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ABSTRACT

Micropropulsion systems are rapidly gaining attention from the small satellite community as they can increase the mission lifetime and allow the satellite to perform complex maneuvers and precise attitude control. These systems need to be fully operational with the low power available on satellites. Various thruster concepts based on vacuum arcs are currently under development, predominantly in the pulsed regime due to the power constraints on small spacecraft. Pulsed vacuum arc thrusters are capable of efficiently producing highly-ionized supersonic plasma at very low average power. This Perspective article provides a critical analysis and a review of various aspects of electric propulsion technology based on vacuum arcs. Furthermore, we give a personal assessment of the present status and provide an outlook on the field, including the growing role in small satellites such as CubeSats. Vacuum arc micropropulsion systems could play an important role in mitigating the problem of space debris. Such a system could be integrated with a satellite so that, at the end of its mission and using metal components as solid fuel, it will lower the satellite's orbit and accelerate reentrance into the atmosphere faster than by its natural decay rate.

I. INTRODUCTION, VACUUM ARC PHYSICS

Vacuum arc technology is currently in use for industrial applications such as ion implantation,[1] thin film deposition of hard coatings,[2] and transparent conducting oxides.[3,4] Some examples of hard coatings are TiNAl coatings for end mills and drill bits. Another well-known terrestrial application of vacuum arcs can be found in high-power switches, commonly known as vacuum arc interrupters or vacuum circuit breakers.[5,6] Less known is the fact that vacuum arc technology can also be used as a means of providing thrust for small satellites with devices known as vacuum arc thrusters (VAT). They can be operated both in direct current (DC) and in pulsed mode, although no DC VATs have been flown to date due to power and cooling issues. The average available power on microsatellites, i.e., satellites with a mass lower than 100 kg, is usually limited to 100 W and, therefore, only pulsed vacuum arc systems are practicable. Micropropulsion devices have enabled a myriad of options to small satellite mission designers and have allowed them to envision more complex missions than ever before,[7–9] such as the first interplanetary CubeSats launched by the Jet Propulsion Laboratory (JPL) in 2018.[10,11] The propulsion system onboard these CubeSats will allow the spacecraft to perform trajectory adjustments throughout the trip to Mars to ensure that the flight path remains nominal. Moreover, since the popularization of the CubeSat standard, many satellite operators have raised flags due to the increase of small, hard to detect spacecraft orbiting Earth. Simulations show that there will be an increase in catastrophic collisions involving CubeSats within the next 200 year projection window.[12] The authors assume that the CubeSats will not perform their own propulsive evasive maneuvers to avoid collision. Therefore, micropropulsion devices could help ease this issue by providing CubeSats with an active way to reduce their orbital lifespan and thus reduce the amount of space debris.

Vacuum arc discharges are known for their high plasma densities with high degrees of ionization, usually near 100% as evident by the ion charge state distribution, since this type of discharge produces multiply charged ions for most metals.[13,14]

Cathodic arcs discharges are complex discharge processes that have been observed and investigated since the 18th century.[15] The historical development of this technology includes works by renowned scientists.[16–23]

Vacuum arcs have been comprehensively described by many authors in several key publications, such as in reviews[24–27] and books.[15,28–30] Therefore, only a brief description of vacuum arcs will be presented here, as it will be useful to understand the plasma characteristics of this discharge to appreciate its use for thruster applications. It has been known since the late 1920s that the vacuum arc produces a force on the cathode, which is the electrode from which electrons are emitted.[16] Anodic arcs also exist,[31] but they are a special case of vacuum arcs that will not be further discussed here since only the cathodic arc plasma contains ions of high energy relevant to thrust. Cathodic arc plasma is produced in minute regions on the cathode's surface called arc spots. Once the discharge occurs, the arc spots leave behind craters of different diameters which follow the power law and denote the fractal character of cathode spots.[29] The fractal power exponent is material-dependent. These discharge regions can have current densities in the wide range of 10^8–10^{12} A/m^2.[32] Cathode spots are nonstationary on a nanosecond to microsecond timescale.[28,29] New spots are usually formed near the previously extinguished arc spots where the ignition conditions are most favorable.

The rapid succession of arc spot extinction and ignition appears to the eye as "apparent cathode spot motion," as illustrated by Figs. 1 and 2. Figure 2 was taken with a camera with a shutter speed of 1/29th of a second, similar to how the human eye would perceive it. The cathode, seen in the center of the image, was made of zinc and originally had a shape similar to the cathode shown in Fig. 3. The magnetic field configuration was such that the magnetic field lines pointed "out of the plane" toward the observer. The apparent motion follows the $-\boldsymbol{j} \times \boldsymbol{B}$ law and is known in literature as "retrograde motion." This phenomenon is not yet fully understood, but there are many different models that try to explain it.[30] It is worth reiterating that it is the process of arc spot extinction and reignition that creates the illusion of movement.[32] The ignition of new cathode arc spots occurs in a seemingly random manner, giving the appearance of "zigzagging,"[29,30] which is somewhat wrongfully referred to as "chaotic motion," since these spots do not move. The location of new arc spots will depend on various surface conditions, such as surface roughness, grain orientation, and presence of surface layers, which all will affect the electron emission density, which is known to be a function of temperature, electric field, and cathode material.[29] When a magnetic field is applied, the recurrence of new cathode spots becomes directional following $-\boldsymbol{j} \times \boldsymbol{B}$ in addition to what is referred to as the random component. This is explained by taking the self- and external fields into account, which produce a large magnetic pressure on one side of the cathode spot, increasing the probabilities of the next spot igniting on the retrograde side.[33] The superimposition of a magnetic field to a cathodic arc discharge can be actively used to control where the arc will act and, therefore, provides rudimentary cathode erosion control.

The behavior of arc spots in a superimposed magnetic field has been studied,[34] and recent interpretation of this effect states that the arc spots' new ignition location will most likely occur along the tangential component of the magnetic field.[35]

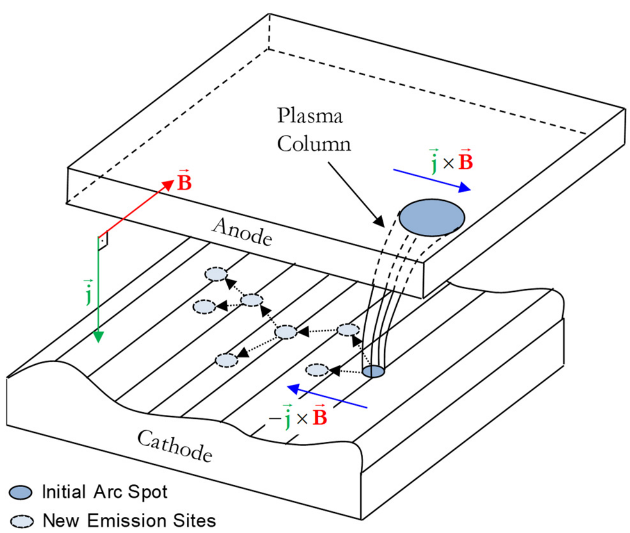

FIG. 1. The arc spots appear to migrate in the $-\boldsymbol{j} \times \boldsymbol{B}$ direction, opposite to the Lorentz force on charged particles, whereas the plasma column is bent in the opposite $\boldsymbol{j} \times \boldsymbol{B}$ direction.

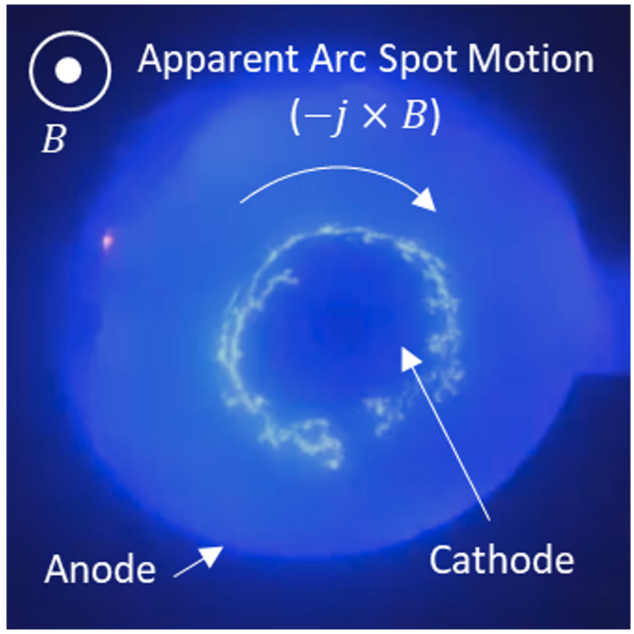

FIG. 2. Apparent cathode spot motion. Image shutter time: 34 ms. The magnetic field comes out of the plane.

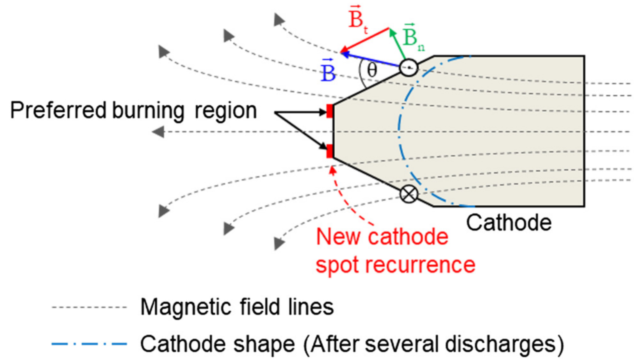

FIG. 3. Effect of the magnetic field on the preferred arc burning region on a conical cathode. The dot-dash line denotes the shape the cathode will take after many discharges.

Figure 3 shows a schematic of this effect on a conical cathode. The axial magnetic field (AMF) intersects the cathode's surface at an angle θ with nonzero normal and tangential components. Arc spots are more likely to ignite following the tangential component of the magnetic field. This effect was first observed on a mercury arc.[19] In the example shown in Fig. 3, each successive arc spot will, therefore, ignite closer to the front of the cathode, shown in the image as the "preferred burning region."[36] Spot steering, as this effect is known, is not unique to conical cathodes and, in fact, it can be observed any time a magnetic field is present. In the example given in both Figs. 2 and 3, the ignition and extinction of the cathode spots will follow a clockwise trend.

The cathodic arc discharge erodes the cathode's surface, leading to the production of ions, i.e., a metallic plasma, and small droplets called macroparticles. The latter will be described further along in the text. The ions emitted by the arc spots are highly energetic and the ion energy is mostly independent on the discharge current.[36] The ion velocity is also nearly independent of the ion charge state for ions of the same metal and changes for different cathode materials.[36] The velocity of the ions is in the order of magnitude of 10^4 m/s.[36] The plasma emitted from the cathode spots has a high density that can reach values of up to $10^{26}\,\mathrm{m}^{-3}$ in the proximity of the cathode spot and approximately $10^{20}\,\mathrm{m}^{-3}$ at few millimeters from the cathode spot.[37] Additionally, the ions are usually multiply charged (e.g., 2+ and 3+).[36,38] Aside from plasma, the byproducts of the cathode spot emission include neutral metal atoms and microdroplets. These microdroplets are heavy and much slower—in the range of a few 100 m/s[39,40]—compared to ions and do not significantly contribute to the thrust of the vacuum arc thruster. Macroparticle emission depends on cathode material and pulse duration. Materials with high melting points such as refractory metals produce fewer macroparticles. Short pulse discharges are also known to produce fewer particles.[28] These particles also may have a detrimental effect on the specific impulse of thrusters due to their high mass and low velocities. Therefore, these particles are undesired for thruster applications. Macroparticles have been studied and it has been concluded that they may assume a charge depending on various factors such as radius, time inside the plasma, and velocity.[41]

The force acting upon the cathode comes from the expanding (accelerating) plasma jet in the cathode region. This jet expands at supersonic speed and reaches this velocity at approximately two to three cathode spot radii.[42] The force experienced by the cathode scales with the current and therefore the effect can be described by the ratio of force over current, which is roughly 0.17 ± 0.03 mN/A for a copper cathode, as noted in the early work of Tanberg.[16] Development of vacuum arc thrusters began in the early 1960s and 1970s[43–48] when the first prototypes were built and tested. After notable initial achievements, a period of stagnation in the field of vacuum arc thrusters occurred until the late 1990s. This hiatus can be explained by the fact that during this timeframe, more mature and powerful technologies were being tested on American and Russian satellites.[49,50] Such technologies include Teflon™ pulsed plasma thrusters (PPTs), nitrogen and ammonia resistojets, Hall-effect thrusters, among others.[49,50] It was not until the late 1990s that viable flight models of vacuum arc thrusters were being designed and built, especially for their use on smaller spacecraft such as CubeSats, and it would take another 15 years to successfully test a VAT in space.[51] During this interlude, the research in the field of vacuum (cathodic) arcs shifted toward the generation of high quality coatings. This development occurred both in the United States and in the former Soviet Union.[44,52] Additionally, researchers focused on gaining a better understanding of the vacuum arc physics.[32,34,39,40,53]

The following sections will focus on the technological aspect of vacuum arc thrusters, such as figures of merit, a brief historical overview, and their modi operandi. Moreover, past and current developments of this technology, such as the work being performed at The George Washington University (GW), are summarized and discussed. Such a manuscript would of course not be complete without the discussion of various performance models and the effects of magnetic fields on the plasma jets. To conclude, the authors offer a look into the future of vacuum arc thruster technology.

II. SPACE PROPULSION: FIGURES OF MERIT

Section I briefly detailed the physics of vacuum arcs. For a comprehensive description of the arc spot phenomena, the reader is referred to other works.[26,28,29,32,53] This brief segment will introduce common figures of merit of space propulsion systems bridging the theory of vacuum arcs and VATs with the field of propulsion in general.

Space propulsion systems can be sorted into three main categories depending on the energy source used to produce thrust. The three main types are chemical, nuclear, and electric propulsion systems.[54] Electric propulsion systems are subdivided into electrothermal, electrostatic, and electromagnetic thrusters.[54] VATs belong to the family of electromagnetic thrusters, which are systems that take advantage of magnetohydrodynamic effects to produce thrust.

The first important figure or merit is the specific impulse or I_{sp}. The specific impulse describes the thrust efficiency of a propulsion system and can be calculated as follows:[55]

$$I_{sp} = \frac{v_e}{g}, \tag{1}$$

where v_e is the effective exhaust velocity of the work medium and g is the gravitational acceleration. The unit of the $I_{\rm sp}$ is seconds. The specific impulse can then be used to calculate the thrust,[55] which is given as

$$T = I_{sp}\dot{m}_p g = v_e \dot{m}_p. \tag{2}$$

In the previous equation, $\dot{m}_p$ is the propellant mass flow. Electric propulsion systems have very high specific impulses in the range of thousands of seconds[56,57] and thrust levels ranging from micronewtons (vacuum arc thrusters) and other devices such as electrospray thrusters[58] to a few newtons.[56] The efficiency, in the simplest of cases, can be defined as

$$\eta = \frac{P_{jet}}{P_{in}}, \tag{3}$$

where P_{jet} is the plasma (or ion beam) jet power and P_{in} is the total electrical power supplied to the thruster.[55]

The field of small satellite propulsion systems has seen significant growth in the last decade, mainly attributed to the increasing popularity of CubeSats, which are small satellites comprised of units of one cubic decimeter. Each unit is called a "U." The complexity of CubeSat missions has driven the development for miniaturized propulsion systems (further details in Refs. 8 and 59–62).

III. VACUUM ARC ION THRUSTERS AND VACUUM ARC THRUSTERS: 1990s–PRESENT

In the late 1990s, after almost two decades without published research in the field of vacuum arc thrusters, the field was resurrected with new ideas. In 1998, researchers from California-based Alameda Applied Sciences Corporation (AASC) and Lawrence Berkeley National Laboratory (LBNL) submitted a Phase-I final report in which they described a vacuum arc ion thruster (VAIT).[63] In contrast to VATs, VAITs have a dedicated ion extraction (hence ion acceleration) stage, usually an electric field region provided by a set of grids. Therefore, vacuum arc ion thrusters belong to the family of electrostatic thrusters which all use an electric field to accelerate ions to high velocities. In contrast to electromagnetic thrusters, only ions are expelled from the thruster, and, therefore, the ion beam must be neutralized after extraction to avoid electrostatic blow-up of the ion beam, charging of the spacecraft, and return of ions to the spacecraft.[54] The design of the VAIT was based on the low-energy version of the MEVVA (Metal Vapor Vacuum Arc[64,65]) shown in Fig. 4.[66]

VAITs use the cathode material as propellant, as opposed to conventional gridded ion thrusters which use gaseous propellants. In contrast to conventional ion thrusters, VATs and VAITs do not require gas containers, flow rate meters, valves, or tubing. As mentioned above, plasma is produced in minute cathode spots. As such, thrusters based on a vacuum arc can be scaled down to very small sizes. As mentioned in the vacuum arc section, the state charges of the ions are predominantly 1+ to 3+ depending on the metal propellant. Some of the metals tested for VAITs were tantalum, tungsten, iridium, gold, bismuth, and thorium. Vacuum arc (ion) thrusters require the propellant to be electrically conducting and therefore, in principle, any metal and alloys can be used. This gives these systems a versatility that other propulsion systems do not have. The device built by AASC and LBNL produced a thrust of approximately 0.13 N using time-of-flight performance predictions.[63] The ion stream velocities were in the order of 5×10^4 m/s with an extraction voltage of 3 kV and grids with a diameter of 12 cm at a peak discharge power of 900 W with a peak grid power of 3900 W. The duty factor could be reduced to approximately 10%, therefore showing the feasibility of a vacuum arc ion thruster with an average power of 50 W. The device is shown in Fig. 5. The laboratory experiment[63] did not make use a beam neutralizer, which is needed in space to avoid charging of the spacecraft, but not completely necessary in a laboratory setting, since the ion beam produces secondary electrons as it hits the chamber's walls, thus neutralizing the beam.

The device had a maximum thrust of 270 mN with an overall efficiency of approximately 80%.[67] The beam divergence was in the order of 50–80 mrad,[67] but could have been reduced if the system had had active beam neutralization by means of a neutralizing cathode. Not too long after, a study for a pulsed two-stage plasma

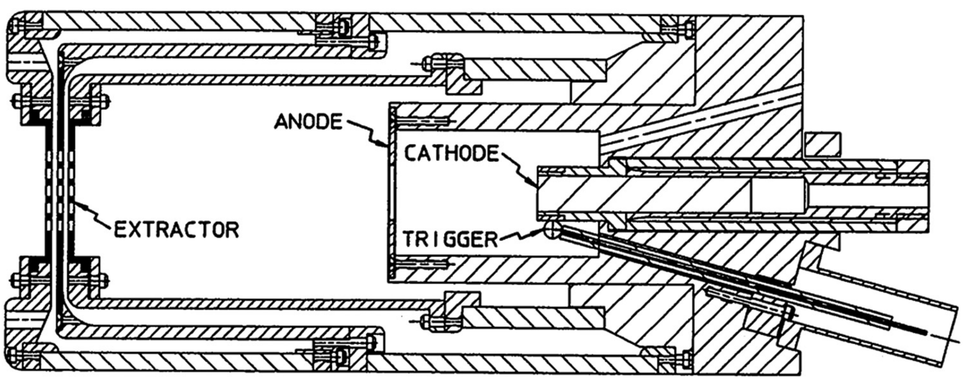

FIG. 4. Outline of the MEVVA ion source that inspired the work on VAIT. Reproduced from Brown *et al.*, Rev. Sci. Instrum. **65**, 1260–1261 (1994). Copyright 1994 AIP Publishing LLC.

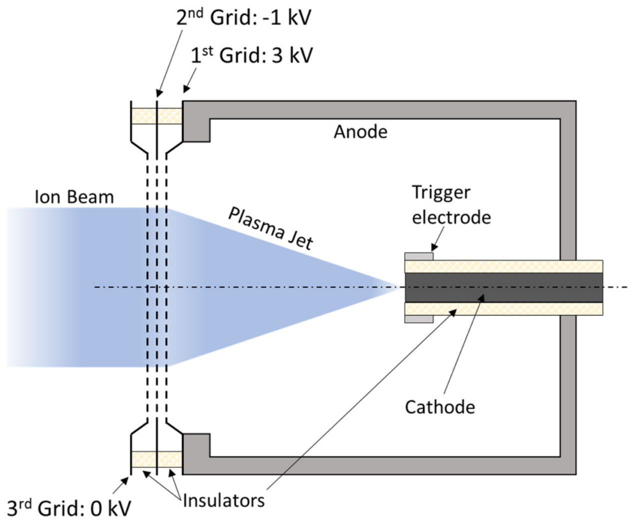

FIG. 5. Generic schematic of a vacuum arc ion thruster (without space charge neutralizer).

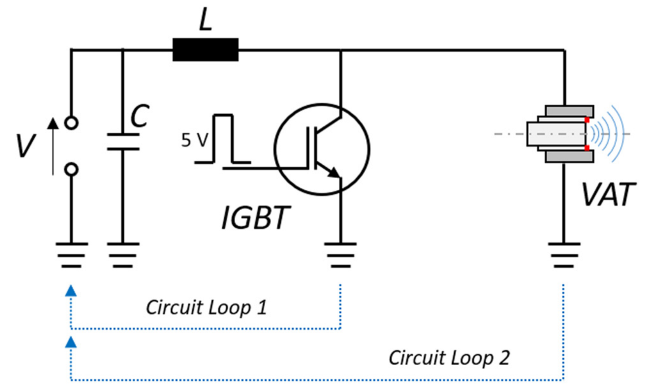

FIG. 6. Schematic of a typical booster circuit for a pulsed vacuum arc thruster, where the interruption of circuit loop 1 produces the voltage to ignite the discharge in circuit loop 2.

accelerator with metallic propellant was published.[68] Even though this device is not entirely a vacuum arc thruster, the authors saw the importance and usefulness of vacuum arcs in space applications.

However, to this date, no VAIT has been flown because xenon ion thrusters are well established in the field and have been flown on several missions. Additionally, ion thrusters with xenon as propellant are more efficient at average powers higher than 1 kW. Solid propellants are also seen critically by the community because of the possibility of ions returning to the spacecraft and unintentionally coating important components, such as solar cells and optical instruments.

One concern of using both VAT and VAIT is the triggering of arcs. Therefore, the triggering issue deserves special attention. VATs and VAITs are usually triggered by a "triggerless" or "self-triggering" method,[69] and recent efforts focus on developing a better understanding of the arc ignition process.[70] It was shown that the insulator material plays an important role in "triggerless" or "self-trigger" arc ignition. To ignite vacuum arc thrusters, it is common to use booster circuits (Fig. 6). The first segment of the circuit depicted by circuit loop 1 consists of a power supply, generally with a voltage between 15 and 25 V powered either directly by the spacecraft's power supply unit and batteries, or stepped up from any of the satellite's bus voltages using DC-DC converters, which charges the capacitor C. When a 5 V square-wave is applied to the insulated-gate bipolar transistor (IGBT), the device "closes" and completes circuit loop 1, which leads to a buildup of the magnetic field of the inductor L. After a charging period defined by the inductance and capacitance of the components and controlled by the length of the pulse-width modulated square pulse, this signal is turned off and the IGBT opens again. The energy stored in the inductor is then released onto the thruster as a high-voltage pulse in the order of LdI/dt, causing breakdown between the two electrodes through a conductive film and, therefore, closing circuit loop 2. This process leads to the production of plasma which expands from the cathode and thereby produces thrust. Theoretically, this process can be repeated at high repetition rates, of hundreds to thousands of pulses per second. Typical repetition rates are below 50 Hz due to the charging time of the capacitor and energy stored in the inductor and the thermal properties of the thruster. For higher repetition rates (higher duty cycle), measures would need to be engineered to remove the dissipated energy. It is worth mentioning that the circuit, due to its transient magnetic fields, is prone to producing a large quantity of electromagnetic interference (EMI). Measures should be taken to shield this power processing unit (PPU) from other critical components in a satellite, such as the onboard computer or other sensitive sensors. Moreover, the spacecraft operator should plan accordingly and avoid sensitive measurements or radio communications, while the thrusters are firing to avoid any issues. The CubeSat BRICSat-P operated in such a way that during propulsive maneuvers, only the vital subsystems were operational. The CubeSat operated without anomalies during these maneuvers. Still, managing EMI issues remains one of the challenging tasks in future VAT and VAIT developments and deployments.

The PPU is the heaviest component of the thruster subsystem. For CubeSat-sized vacuum arc propulsion systems, the PPU makes up approximately 90% of the mass, a large fraction of this mass stems from the inductor. The inductance depends on the windings, usually made from copper wire, and the core material, commonly a ferrite, which explains its weight. This can cause the propulsion system to weigh between 100 and 300 g, depending on the amount of PPUs one may want to cluster into a circuit board, since each PPU will require its own inductor.

To promote the breakdown (plasma formation) between cathode and anode, the insulator between electrodes is coated with a thin conductive film. The voltage spike of scale LdI/dt breaks down on the conductive film, releasing plasma from the coating into the interelectrode gap. The plasma is conductive and closes the circuit between the electrodes, thus allowing the flow of current.

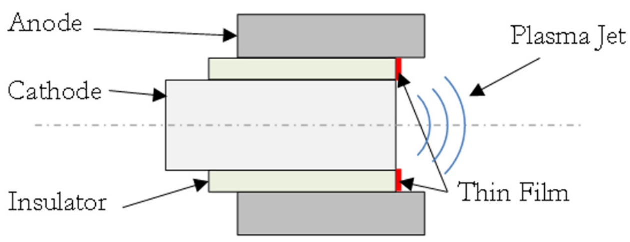

FIG. 7. Schematic of a "triggerless" trigger for a vacuum arc thruster: a high voltage applied between cathode and anode leads to breakdown and plasma formation.

A schematic can be seen in Fig. 7. A low mass propulsion device of less than 300 g including the power processing unit (PPU)[71,72] is shown in Fig. 8. This device was tested with different cathode materials, such as tantalum and aluminum. The specific impulse for the former was approximately 1100 s, while the latter had a specific impulse (I_{sp}) of nearly 3000 s.

Experiments performed with titanium showed a thrust-to-power ratio of 2.2 μN/W. Thrust measurements were carried out with a torsional thrust balance at the Jet Propulsion Laboratory.[73] The motivation for such small thrusters came from the growing interest of space agencies in so-called nanosatellites, which are satellites with a wet mass (mass including propellant) of less than 10 kg. An example of a miniature thruster and its PPU is shown in Fig. 8. Station keeping of small satellites has been suggested as the main use for this thruster.[71,72] The thrust of VATs scales almost linearly with the input power as shown in Fig. 9 suggesting that the thrust-to-power ratio is independent of power. This is somewhat unusual for electric thrusters, in which the thrust-to-power ratio and the efficiency increases with the applied power.

In 2002, the thruster planned for the Illinois Observing Nanosatellite (ION), a 2U CubeSat from the University of Illinois at Urbana-Champaign, was presented.[74] The thruster was named

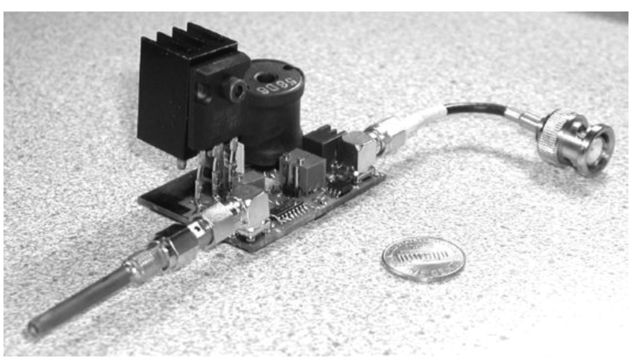

FIG. 8. Image of a VAT with PPU.[71] Used with permission from Schein *et al.*, in *27th International Electric Propulsion Conference, IEPC-01-228, Pasadena, CA* (Electric Rocket Propulsion Society, 2001). Copyright 2019 Electric Rocket Propulsion Society.

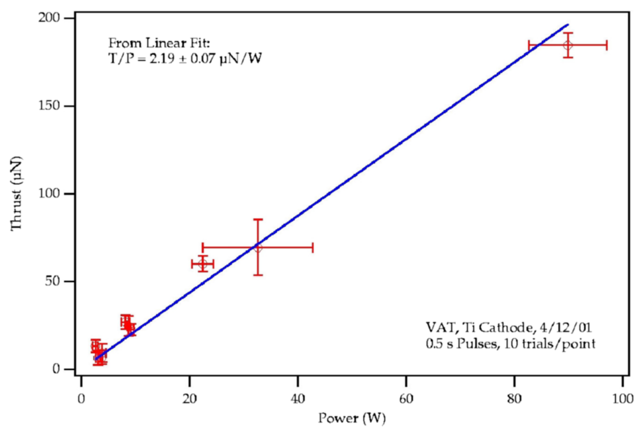

FIG. 9. Average thrust as a function of average power.[71] Used with permission from Schein *et al.*, in *27th International Electric Propulsion Conference, IEPC-01-228, Pasadena, CA* (Electric Rocket Propulsion Society, 2001). Copyright 2019 Electric Rocket Propulsion Society.

µBLT due to its size and the fact that the cathode, insulators, and anode are "sandwiched" together (Fig. 10). This thruster design is also shown and described in another paper.[75] This type of thruster was embedded in the satellite's structure as a means of saving mass and space. Furthermore, this simple design allowed the thrusters to utilize the structure of the spacecraft as an anode. The ION team considered a concentric design, but the high machining tolerances required to produce such a thruster and the uncertainty of the propulsion system's ability to withstand launch vibrations led the team to go for this simplistic geometry. The design of course has its drawbacks, such as having a flat elongated cathode, which means that there will be high uncertainty on where the arc spots will ignite, and, therefore, the thrust vector is not precisely controlled. The PPU of this thruster measured $4 \times 4 \times 4\,\mathrm{cm}^3$ and had a total mass of 150 g. The thruster and the respective PPU can be seen in Fig. 10. These thrusters were placed on the satellite in such a way as to allow translation and 2-axis rotation. The thruster is fired with an average power of 4 W, producing approximately 54 μN of average thrust using aluminum as a propellant.

This system allows the use of the satellites structure as propellant; therefore, an additional propellant is not required (a feature we will dwell on in our outlook). The observation satellite ION was launched in 2006 atop a Russian Dnepr launch vehicle. Unfortunately, the satellite was lost due to a launch vehicle failure 86 s after takeoff.[76]

A significant improvement to the vacuum arc thruster was obtained and measured when a magnetic field was superimposed axially to the thruster's head.[77,78] The result of this improvement was named the MVAT or the magnetically-enhanced vacuum arc thruster.[79] Even though the beneficial effect of using a magnetic field had already been observed in the 1960s, current thruster designs do not take advantage of it. The magnetic field increases the burning voltage of the arc since the electrons face a higher impedance when they move across magnetic field lines to reach the

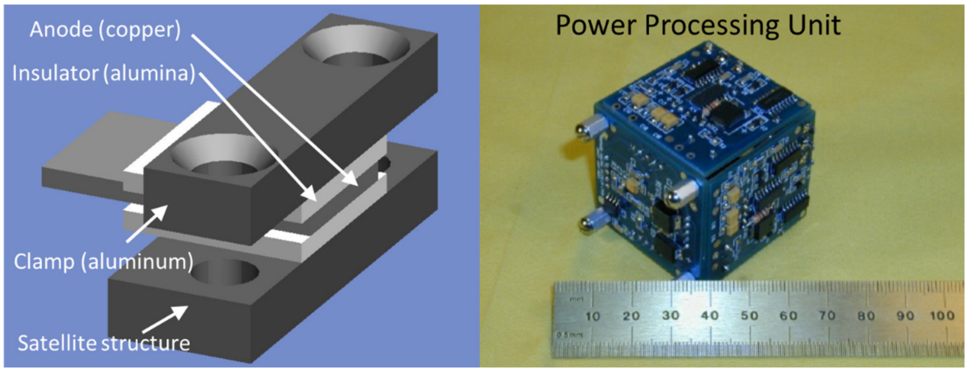

FIG. 10. Schematic of the μBLT vacuum arc thruster (left) and its power supply unit with a millimeter-scale ruler (right). The PPU was designed by Alameda Applied Sciences Corporation and is capable of controlling all four thrusters on the satellite.[74] Used with permission from Rysanek *et al.*, Presented at the 16th SmallSat Conference, SSC02-I-2, Logan, UT, 2002. Copyright 2002 Jochen Schein.

anode. This increases the power required by the discharge, which, given the tight power budgets of small satellites, can be a difficult tradeoff. A significant benefit of having an axial magnetic field is that it constricts the plasma by decreasing its radial expansion and thus drastically increases the ion energy in the axial direction.[36,80] Additional advantages of an axial magnetic field is a more uniform erosion on the cathode (arc steering) and an increase in the ion current.[81]

Research and development in the field of VATs is also done in Australia,[82,83] Germany,[84–88] United Kingdom,[89] Israel,[90] Japan,[91–93] South Africa,[94–98] France,[99,100] and the Ukraine.[101]

The thruster shown in Fig. 11, built between 2008 and 2009, was the beginning of the micropropulsion research in the field of vacuum arc thrusters conducted at The George Washington University (GW).[81] Section IV will be dedicated to the device known as microcathode arc thruster, or μCAT for short, and the research conducted at GW.

IV. GEORGE WASHINGTON UNIVERSITY'S MICROCATHODE ARC THRUSTER (μCAT)

The first version of the μCAT developed at GW was shown in the previous segment. This device, shown in Fig. 11, consists of tube-shaped cathode and anode, separated by an insulator ring. This system is called the ring electrode μCAT (RE-μCAT).[102–105]

The inside of the ring is coated with graphite to facilitate "triggerless" triggering method (as explained in Fig. 7). The anode is fixed to the main structure of the thruster. A spring applies a force on the cathode to keep it in contact with the ceramic insulator. The spring also functions as a propellant feed system. Plasma is produced using a booster circuit similar to the one shown in Fig. 6.

The plasma is guided through the anode opening by an axial magnetic field. The magnetic field is also used to steer arc spots, as explained in Sec. I, to obtain a uniform cathode erosion. Using a four-point-probe placed at an angle of 90° from each other along the circumference of the plasma exhaust plane, the researchers determined that the average spot rotation velocity was approximately 75 m/s.[81] The coil was connected in series with the thruster, and, therefore, the magnetic field is produced by the discharge current. This is a common approach used in pulsed filtered arc sources.[106] Applying a magnetic field drastically increased the ratio of the ion current to the total discharge current.[107,108]

This initial design performed well, but analysis showed that the prototype suffered from plasma losses during the discharge. A significant fraction of the ions was not able to produce thrust due to the geometry of the thruster. The plasma is ejected at an angle from the arc spot, shown in red in Fig. 12. The local magnetic field is strong enough to magnetize the electrons emitted by the discharge. As a result, such partially magnetized plasma can be guided by a magnetic field due to the electric coupling between electrons and ions. This is the same effect known in magnetized vacuum arc filters.[108] Overall, the plasma jet emitted by the cathode spot is

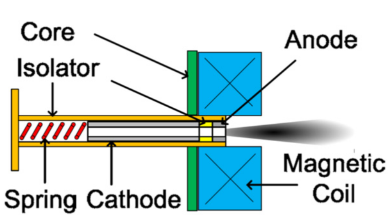

FIG. 11. Microvacuum arc thruster with extended lifetime. The spring is used to feed the cathode toward the insulator which is coated with a conductive thin film.[81] Used with permission Zhuang *et al.*, in *31st International Electric Propulsion Conference, IEPC-2009-192, Ann Arbor, MI* (Electric Rocket Propulsion Society, 2009). Copyright 2019 Electric Rocket Propulsion Society.

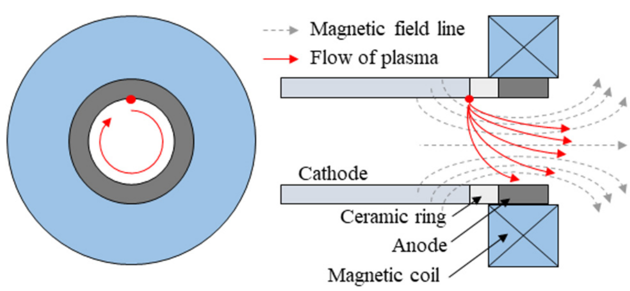

FIG. 12. Front view (left) and side cross section (right) of the ring electrode μCAT thruster (RE-μCAT). The image on the left shows the circular motion of the arc spot caused by the magnetic field.

guided along the magnetic field lines and plasma losses due to collisions and various plasma instabilities are reduced. A measure of this effect is the increase of the ion current fraction. The neutral atoms and macroparticles produced are unaffected by the magnetic field and will most likely coat the inside surface of the anode and the ceramic ring, not contributing to thrust though replenishing the coating required for the "triggerless" trigger principle. This thruster concept is limited by the magnetic field's ability to transport the majority of the plasma out of the channel. A fraction of the ejected electrons must still interact with the anode to close the circuit and keep the arc discharge stable.

To further reduce plasma losses, a new concept was proposed. The idea is based on the understanding that plasma losses are due to interaction with walls and thus the reduction of plasma interaction with surfaces can have some effect. This arrangement, called the coaxial μCAT (CA-μCAT),[109] is shown in Fig. 13. Since cathode spots are formed at the face surface of the thruster, the plasma plume expands into vacuum without significant plasma deposition onto the inner surfaces. This, in return, reduces the replenishment of the conductive coating over the insulator. In this case, ion deposition is relatively small and as such, the coating is very limited. Related to this is the contamination due to charge exchange known to be a primary concern for electric thrusters use in space. Studies showed that, due to the high degree of ionization produced by the vacuum arc in pulsed mode, the back-flux contamination is nonexistent. This was measured using ion collectors placed at various angles from the centerline.[110] No signal was measured with the probe that was mounted at 90° with respect to the center axis of the thruster. This means that the highly-ionized plasma of the μCAT system is highly directional and that nearly 100% of the plasma is directed away from the thruster.[110]

The performance of both the ring electrode and the coaxial μCAT systems has been investigated. Both thrusters can be operated with the same booster circuit. The peak ion current was approximately 3.5% of the discharge current for a magnetic field strength of 420 mT. In the case of the CA-μCAT system, the value for the ion current vs total current remained almost constant at about 3.5% with magnetic fields between 0 and 300 mT.[109] The result showed that the ion current does not depend on the magnetic field for the latter. This suggests that the magnetic field primarily affects the flow by collimating the plasma jet and not by increasing the

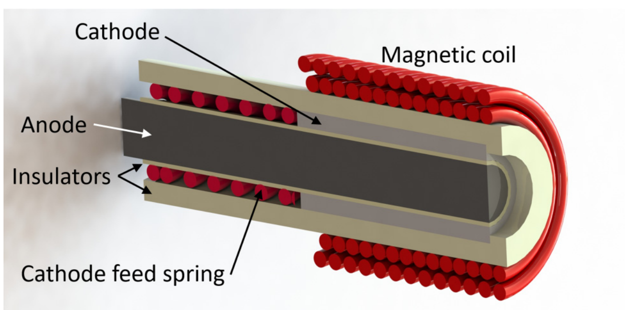

FIG. 13. Schematic of the coaxial μCAT system (CA-μCAT).

ion charge state. It is believed that this occurs because of the geometry of this specific thruster so that any possible increase in the ion flux due to the magnetic field is being cancelled out by the thruster's geometry, e.g., due to increased wall losses. Even though the ion current does not seem to be affected by the magnetic field, the ion velocity is highly dependent on it. The ion velocity increases twofold from approximately 20 km/s at 0 T to approximately 40 km/s at 300 mT.[109] Ion acceleration was also predicted by Particle in Cell (PIC) simulations.[111] A simple estimate suggests that the ions are accelerated by a $\boldsymbol{J}\times\boldsymbol{B}$ force.[105] To that end, the following physical arguments can be considered. The plasma flow is subject to the electromagnetic force in the divergent magnetic field region, which can be described with the following equation:

$$M\,n\,\frac{dV}{dt} = j_\theta B_r, \tag{4}$$

where M is the ion mass, n is the plasma density, j_θ is the azimuthal electron current, V is the ion velocity, and B_r is the radial component of the magnetic field. The azimuthal electron current density j_θ can be estimated as

$$j_\theta = \frac{\omega_e}{\nu_{ei}} j_r, \tag{5}$$

where j_r is the electron radial current density, ω_e is the electron cyclotron frequency, and ν_{ei} is the electron-ion collision frequency. In the plasma jet outside of the interelectrode gap, the total current is zero, and, therefore, the radial electron current is equal to the radial ion current. Thus,

$$j_{er} = j_{ir} = enV_r, \tag{6}$$

where V_r is the radial component of the ion velocity and e is the elementary charge. The radial component of the plasma velocity V_r is developed in the course of plasma expansion[37] and could be about 0.3 of the axial component in a high magnetic field.

Based on the above scenario, one can estimate the ion velocity change in the axial direction ΔV_z as

$$\Delta V_z \approx \sqrt{\frac{2e^2 B_z B_r V_r \Delta z}{mM\nu_{ei}}}. \tag{7}$$

Using the following typical parameters of the plasma jet: $B \sim 0.1$ T (i.e., both magnetic field components in radial and axial direction, B_r and B_Z), $n \sim 10^{20}\,\mathrm{m^{-3}}$, $V_r \sim 10^4$ m/s, and $\Delta z \sim 0.01$ m, one can estimate that the change in velocity ΔV_z is approximately 10^4 m/s. This result is in good agreement with experimental measurements.[105]

The acceleration trend is similar for both the RE-μCAT and the CA-μCAT. In the case of RE-μCAT, there is significant ion collimation that leads to a decrease of ion losses and consequent ion current increase.[109–111] The measurements were performed using the time-of-flight (TOF) method.

The physical nature of arc spots brings a myriad of technical challenges. Some of these challenges are related to the ignition and reignition of arc spots during the discharge. During the ignition of the arc spots, the plasma column is affected by the magnetic field, as described at the beginning of the article. Depending on where the arc spot ignites on the cathode, the plasma jet may not be perfectly aligned with the thrust vector, reducing the thrust efficiency and possibly creating an unwanted torque on the spacecraft. Therefore, an active effort needs to be taken to counter this, such as thrust vector control. A thrust vector control system was designed for the μCAT systems. The system uses three noncoaxial magnetic coils to steer the plasma,[112] similar to an approach proposed in the early 1970s.[46] By activating a specific sequence of coils and by regulating the magnetic field strength, it should be theoretically possible to steer the thrust vector.[112] The introduction of these magnetic fields will of course change the expansion of the plasma plume and thus the possible back-flux of ions onto the spacecraft. However, modest steering angles, i.e., between 10° and 15°, will have a small effect on the potential particle back-flux since this is controlled by the charge exchange between particles, which is small in vacuum arc-based thrusters due to the high ionization degree of the plasma and the relatively low density of neutrals. A field of research is the mechanism of plasma detachment from the magnetic field: it is empirically known that the plasma plume does not follow magnetic field lines returning to the plasma source. Plasma detachment from the magnetic fields is a topic that needs to be researched further to understand the effects on spacecraft back-flux.

An additional challenge caused by the arc spots is the ablation of the cathode, which is critical and central to the discharge since it is the source of electrons and ions for the plasma. As the number of arc pulses increases, the cathode is consumed and, therefore, eventually it will be necessary to provide a means of replenishment of the propellant to ensure that there is enough material for the forthcoming discharges. A linear cathode feed system was developed to solve the problem of propellant feeding.[113] The system uses a stepper motor to feed the cathode material once the system detects that no arcing is occurring. The propellant (cathode) is slowly fed until arcing resumes. The thrusters shown in Figs. 11–13 possess a passive, spring-fed cathode instead of a motorized cathode to constantly feed the propellant when needed. Not having a feed system severely limits the lifetime of the thrusters since vacuum arc thrusters rely on the medium-impedance electrical contact between the cathode and the anode through a thin carbon layer. If the cathode is eroded to the point that there is no more physical contact to this carbon layer, then the thruster will cease operation since the triggering voltage is insufficient to cause the breakdown of the gap.

A further development in the microcathode arc thruster family was the bi-modal thruster, named BM-μCAT.[114] The system takes advantage of the previous CA-μCAT design. The propellant for the CA-μCAT can be almost any metal, although titanium and nickel are usually the preferred propellants. The propellant choice heavily depends on the requirements for the propulsion system. If a higher specific impulse is required, then titanium would be the propellant of choice. If the focus is shifted toward higher thrust, then nickel would be the propellant. The BM-μCAT takes advantage of the properties of nickel and titanium and combines them in one thruster. This capability allows the thruster to fire in either mode when required, allowing mission planners to "adjust" the thruster according to their necessities. If the maneuver requires higher thrust, the BM-μCAT would fire using nickel as cathode and titanium as anode. Should high specific impulse be the requirement, then the electrodes would be switched by the on-board electronics. Experimental work showed that using a titanium cathode, an impulse bit of approximately $1\,\mu$Ns could be produced, whereas with nickel, the impulse bit was about $2\,\mu$Ns. Both impulse bit values were calculated with a 1 Hz repetition rate.[114]

The performance of the RE-μCAT microcathode arc thruster has been characterized using a thrust balance at the University of Southern California.[115] The results showed that the impulse bit was slightly above $1\,\mu$N s when the applied magnetic field was 300 mT. The thrust produced by the RE-μCAT at the aforementioned magnetic field strength was approximately 9.5 mN at a firing frequency of 50 Hz. The applied magnetic field of 300 mT increased the thrust by a factor of 10 when compared to the performance without a magnetic field. The efficiency of the thruster at 300 mT was increased by a factor of five.[115] Further characterization was also performed to simulate the near plume of the RE–μCAT[116] and the plasma detachment from the magnetic nozzle.[117]

A novel end-of-life (EOL) deorbiting system was presented at the 2015 IEPC in Kobe, Japan. Normally, CubeSats are deployed in low Earth orbit (LEO), where their lifespan is usually less than two years before their orbit decays and the satellite disintegrates in the atmosphere. Deploying CubeSats in higher orbits brings up the problem of decommissioning and disposal of satellites after their useful life. These satellites have limited space on board and carrying a propulsion system for the EOL deorbiting burn is often not feasible. Therefore, the possible use of silicon as a cathode material was investigated.[118] Silicon is the most common element used in solar cells and abundant on a spacecraft. However, semiconductors like silicon pose challenges when it comes to sustaining an arc discharge, which is associated with silicon's limited conductivity and slow apparent arc motion. In order to move the fairly immobile arc spots, a magnetic field is needed, or one could alternate between two negative leads contacting the cathode.[118]

The latest addition to the microcathode arc thruster family is the μCAT with ablatable anode. Research has shown that 5%–19% of the arc current is transported by the ions, depending on the cathode material. Hence, electrons carry about 105%–119% of the discharge current.[29,119,120] High speed ions emitted by the discharge are the main source of thrust which means that the energy that goes to the electrons is unexploited. Electrons flow toward the anode and close the circuit. A byproduct of this is work function heating (electrons entering the anode) and Joule heating (electrons move through the anode). Lukas *et al.* found that the ratio of ion current vs discharge current could be increased by nearly 40% when a low melting temperature anode material was used.[121] Research is currently underway to perform thrust measurements together with ion current measurements to determine if the increase in ion current leads to a higher production of thrust. While this scheme is intriguing, uncontrolled condensation of metal neutrals on components of the spacecraft is an even greater concern compared to a "pure" vacuum arc approach, and, therefore, one should retain a cautious skepticism about this approach.

V. PERFORMANCE MODELS

Currently, several models describe or predict the performance of vacuum arc thrusters. The following paragraphs give a short overview of these models and reiterate that while the cathodic arc has been studied for over a hundred years, there are still many aspects that are not yet completely understood.

In 2001, Polk *et al.*[122] presented a theoretical model for VAT and VAIT performance based on empirical data taken from the experiments done by Alameda Applied Sciences and LBNL together with JPL. This model makes predictions for different cathode materials. The model provides an empirical formula for the expected specific impulse of both vacuum arc thrusters and vacuum arc ion thrusters. For the former, the specific impulse can be calculated using the expression

$$I_{sp} = \underbrace{\frac{T}{\dot{m}_p g}}_{\text{see Eq. (2)}} = \frac{F_i u_i C_t}{g}, \tag{8}$$

where F_i is the ion fraction (assumed to be $F_i = 0.1$), which describes the total mass loss in the form of ions, u_i is the ion velocity in m/s, and C_t is the thrust coefficient.[122] Furthermore, the authors assume that the current density distribution in the plasma plume follows an exponential distribution during the discharge.[122] The efficiency of the VAT is given by the equation

$$\eta = \frac{M_i^2 f_i^2 u_i^2 C_t^2}{2e^2 E_r V_d Q^2}, \tag{9}$$

where M_i is the ion mass, f_i is the ion current fraction, V_d is the discharge voltage, E_r is the erosion rate in μg/C, and Q is the average charge state number, which is defined as the average of all ion charge states within the plasma and depends on the cathode material. The model established by Polk *et al.*[122] could reproduce observed performance characteristics for several cathode materials (Fig. 14).

As it was already noticed in the 1960s,[48] the material of the cathode drastically affects the performance of the vacuum arc (ion) thruster. The performance values account for the relative position between cathode and anode assuming the electrodes were flush.[122] The results show that chromium, yttrium, tantalum, and tungsten are the cathode materials of the highest performance are with efficiencies ranging from 0.07 to 0.12 and specific impulses from 860 s to 1660 s. This increased performance is caused by the high ion velocity and the high ion fractions of these elements.[122]

Performance models always make simplifying assumptions, and in the simplest case, one could use a one-dimensional description of the cathode region under steady-state conditions. Such a model was developed by Lun *et al.*[98] The researchers used a variety of cathode materials to determine ion current, average ion velocity, erosion rate, and maximum arc spot current. Of course, one should keep in mind the factors that limit the applicability of such a model. In this case, their results are valid for nonrefractory metals when the current is in the range of 80–300 A and for pulse lengths longer than 250 μs. Lun *et al.* describe the specific impulse from the vacuum arc with the following equation:

$$I_{sp} = \frac{C_t \left(m_i \frac{F_i I_d Q}{e} \right) u_i}{g E_r I_d}, \tag{10}$$

which is based on Eq. (8) and, therefore, shares some of its variables, with the addition of the ion mass m_i, the discharge current I_d, and the electron charge e. The numerator in Eq. (10) is the thrust T, which is used to calculate the efficiency η, which is calculated using the following equation:

$$\eta = \frac{T^2}{2E_r I_d^2 V_d}, \tag{11}$$

in which all variables have already been discussed. For chromium, the specific impulse using this model is approximately 600 s lower than the I_{sp} that is obtained using Polk's model. For most cathode materials, Lun's model tends to provide higher values than Polk's model. The authors attribute this discrepancy mainly to Polk's assumption of $F_i = 0.1$,[122] the overestimation of ion velocities by Lun *et al.*,[98] and the discrepancies in the erosion rate E_r.

More recently, further analysis of cathode materials was conducted by Neumann *et al.*[83] from the University of Sydney. The research includes detailed predictions on thruster performance depending on the selected propellant. Results show that refractory metals excel on impulse delivered per mole of ions. On the other hand, heavy nonrefractory metals such as lead and bismuth perform better when it comes to impulse delivered per energy unit expended. Light elements produce the highest amount of impulse per mass of ion flux. Of course, metals with a low melting point, such as lead and bismuth, are more prone to produce macroparticles, thus lowering the overall efficiency of the thruster. Additionally, they are more likely to melt due to overheating.

Theoretical and experimental work was performed by Beilis which resulted in the development of a self-consistent model for cathode erosion rates and plasma jet velocities for copper, silver, aluminum, and tungsten cathodes for a given current.[123]

VI. MODELING OF VACUUM ARC PLASMA JETS

In this section, we describe modeling efforts leading to understanding vacuum arc jets in a magnetic field. The theoretical and numerical study of vacuum arc plasma jets has been focused on the plasma jet formation and magnetic collimation effects as they are typically employed in another type of vacuum arc application, the vacuum arc switch or vacuum arc current interrupter or "vacuum interrupter" for short.[5,124] Even though the vacuum interrupter's geometry is not useful for thrust generation, given the fact that the anode is in front of the cathode, and therefore, produces zero net thrust, it is a valuable example that helps describing the behavior of arc jets in a magnetic field. In the low-density part of the cathodic plasma jet, an axial magnetic field (AMF) has a very significant effect on the jet expansion. To that end, a 2D free jet plasma expansion in an AMF was analyzed and simulated.[37] One of the main difficulties in the jet expansion problem is the formulation of the physical conditions at the plasma–vacuum boundary. The character

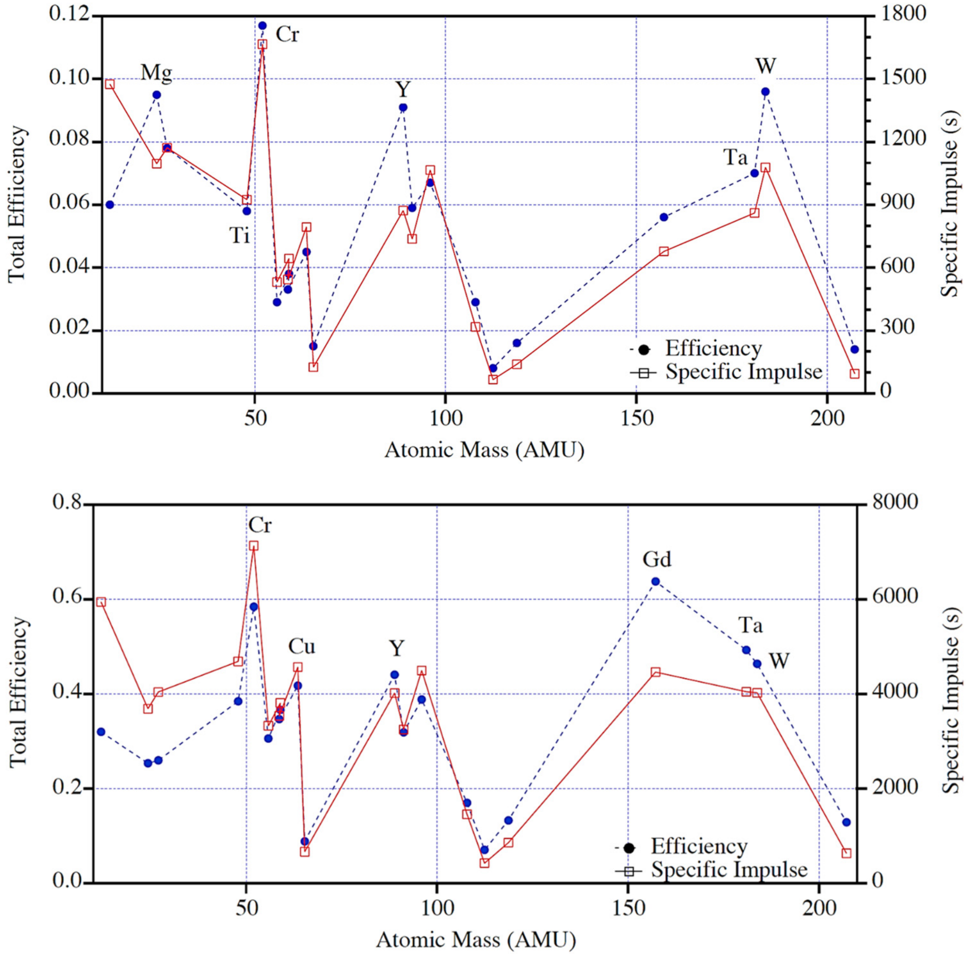

FIG. 14. Performance (predicted) of various cathode materials for VATs (top) and VAITs (bottom).[122] Used with permission from Polk *et al.*, in *27th International Electric Propulsion Conference, IEPC-01-211, Pasadena, CA* (Electric Rocket Propulsion Society, 2001). Copyright 2019 Electric Rocket Propulsion Society.

of the plasma flow depends on the anode geometries relatively to the expanding plasma jet.[80] Additionally, it was found that multiply charged ions in the expanding jet might be separated due to the formation of an electric field in the plasma jet.[125]

Overall, the magnetic field leads to a strong collimation of the cathodic jet and separation in the case of a multiple jets as shown schematically in Fig. 15. This was proposed and studied in detail in Ref. 78.

To illustrate this situation, let us consider the scenario shown in Fig. 15. It has been found through experiments and simulations that the interelectrode plasma is generated by many cathode spots at the cathode surface, as depicted schematically in Fig. 15. Each individual cathode spot produces a supersonic plasma jet, which is also an individual current channel. Due to its internal pressure gradient, each plasma jet expands radially. Because of the radial expansion, the jets mix at some axial distance and form a common

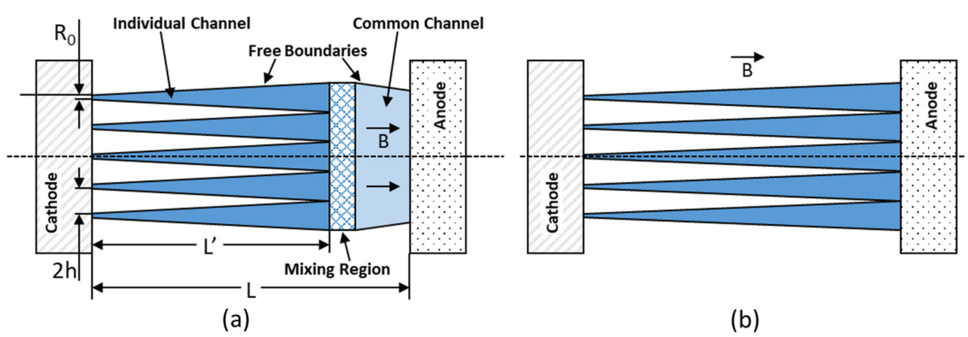

FIG. 15. (a) Sketch of the two interelectrode plasma regions, with mixing of individual plasma jets. (b) Fully separated jets in a higher AMF.

current channel. As a result, it was concluded that two regions can be present along the length of the gap: (1) individual channels up to a certain distance and (2) a common channel beyond this distance, as depicted in Fig. 15. As the axial magnetic field increases, the length of the common current channel decreases due to collimation of the plasma, mainly because the electrons are prevented from "crossing" field lines by the strength of the magnetic field. In an extreme case, the magnetic field can be strong enough that it prevents the individual plasma jets from forming a common channel (Fig. 15), which results in a stronger jet collimation. This collimation into smaller, discrete jets can be advantageous if used in combination with ion extraction grids, such as those found in VAITs. The plasma jets can be "aimed" at the extraction optics, thus reducing the amount of plasma lost to the grid. The effects of the shortening of the common channel and limiting of the overall plasma current constriction by the AMF lead to a decrease in the total arc voltage. This effect is mostly pronounced in high current vacuum arcs with disk anodes, but nevertheless is quite illustrative of the idea of plasma jet collimation of the magnetic field. If the jets are not overlapping at the anode, on average, the arc voltage can be treated as the potential drop of an individual jet, which does not depend on the total arc current. On the one hand, regular single-stage VATs typically utilize ring anodes, and the aforementioned model cannot be applied to this type of geometry. In the common case of a VAT with annular anode, the magnetic field, in addition to collimating the plasma jet, leads to the magnetic isolation of the anode, which manifests itself as an increase in the arc voltage.

VII. THE ROLE OF VACUUM ARC THRUSTERS IN SPACE MISSIONS

The relatively small size and low average power consumption of vacuum arc thrusters make them perfect candidates for CubeSats. These devices have several advantages compared to other small satellite propulsion devices. Vacuum arc thrusters use solid metallic propellants and can, therefore, be built in a very compact way. Thrusters with a volume as small as $2\,\mathrm{cm}^3$ are practicable. Since the cathode material is in the solid phase, there will not be any loss of propellants due to leaks. No gas-related components are required, and, therefore, these thrusters pose no danger to the satellite from a possible uncontrolled explosion point of view, particularly due to the pressurized tank bursting. Additionally, valves and mass flow controllers tend to be pricey components that add complexity to the system. Due to their pulsed nature, vacuum arc thrusters can produce finite and controllable bursts of thrust, and, depending on the mission requirements, these devices can assume the role of a main propulsion system or of attitude and orbit control systems. Controlling the frequency can be an easy way of throttling the spacecraft. Their use for station keeping has been discussed in several papers and the idea was proposed as early as 1966 and suggested by many researchers.[45,71,85,111] More complex missions such as formation flying,[85] rendezvous and docking,[126] and orbit change maneuvers including lunar missions have also been proposed.[127] Kronhaus described an attitude control system that uses a bang-bang control system and four vacuum arc thrusters embedded onto the structure of a 1U CubeSat, called UWE-4.[84] According to simulations, vacuum arc thrusters could overcome orbit perturbations and have a pointing accuracy of approximately 0.5° even if the thrusters produced thrusts as low as $1\,\mu$N.[85]

In addition to the inherent benefits discussed before, these thrusters offer a high operational versatility. Vacuum arc thrusters can be operated in different modes, for example, in clusters of two or more VATs. Depending on the requirements placed on the propulsion system, several thrusters can be operated with one single power processing unit such as the one shown in Fig. 6. Here, the limitation is that only one thruster can be operated at any given time. This configuration could be useful for simple attitude control when only one axis is being changed at a given time. Having a higher number of PPU circuits will of course enable the use of more than one thruster at the time, which is useful for more complex attitude control maneuvers and pointing. The limitation here is the power provided by the CubeSat's solar panels and energy storage unit. An overview of the different configurations is given in Ref. 128. The paper also describes the propellant, maneuver duration, and firing rate requirements for different orbital maneuvers, including the minimum altitude on which VATs are still capable of overcoming orbit perturbations in LEO, when launched from the International Space Station (ISS). For example, numerical results show that at 10 Hz, a μCAT system could possibly circularize a LEO by correcting the semimajor axis by 26.4 km within 21.56 days after being deployed from the ISS. This maneuver would consume 0.25 g of metallic propellant. The calculations were performed for a 1U CubeSat with a mass of 1.124 kg.[128] It also assumes that the CubeSat can determine its position (relative and absolute) and maintain the right attitude during the propulsive maneuvers.

VIII. OUTLOOK

Vacuum arc thrusters such as the μCAT are slowly gaining terrain in the market of small satellite propulsion systems. The fact that they do not require ion beam neutralizers (since quasineutral plasma is ejected) or gas-related components such as valves, pressurized tanks, or gas feed lines reduces costs and also the hazards posed to launch vehicles and the satellite itself.

The small size and low mass make them perfect candidates for small satellite missions, particularly CubeSat missions where the propulsion or attitude and orbit control overhead must be small because of the stringent volume and mass constraints. VATs are preferable for tasks such as attitude control, due to their small impulse bits, which can be designed to obtain precise control of the spacecraft. Of special interest, very likely growing in the next decades, is the integration of VATs with satellites, perhaps using otherwise non-needed metal components as solid fuel, to promote the decay into lower orbits, thereby terminating the mission and help removing the material from near-Earth space. In other words, VATs could become a major technology mitigating the space debris problem. For missions that require higher thrusts, such as those that need to perform relatively large orbital maneuvers such as changes in the Kepler elements, vacuum arc thrusters could be used in clusters to provide the required thrust. It is quite possible that, depending on the requirements, a cluster of VATs may be incapable of producing the required thrust, and, therefore, the mission designer will have to verge toward more conventional propulsion systems, such as resistojets. Additionally, thrusters based on vacuum arc technology such as the μCAT are highly scalable systems. They can operate from 0.1 W to 20 W average power by increasing the repetition rate and be set up as arrays or clusters of thrusters.

Future efforts are related to continuously increasing the efficiency and the lifetime of the thruster. There are several key issues that require further work.

One of the important issues related to reliability is discharge ignition. Recent research showed that the insulator material and geometry play an important role in preserving the initial coating and in developing a partial recoating due to cathode erosion. The gap size is one of the parameters that are important to optimize when it comes to the recoating of the insulator with cathodic material, which is required to ensure proper triggering. In general, a small gap leads to a higher deposition of metallic material in the interelectrode gap, which can result in a short circuit. A too large gap leads to an insufficient coating of the insulator, which increases the resistivity over the insulator and, thus, to thruster failure. A proper balance between ablation and recoating of the interelectrode gap must be obtained. The complexity of this research arises from the fact that, as mentioned before, the redeposition depends on multiple parameters, such as gap size, insulator material, average pulse power which is directly proportional to the cathode's erosion rate, and the applied magnetic field. The magnetic field plays an important role for various reasons; on the one hand, it can significantly increase the lifespan of the thruster by ensuring uniform cathode erosion. On the other hand, the magnetic field configuration at the surface of the cathode and further downstream of the cathode provides collimation of the plasma and thus a higher ionization rate of the plasma plume and thus higher thrust.

Another important issue is the cathode material selection. It is known that different cathode materials produce plasma plumes varying characteristics, particularly when it comes to ion velocities, since the ion velocity is dependent on the cathode material. A careful selection of the cathode material allows the engineers to tailor the thruster's performance to the mission requirements, such as the need for higher thrust vs the need for higher specific impulses. Moreover, the topic of anode material selection should not go undiscussed. At low duty cycles and pulse frequencies, thermal problems are unlikely to arise. Therefore, anode materials such as aluminum can be used. For higher duty cycles, one may resort to metals with higher melting temperatures, such as titanium or stainless steel, or even refractory metals such as tungsten. Another option would be to take advantage of the anode heating to increase the thrust production, for example, by using an ablative anode.[121,129]

A key aspect driving further development of vacuum arc thrusters is the desire to increase the thrust-to-power ratio and thus their efficiency. The relatively modest $10\,\mu$N/W commonly achieved by VATs limits thruster application to mostly attitude control and station keeping. The research in this area is motivated by the proliferation of more complex CubeSat missions that will require high delta-**v** maneuvers such at orbit raising or lowering and orbit plane change. Given the physical limitation that the ion current-to-arc current ratio is limited at about 10% and that ions are the major contributors to thrust, one can consider multistaging concepts. One possible approach to address this is to have an additional acceleration stage, a second stage, *per se*.[130] Various approaches are currently being pursued at The George Washington University, such as the development of a magneto-plasma-dynamic acceleration stage, an ion grid acceleration stage, and a thruster with anode layer configuration.

One of the important issues related to this technology is scalability. In the early 1960s, research focused on large VATs, mainly for large geostationary satellites. Their efforts were quickly shadowed by much more efficient and powerful propulsion systems such as resistojets, arcjets, Hall thrusters, and gridded ion thrusters. The technical limitations of the large vacuum arc thrusters, such as the requirement for very large discharge currents and the resulting heat production, led to the research to die off rather abruptly in the 1970s. Downscaling, on the other hand, has led to various promising devices. The nature of the arc spot gives the advantage to small pulsed VATs. Heat production is contained due to the usually low duty cycle in which the devices are fired. Under equal conditions, an arc spot will produce the same amount of plasma, whether it is produced on a small or a large cathode. Therefore, considering the same discharge current, the thrust produced per thruster mass is much higher when using small cathodes than it is on large cathodes, since a larger cathode implies that also the insulators and the anode will be larger and thus heavier. Therefore, to produce a similar impulse, large cathodes require higher current densities, which lead to overheating. Small pulsed VATs offer flexibility to the mission designers and operators. For example, the thrust of vacuum arc-based thrusters can be controlled by tuning the repetition rate and the arc current.

There is a need for developing modes of operation with higher thrust to perform maneuvers such as orbit transfer, inclination changes, etc. For example, multiple stages might be considered.

Solving the challenges related to the ignition of the arc, as well as scalability, material selection, and modes of operation will greatly affect the acceptance of VATs and VAITs and their deployment in actual missions.

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