronics and miniaturized systems established a breeding ground to actualize the efforts devoted in recent years 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.[98]

The traditional hollow cathode architecture (**Figure 14**) has been adopted by various research institutions and industries,[99 - 104] based on lanthanum hexaboride or barium-oxide tungsten impregnated inserts. Another promising insert material is the electride C12A7e-, which is currently under study for the low current class of hollow cathodes.[105,106]. 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), 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 as used to heat the high-current hollow cathodes (Section 0) could be also used for the low current cathodes, provided the cable dimensions will be efficiently scaled down to fit the smaller geometrical envelope.

To overcome the reliability and manufacturing issues tied to the heater, the Heaterless Hollow Cathodes (HHCs) architecture was devised not to require external heating to bring the electron insert to its operation temperature.[82] Instead of using external heating, as with conventional cathodes,[82] HHCs are heated via plasma heating. When the electron insert is sufficiently hot, the HHC may function as any other conventional hollow cathode, 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.[107,108]

In recent years, HHCs have seen an increased interest, specifically for low current hollow cathodes.[109,110,111,112,113,114] The quick ignition time, low power demand during the ignition phase, and the potentially longer lifetime have made these cathodes attractive options for low power ion and Hall thrusters. To date, the HHC technology has overcome two technological challenges: the ignition voltage is reduced to merely several hundred volts,[104] and the transition to operational temperature of the insert is with minimal damage to the cathode, thus allowing for thousands of ignitions.[114] Further, it was shown that low-power HHCs can operate adequately with different insert materials such as the electride C12A7e-,[110,111] BaO-impregnated tungsten,[113,114,115] and LaB_6.[112,113]

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

1) **Cathode Conditioning**: after exposure to ambient air the insert must be conditioned, that is gradually heated to emit impurities.[116] However, since HHCs are heated via plasma formation in the cathode cavity, a dedicated rigorous and methodological research is required to define the appropriate cathode conditioning schemes. The research should include the correlation between keeper (or anode) current, insert temperatures, and the required time to achieve the cathode conditioning for each current level;
2) **Breakdown voltage sensitivity to temperature**: it was shown that in cylindrical geometry the breakdown voltage increases with decreasing temperatures.[117] An apparatus that enables the reduction of HHC temperatures prior to ignition was proposed and designed.[118] However, test results of the sensitivity of cathode ignition to cathode temperature were yet to be published. 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 include new designs, new concepts, and new advanced materials. 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.[119] Carbon nanotubes possess a potential for cold, propellant-free cathodes, whereas nanoscale metamaterials capable of reversal heat transmission could help to reduce heat losses.[120]

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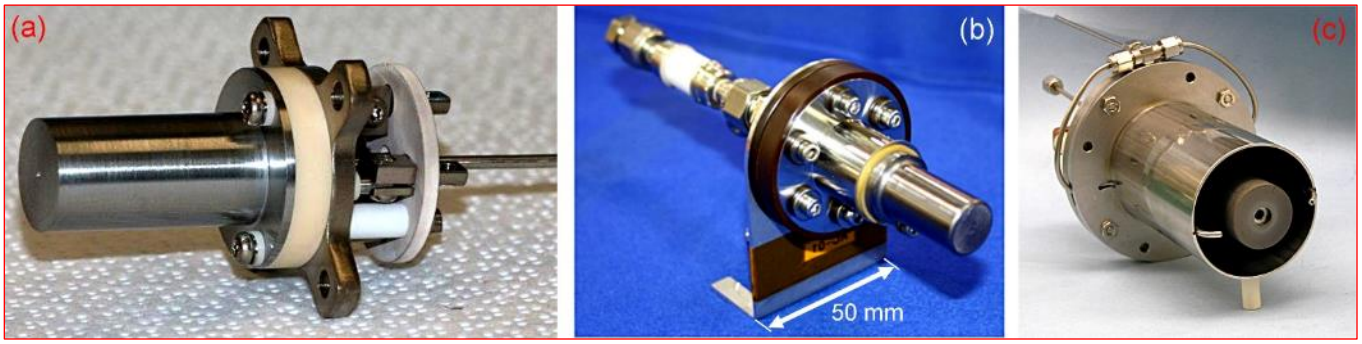

FIG. 14. (a) SITAEL's HC1 cathode, and (b) Rafael's RHHC cathode. (c) The X3 cathode assembly with external gas injectors required for operation over 200 A of discharge current. Reprinted with permission from *J. Prop. & Power* **30**, 1155 (2013). Copyright 2013, AIAA.

Concerning the large production of hollow cathodes, advanced manufacturing techniques (e.g. additive manufacturing) could play an important role, with simplification of the cathode design and manufacturing flow for the new, ambitious satellite constellations.[121]

High Current Hollow Cathodes. Hollow cathode used in present flight ion thrusters and Hall thrusters are capable of producing discharge currents of up to about 25 A. The next generation of Hall thrusters planned to operate in the 5 to 20 kW range require discharge currents of less than 50 A. Development of higher current hollow cathodes was first performed in the 1970's,[122] primarily for non-thruster applications such as ion sources for neutral beam injection heating in fusion experiments. These cathodes routinely operated from 50 to over 500 A of discharge current, which we will consider as "high current" hollow cathodes. There are five major issues that dominate the design of high current hollow cathodes:

1. *Insert emission current density and evaporation;*
2. *Plasma contact area inside the insert;*
3. *Orifice plate design;*
4. *Heater capability;*
5. *Energetic ion and electrode sputtering suppression.*

Comprehensive modeling and numerical simulation of hollow cathodes, required to provide design guidelines or explanations for the performance and life of high current hollow cathodes, as described in Section III. MODELING AND SIMULATION.

At temperatures over 1100 ˚C, BaO dispenser cathodes have significant evaporation rates and tend to form tungstates, both of which 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) means that the insert radiates effectively and overheating is not a significant issue.

Of critical importance in high current hollow cathodes is the axial plasma density profile in the insert region because the insert temperature profile depends on the plasma contact area.[123] More uniform axial densities result in more uniform insert temperatures and evaporation rates. Also, space charge effects can limit the thermionic emission current if the plasma density becomes too low toward the upstream end of the insert. This will limit the electron emission area and how much current the insert can provide into the plasma. Operation at higher discharge current and higher gas flow rates often required by higher power thrusters tends to push the plasma downstream toward the orifice plate, further limiting the insert contact area. The only solution is to make larger diameter cathodes with larger diameter inserts, and increase the cathode orifice size to maintain the pressure in the nominal 1-Torr range required to get proper hollow cathode operation.[82]

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The orifice plate in hollow cathodes often limits the current capability of the device. This is because the orifice size determines the current density of the extracted electrons, which affects the generation of instabilities and energetic ions in the cathode plume. The orifice size also determines the pressure inside the cathode for a given gas flow, which as described above impacts 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,[124] 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 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.[124] Alternative heaters based on refractory metal filaments in ceramic mandrels or thin film heaters on ceramic substrates are in development for this application.

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.[125] These produce energetic ion generation that erode the cathode and keeper orifice plate and limit the cathode life. Proper selection of the cathode orifice size and the gas flow rate at a given discharge current has been used in lower current hollow cathodes to avoid these modes.[126] Unfortunately, this is not usually sufficient in high current hollow cathodes and extraordinary measures are required to avoid or damp these instabilities. The only successful method to date of damping both the ionization and ion acoustic instabilities has been the injection of extra neutral gas in the near-cathode plume.[127] It is undesirable to simply increase the cathode flow rate to achieve this damping because (as described above) the resulting higher pressure inside pushes the plasma in the insert downstream toward the orifice plate and reduces the plasma contact area with the insert (affecting life). However, extra gas on the same order as the cathode flow rate can be injected external to the cathode or into the plume through the cathode to keeper gap to damp the instabilities. Gas injection external to the cathode orifice plate has been used in the 2.1-cm-dia. X3 cathode for all operation from 200 A to 330 A of discharge current. **Figure 14c** shows a photograph of the external gas injectors on the X3 cathode assembly.

High current hollow cathodes that are capable of producing 50 to 300 A of discharge current are available now for development as flight 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. While LaB_6 provides high current operation with long life (many tens's of khours), robustness against poisoning, and the ability to handle the high-power heating at high discharge currents, new thermionic cathodes with low work functions and evaporation rates are desirable. Modeling of the cathode operation, thermal performance, and the plasma discharge instabilities needs to be continued until fully predictive design codes are available.

III. MODELING AND SIMULATION: CHALLENGES AND FRONTIERS

A. Modeling approaches

Numerical modeling and simulations are very powerful tools that ensure strong reduction of time and resources needed to design, test, and optimize space propulsion thrusters. Moreover, modeling and numerical simulations become even more important for miniaturized plasma thrusters, since with the scale reduction, measurements become more and more difficult and invasive. In addition, with the progress made in the high-performance computer (HPC) technology, the high-fidelity of reproduction and fast execution time of numerical models are rapidly improving. As a proof of the importance of numerical modeling in electric propulsion community, a dedicated project named LANDMARK[128] (Low temperAture magNetizeD plasMA benchmaRKs) has been developed in the last two years. The project aims at: (1) providing an open forum for evaluating methods of description of plasma transport in non-fusion magnetized plasmas (eg. ion sources, HTs, magnetrons, cusped-field thrusters, etc.); (2) defining benchmark test cases for full-kinetic, fluid and hybrid methods; (3) addressing physics issues related to the questions of anomalous transport across magnetic field, instabilities, plasma-wall interactions and their influence on particle and energy transport; (4) facilitating international collaboration and enhance mutual understanding among researchers.

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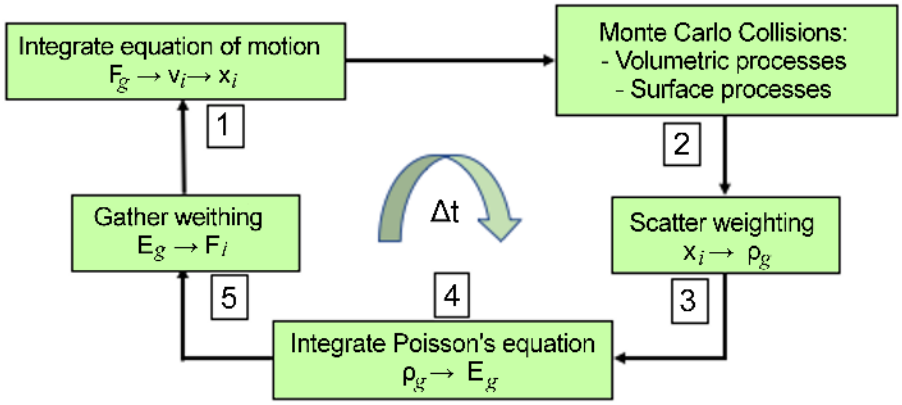

FIG. 15. Diagram showing one integration time step of a PIC MCC simulation.

B. Kinetic techniques

The full kinetic description has been often applied to HTs 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 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, Particle-in-Cell-Monte Carlo Collision (PIC-MCC)[129] model in the electrostatic approximation is the most 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 macro-particles (clouds of real particles representing small regions of the phase space). Fig. 15 illustrates the PIC-MCC typical cycle. The charge density is deposited on a spatial mesh (whose size 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 macro-particle locations (step 5). After pushing the virtual particle (step 1) and before restarting the PIC cycle again, a MCC[130] module (step 2) is called to process volumetric (electron-neutral, ion-neutral and Coulomb collisions) or surface events (secondary electron emission[131], ion sputtering[132], etc.). PIC-MCC is a very powerful numerical tool which allows 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, because 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.

The most important features of HTs PIC-MCC models are:

(i) Solution of 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 interaction.[133] With a high surface-to-volume ratio, plasma-wall interaction plays an important role, not only as loss but also as an active source of particle and energy terms;

(iii) Ability to reveal micro-instabilities and self-organized structures typical of E×B partly magnetized low temperature plasma devices, such as electron E×B drift,[134,135] spoke,[136] sheath,[137] and two-stream[138] instabilities. Detailed description of methods, advanced numerical algorithms and high-performance computing techniques applied to PIC-MCC models be found in a recent review publication.[139,140]

Fig. 16 shows examples of self-organized structures detected by PIC-MCC models. In Fig. 16(a) the temporal evolution of the azimuthal profiles of electron density is reported. It is evident the electron E×B drift instability characterized by a non-linear evolution towards longer wavelengths by inverse energy cascade. Fig. 16(b) reports the m=1 spoke instability rotating with a velocity of 6.5 km/s. Both phenomena leads to similar high-frequency electric field oscillations characterized by a wavelength of mm-scale, frequency of few MHz and amplitudes of the order of 100 V/cm that have also been experimentally observed[141] and are considered as very effective to induce the anomalous electron cross-field transport.

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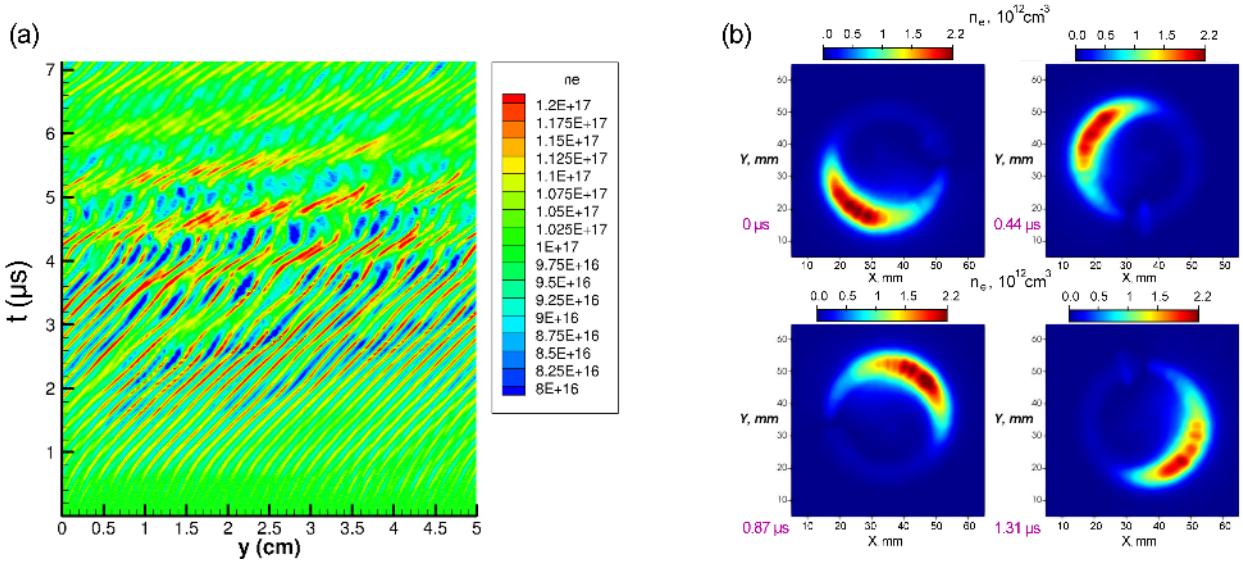

FIG. 16. (a) Temporal evolution of the electron density profile along the E×B direction y in the acceleration region of HT. (b) Evolution of the plasma density 3 mm above the anode during the spoke cycle. Reprinted with permission from [120]. Copyright 2019, IOP.

The primary challenge concerning PIC-MCC codes is being able to describe HTs through a full three-dimensional representation. This result will be possible by increasing their scalability up to 10^5 processors using optimized Poisson equation solvers, implementing particle sorting techniques and taking advantage of particle domain decomposition on modern supercomputer architecture (CPU/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 a high demand.*
- ✓ *Kinetic numerical modeling is efficient for investigating self-organized structures and micro-instabilities typical of E×B partly magnetized low temperature plasma devices.*

C. Fluid-Hybrid technique

The main difference between fluid and hybrid approaches lies in the fact that the description of ions through macroscopic equations solved to obtain density, mean velocity and energies (assuming Maxwellian distributions) is replaced by a kinetic description where the ion energy distribution is self-consistently calculated. Fluid-based models are valid when the distributions of particles are closed to equilibrium meaning that the pressure is high enough for charged particles to collide between them rather than with walls, as in electromagnetic engines and thermionic cathodes. In electromagnetic thrusters, fluid equations are coupled with Maxwell's equations to self-consistently determine the induced electric and magnetic fields profiles.[142,143] The complexity of electrodynamic thrusters in terms of dynamics of instabilities shows the very big challenges that fluid modeling must tackle in the coming years.

In electrostatic thrusters, the ion energy distribution varies in time and space and corresponds to a peaked distribution far from equilibrium and those properties have to be self-consistently determined. In that way, a hybrid approach is preferably employed. In ion thrusters, the modeling efforts are mainly related to ion optics and its consequence on grid erosion. The fluid transport of electrons is most of time simplified through a Boltzmann relation with a given electron temperature that makes electrons immediately respond to electric potential variations. Poisson's equation is solved to calculate the electric

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field profile due to space charge face to grid apertures,[144,145,146] Fig. 17 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 are now able to properly define a best design for the grid system according to the thruster operation and challenges have to be focused on basic data of ion sputtering for different grid materials.

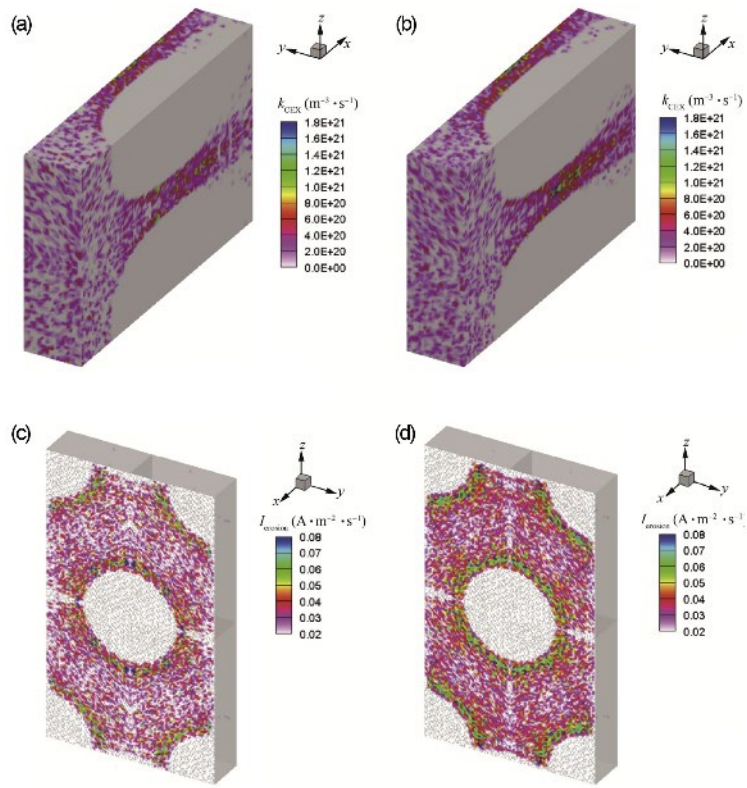

FIG. 17. Distribution of charge exchange collision rate and its influence on current density on the accelerator grid. (a, b) CEX collision rate of Kr and Xe ion thrusters, respectively; (c, d) Current density on accelerator grid of Kr and Xe ion thrusters by CEX ion impact. Reprinted with permission from M. Chen *et al*. Copyright 2018 Elsevier [145].

HTs being not space-charged limited and self-induced magnetic field ignored, self-consistent electric field is deduced from the electron fluid transport assuming the quasi-neutral hypothesis. Sheath properties (including the effects of secondary electron emission and sputtering) are analytically described.[147] Hybrid approaches have encountered a large success in the HT operation description with the prediction of so-called breathing mode and transit-time oscillations, as illustrated Fig. 18.

To go further in HT fluid and hybrid modeling, a first challenge concerns the capability to propose efficient numerical schemes able to capture the effect of non-diagonal terms in the tensor of transport coefficients to be able to model a large variety of magnetic field configurations,[148,149] The second and main challenge concerns the including of mechanisms responsible for anomalous transport through electron-wave interactions (high frequency-small scales and low frequency-large scales, as illustrated in Fig. 18 and its implementation via wave-interaction equations[134,150,151] or analytical laws derived from numerous experimental campaigns.[152]

Finally, whatever the type of electric propulsion system, the study of interactions between the plume and the satellites and the induced spacecraft charging is on first importance. Hybrid approach assuming a Boltzmann equilibrium for un-magnetized electrons is the more often used. Three-dimensional large scale tools like the open-source SPIS software[153,154] are able to contain all the geometry satellite but actually with simplified boundary conditions for charged particle properties coming from 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.

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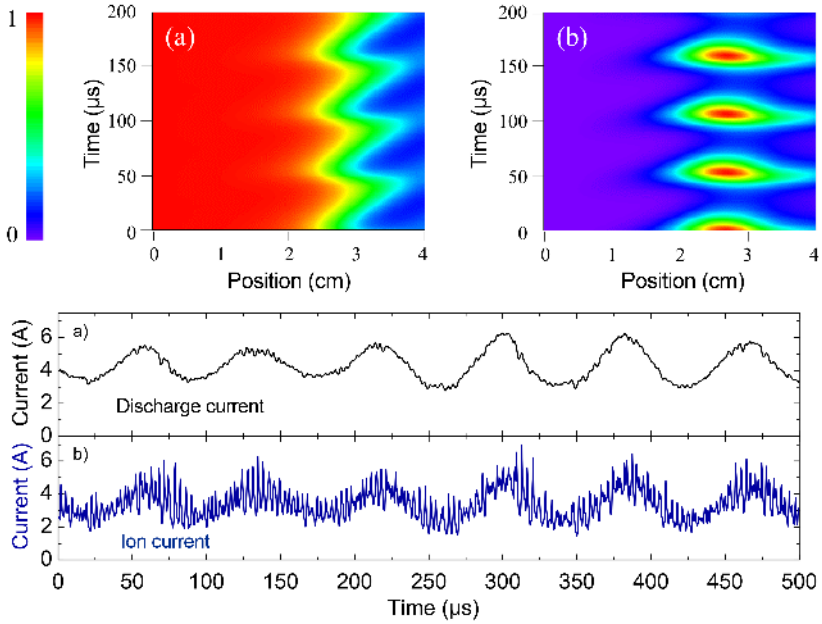

FIG. 18. (Top) 1D axial hybrid model results. (a) Neutral density (maximum 1.6×10^{19} m^{-3}), (b) Plasma density (maximum 1.6×10^{18} m^{-3}). Reprinted with permission from F. Darnon *et al*. Copyright 1999 IEEE [155]. (Bottom) 2D (axial-radial) hybrid model results. Discharge and ion currents as a function of time showing the breathing model oscillations at a frequency of 20 kHz with ion transit-time oscillations at 200 kHz superimposed. Reprinted with permission from J. Bareilles *et al*. Copyright 2004 AIP [156].

IV. NEXT STEPS

Where should the future electric and plasma propulsion technology go in the nearest future? We would like to emphasize three directions of high priority: 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.

3.1. Miniaturization

Our built environment is in the process of overwhelming miniaturization. Handy, portable and wearable devices, multifunctional smartphones, crystal-size computers and other new-sprung inventions are now penetrating even facet of our life and revolutionizing how we deliver and consume products and services. Miniaturization of space assets is steaming ahead, bringing along obvious advantages. 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 often than operational satellites. Moreover, miniaturization along with use of small and ultra-small satellites *en masse* means new capabilities – that's the main point.

Miniaturization means lower cost and hence, much higher affordability and easier access to space for those who need some special functions but cannot spend millions to purchase the entire launch – example include small scientific labs, private companies and universities. Most importantly, small satellites could form networked distributed systems – dynamically changing, adaptive constellations for the mission-oriented, coordinated formation flights of a large number of mini-satellites that feature expressive capabilities not really available using several satellites with the total mass comparable to 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 that open new horizons for the efficient, robust space exploration.[1] And this holds true not only near the Earth. Small yet organized groups of small satellites at the Moon and Mars orbits could be quite realistic and a much cheaper alternative to large, heavy universal probes that require heavy launch vehicles to reach remote planets. Deep-space Cubesats are nearing reality.[157]

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However, significant stumbling blocks still hinder the wide proliferation of organized mini-satellites, albeit launching them in hundreds at a time is nowadays a routine practice *(104 satellites were deployed by the Polar Satellite Launch Vehicle C37 mission on February 15, 2917)*[158]. Yet, *most of them are rather passive spacecraft, capable of orientation but not active maneuvering – while organized, coordinated* flight requires highly efficient, reliable thrust systems capable of maintaining active work and coherent maneuvering of small satellites within the formation. On the other hand, the efficiency of small thrusters, at the power level of hundred and even tens watts as required for typical Cubesats of one to ten U form-factor, is extremely low, sometimes below 10 %. Such low efficiency implies the need for considerable amounts of propellant and electric power, apparently at the expense of payload and orbital service life.

How to proceed with specific space propulsion systems?

Cold gas and hydrazine systems, when scaled down to tens of watts, feature extremely low specific impulses. This is quite expected from the physics point of view, because of high hydraulic losses in the accelerating channels and nozzles due to very high surface-to-volume ratios in tiny systems. Early attempts to enhance them by increasing specific impulse via electric heating resulted in hybrid thrusters that were rather cumbersome but still not too efficient, yet demanded the use of both electrical energy and chemical fuels, the latter often harmful and corrosive. Not surprising, such systems did not find a niche in the space technology, yet were used in several missions.

Therefore, the current trend is *all-electric space thrust platforms* accentuated by many relevant companies, e.g. by Airbus with its Eutelsat 172B launched on 2 June 2017.[159] These systems are very flexible and diverse, and an amazing assortment and versatility are the most prominent signature of the electric thrust platforms. Not surprising, a wide range of electric thrusters was produced and tested in labs and directly in space. Among others, the following types could be pointed out as the major trends:

- *Hall thrusters that rely on a closed electron drift and feature 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 feature low thrust density but very high specific impulse;*
- *Pulsing and direct-current thrusters that accelerate plasma as a whole medium by 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 various configurations, and*
- *Printable cathode arc thrusters.*

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

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 towards sizes compatible with Cubesats. An interesting and promising step forward is the invention and testing of *Cylindrical Hall Thrusters* featuring a simplified geometry without the central cylindrical part. This configuration decreases the efficiency yet it opens wide prospects for miniaturization by providing a way to build a tiny acceleration channel with a very small diameter. Owing to the pioneering works at the Princeton Plasma Propulsion lab, these thrusters have gained a wide recognition and may be soon adapted to Cubesats.[160,161,162]

Hall thrusters designed and tested at the Space Propulsion Centre in Singapore (SPCS) combine novel materials with exceptional properties for acceleration channels, flexible permanent magnet-based magnetic circuits, and 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.[163]

Another promising way to enhance the efficiency of small Hall thrusters is the so-called wall-less configuration where the plasma discharge is shifted outside the channel therefore drastically reducing losses at walls and making the device very simple hence more reliable.[38 - 42] Although preliminary works 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.

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Ion thrusters is the second major type of promising electric propulsion systems that are considered as candidate thrusters for active maneuvers, orbit keeping and gaining impulse for the interplanetary transitions. With the ion flux being accelerated by the DC potential applied to grids, these thrusters feature very high specific impulse. However, in contrast to Hall thrusters, the ion thrusters demonstrate low thrust density due to electric space charge in the discharge chamber. Thus, their capabilities towards miniaturization are limited. However, the low value of the thrust density could be compensated by higher accelerating voltage applied to the grids. This is also not a trivial task for the miniaturized systems, where electric breakdowns are highly possible due to small gaps between the powered electrodes, and thin insulators. Besides, robust and safe generation of high potentials in highly miniaturized systems on board of Cubesats requires advanced semiconductor technology. Thus, miniaturization of ion thrusters relies mainly on the progress in material science and engineering, rather than advancement in plasma physics and technology. Nevertheless, some efforts are being made to design the miniaturized ion thrusters, see e.g. the article in Journal of Spacecraft and Rockets.[164] Busek Co. Inc., a private propulsion company, has recently reported the radio frequency ion thruster of 1 sm size with the power of about 10 W, designed for Cubesats.[165]

Pulsing and direct-current thrusters accelerate plasma as a whole medium. As such, they do not suffer from low thrust density and hence, they are quite suitable for applications in microthrust configurations. Indeed, they have multiple applications in small satellites and Cubesats of various sizes, including smallest ones – Cubesats of 1U form-factor and less. However, these types of electric thrusters feature low power efficiency as compared to Hall and ion types (mainly due to high energy losses for metal evaporation and ionization in non-equilibrium plasma and non-station discharge transition processes). From this perspective, they are less suitable for applications requiring significant delta-v changes, such as orbit rising and inter planet transitions. They are better suited for precise attitude control and positioning. On the other hand, these operations require high accuracy for small satellites that are designed for the highly organized formation flights. Moreover, further miniaturization is vitally required to fulfill raising requirements to the accuracy of attitude control in constellations. That is why a new generation of pulsing thrusters based on the flat (material form-factor) **printed arc thrusters** have appeared.

Printable cathode arc thrusters are physically the pulsed type devices that utilize a pulsed or DC discharge between the two electrodes, and the erosion of electrode (usually cathode) supplies the mass to be ionized, accelerated and expelled to create a reactive thrust. In contrast to conventional pulsed thrusters, printed thrusters have flat geometry of two or more concentric electrodes, printed by metallic ink on some dielectric wafer, usually a thin flexible polymer film. These thrusters are extremely small (typically, of several mm in diameter and fractions of mm thick), very cheap and simple, and importantly, they are capable of producing extremely small thrust impulses for the extra-precise attitude control of smallest, but still active satellites (e.g., picosatellites of less than 1 kg). The further progress in printable thrusters would be expected in optimization of their geometry to enhance efficiency of the material ionization and acceleration in still under-explored flat discharges, and discovering novel materials capable of efficient supplying an easily ionisable propellant to the acceleration zone, and simultaneously, to withstand the harsh open-space conditions (cycling heating-cooling, ionized radiation etc.) without disruption of the thin structure and material exfoliation. The group led by Prof. M. Kim from the University of Southampton, UK, had recently produced a printed cathode arc thruster of about 5 cm size.

Electrodeless systems with rotating and complex-shape magnetic fields are a very promising type of the electric propulsion systems that does not involve current exchange between the plasma and conductive electrodes, thus excluding power and material losses associated with material heating, erosion, and energy spent to work function. Being potentially highly efficient, these systems are just at the initial stages of miniaturization, where exceptionally complex physics of the involved processes is the principal stumbling block. However, significant progress was achieved by several teams working on helicon thrusters (i.e. the group led by Prof. S. Shinohara at the Tokyo University of Agriculture and Technology, see article in Physics of Plasmas)[166], Rotamak-type systems designed by SPCS, Singapore (see Video article in the Journal of Visualized Experiments)[167], and radio frequency electro-thermal thruster ("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)[168]. Right now it is difficult to say if these systems will eventually be scaled down to a Cubesat scale, or will only occupy the niches of medium and high power thrusters; further efforts are in progress.

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Electrospray thrusters occupy a special niche between the flat printed systems that produce ultra-low thrust pulses, and micro-pulsed thrusters. The thrust is produced by applying an electrostatic voltage to electrospray emitters which accelerates liquid propellant, exiting from a small diameter capillary. This is a relatively matured technology that is intrinsically miniature, and further scaling down could involve complex nanostructures to further miniaturize the needles. Porous tungsten emitters are used on the present-day electrospray systems, but silicon technology is still the promising approach for the microfabricated emitter tips. This type of thrusters is highly promising for Cubesat applications due to possible multiplexing of electrospray microthrusters. Further progress in the electrospray thrusters is anticipated by involving complex metamaterials, and optimization of their geometry. The thrusters of this type were used in the Laser Interferometer Space Antenna (LISA Pathfinder) project, see the article in the Acta Astronautica.[169]

Extended efforts are now being applied by many research and engineering teams to miniaturize various space assets, to meet urgent expectations of space industry aimed at responding to global challenges. Global information access, distributed orbital networks and exploration of extra-terrestrial 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.

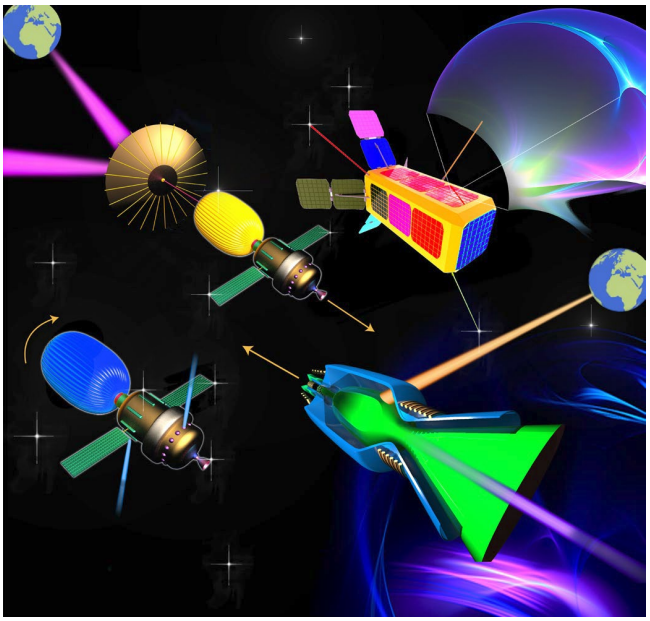

FIG. 19. Artistic presentation of several types of photonic space thrust platforms, where laser beams may be used to power plasma-based thrusters. An externally generated laser beam with a significantly higher power density than that of sunlight could be converted to electric energy, and use it to accelerate working fluid and produce thrust via plasma acceleration. Reprinted with permission from *Nature Photon.* **12**, 649 (2018). Copyright 2018, Springer-Nature.

3.2. Advanced Space Materials

Superrational distances, billions of light years of dark spiritless space and billions years of existence – this is our Universe. Is interplanetary space travel just a dream, or do we indeed have the capacity to develop space 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 the probes, there is not even a crew to control spacecraft configuration and flight path. This calls for spacecraft capable of self-controlled, self-adapting and self-healing behavior to cope with the extraterrestrial spatiotemporal challenges. It is a tough challenge to address using traditional materials and approaches for their assembly. True interplanetary advances may only be attained using novel self-assembled and self-healing materials, which would allow for realization of next-generation spacecraft, where the concepts of adaptation and healing are at the core of every level of spacecraft design.

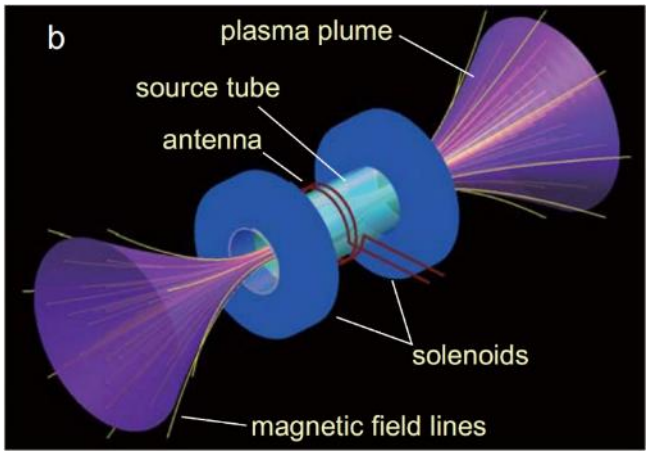

FIG. 20. An open exit magnetic nozzle RF plasma thruster forming the single electric propulsion device where control of the momentum flux imparted onto the debris is obtained via the control of the plasma momentum fluxes ejected at each open exit using variable external parameters (solenoids currents and propellant gas flow rates). Reprinted with permission from *Sci. Rep.* **8**, 14417 (2018). Copyright 2018, Springer-Nature.

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Is a self-healing plasma thruster possible? Self-healing of thruster design elements should rely on a *quite different approach* compared to elements of satellite frame, which primarily suffers from internal cracks and structural degradation, and thus should be healed in the material bulk via reversible and dynamic covalent bonds, supramolecular forces, and reversible crosslinkers described above. In contrast, thruster elements are exposed to plasma, heat and electron fluxes and hence suffer mainly from the surface damage, and hence, the self-healing should be essentially a surface-healing process. Significant progress has already been made to experimentally demonstrate viable strategies for surface healing. Two effects could be involved: an electric-field induced reconstruction of the surface to be healed, and selective deposition of patching material onto the damaged surface. Being a highly reactive environment, plasma is well-suited for synthesis and assembly of nanostructures that can be used as building block for the repair of the surface defects. Their delivery and incorporation into the damaged site can be readily attained by the use of non-uniform electric fields that arise at the interface between plasma and the solid surfaces, and are affected by the extent of roughness and the nature of the surface topography. Under the effect of these fields and determined by the nature of the surface pattern, the motion of ions and building/repair blocks and their subsequent deposition at target locations can be controlled. The success of this strategy has been recently demonstrated experimentally, showing a strong self-organization response and material re-distribution driven by low-temperature plasma and surface electric potential,[170-,172] resulting in fast and efficient repair of damaged sites through filling.[173]

3.3. New paradigms

Apart from the above outlined 'classical' plasma-based propulsion systems, other concepts could be considered in the nearest future, and among them the *laser-plasma systems* may be of the key importance (**Fig. 19**). 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 acceleration of a propellant, which can be solid or liquid.[174,175] A microthrusters that uses light to ablate a solid target is currently being developed.[176] There are several benefits to using light for propellant acceleration. One of the major advantages lies in the ability to physically disconnect 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 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[177] via a transparent window, whereas in the latter, the incident flux of photons will be coaxial to the resultant reactive jet[178]. 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 $m \times s^{-1}$ given that it is possible to achieve an ion temperature of 10,000 K in laser focus. The plasma that is created under the latter conditions would produce an electric filed 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 spacecraft.[179] Lightcraft is the early realization of a photonic-powered object that demonstrate stable flight sustained by the light from a ground-based laser.[174,180] 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.

V. OUTLOOK

In relation to the electromagnetic systems we can state that they 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.

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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 the radio-frequency pre-ionization 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 system therefore provides thrust without the need for additional neutralizers (cathodes).[181]

The field-emission electric propulsion (FEEP) is especially important for Cubesats due to their ultra-miniaturized form-factor, but 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 which 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 (**Figure 20**).[182] Space debris removal from the Earth orbit by using a satellite is an emergent technological challenge for sustainable human activities in space. In order to de-orbit debris it is necessary to impart a force to decelerate it, resulting in its atmospheric re-entry. A satellite using an energetic plasma beam directed at the debris will need to eject plasma in the opposite direction in a controlled manner in order to maintain a constant distance between it and the debris during the deorbiting mission. By employing a magnetic nozzle plasma thruster having two open source exits, bi-directional plasma ejection can be achieved using a single electric propulsion device. Both the forces exerted on the thruster and the target plate simulating the debris are simultaneously measured in a laboratory space simulation chamber showing that a force decelerating the debris and a zero net force on the thruster can be successfully obtained. These two forces can be individually controlled by external electrical parameters, resulting in the ability to switch the acceleration and deceleration modes of the satellite and the debris removal mode using a single electric propulsion device.[183]

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