Miniaturized Cylindrical Hall Thrusters: Magneto-Electrostatic Trap Thruster

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J. Simmonds[1]
Princeton University, Princeton, NJ 08540, USA

and

Y. Raitses[2]
Princeton Plasma Physics Laboratory, Princeton, NJ 08540, USA

Abstract: Miniaturized electric propulsion presents an opportunity to enable small satellite missions, however in low power regimes state of the art thrusters rarely achieve efficiencies above 15%. The Cylindrical Hall Thruster (CHT)[1] was developed in PPPL in 2000 as an alteration of the annular Hall Thruster and achieved efficiency of 15-35% in the 70-220W regime[2], however this efficiency drops rapidly at lower powers. Recent developments in CHT's including an altered magnetic configuration the use of metal propellants present avenues to increase this low-power efficiency. Theoretical work on the propellant utilization of the fuel and expected plume divergence are shown, and preliminary experiments of plume measurements for both Xenon and Bismuth are shown.

Nomenclature

CHT	=	Cylindrical Hall Thruster
MET	=	Magneto-Electrostatic Trap
λ_i	=	mean free path of ionization
L	=	axial length
V_{tn}	=	neutral propellant thermal velocity
n_e	=	electron density
n_i	=	ion density
V_e	=	Electron velocity
σ_{ie}	=	cross section of ionization for electron-neutral collisions
k	=	Boltzmann constant
T	=	Temperature
m	=	propellant mass
I_{sp}	=	specific impulse
g	=	gravitational acceleration constant

[1] PhD Candidate, Mechanical and Aerospace Engineering, jacobbs@princeton.edu
[2] Principal Research Physicist, Plasma Physics Laboratory, yraitses@pppl.gov

I.Introduction

R Recent miniaturization of spacecraft components has allowed satellites to shrink in size down to a few kilograms, decreasing the cost associated with spacecraft and increasing the number of spacecraft launched every year.[3] These SmallSats are typically secondary payloads and are unable to place themselves in their desired orbit. Furthermore, when in orbit, perturbations alter their orbit with time which can decrease available mission time, necessitating some form of propulsion. Due to their small size it is desirable to use some form of electric propulsion. Hall thrusters have been extensively developed for use in the power range of 0.5 to 5 kW, achieving 60% efficiency for state-of-the-art thrusters, and present a good candidate for miniaturization to smaller scales. However, several studies have shown that Hall thrusters become inefficient at small form factors and powers, decreasing efficiency below 15%.[4] This is largely attributed to the surface area-volume ratio increasing with miniaturization, which increases wall-losses and heating issues.

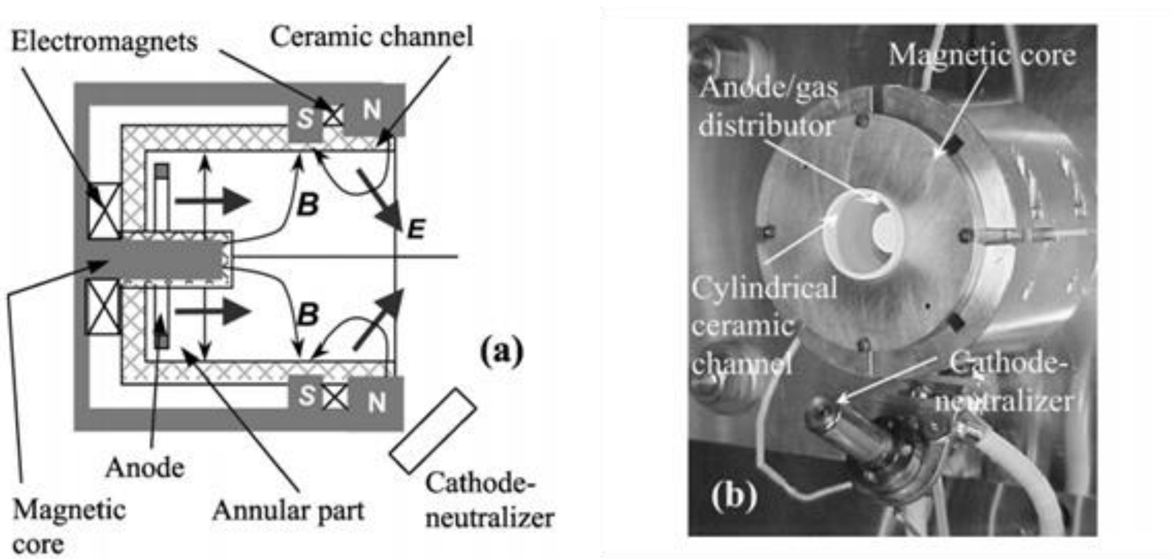

Figure 1. (a) Schematic of a cylindrical Hall thruster. (b) The 2.6-cm cylindrical Hall thruster

The Cylindrical Hall Thruster was developed in PPPL in 2000 to combat such issues and realized this goal by removing the inner wall on the Hall thruster and changing the configuration of the magnetic field profile.[1,5] Hall thruster operation was achieved by maintaining a radial component to the magnetic field but allowing a large axial component (see Fig. 1a). This thruster behaved similarly to typical Hall thrusters, providing a similar 15-25% efficiency at low powers (70-220W) and displayed the expected breathing mode and spoke instabilities. However, when scaling the thruster further below 1.5cm diameter, the efficiency dropped considerably which was attributed to wall losses on the remaining outer walls.

A new thruster was thus conceived for the purposes of miniaturized electric propulsion – the Magneto-Electrostatic Trap thruster (MET thruster). The device was intended to achieve the following objectives: 1) ease of manufacture, 2) ease of size scaling, and 3) high efficiency at small form factors. To achieve these objectives, it was determined the thruster must operate without side walls – relying on the magnetic field and potential profile to confine and direct the plasma. The magnetic field is created by SmCo permanent magnets to lower power usage, to avoid the typical high electromagnet currents when scaling the electron gyro-radius to size. Assuming equipotentiality of the magnetic field lines, the electric

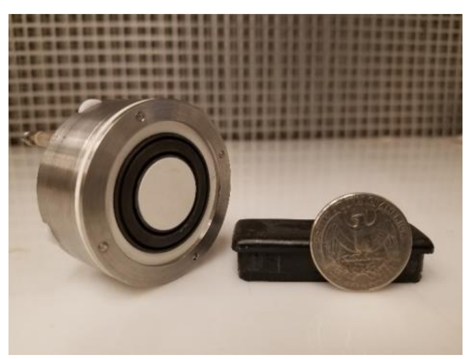

Figure 2. MET Thruster Mk. II with US quarter for scale

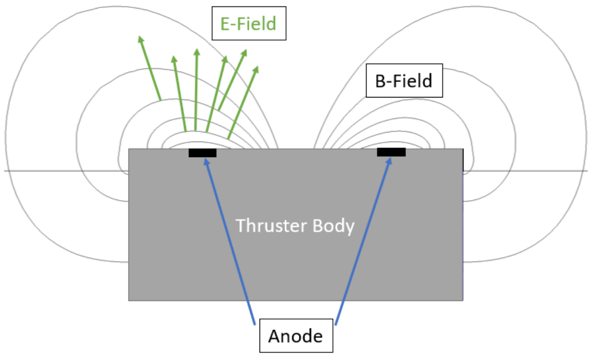

Figure 3. Magnetic Field Lines and schematic of the MET Thruster

field is both axial and focusing at the ionization length of the considered propellants. Figure 3 shows the magnetic field profile of the MET thruster.

Reducing wall losses through a change in geometry or magnetic field has been proposed and developed by several groups. Initial attempts were developed with magnetic shielding, where the magnetic field and channel are shaped to be parallel.[6] A notable further development was the "Wall-Less Hall Thruster" by ICARE, CNRS.[7] The ICARE Wall-Less Hall Thruster introduced a fully wall-less system by a gridded anode that filled the thruster channel and ionization and acceleration regions outside the channel walls. This differs from the MET in that the MET was designed to create a high magnetic field mirror ratio to confine the plasma and further develop the Cylindrical Hall Thruster concept. One other notable difference is that the MET is designed to operate with both gaseous and metal fuel.

Metallic fuels are critical as it is anticipated that Xenon, which is typically used as propellant for Hall thrusters, would have too high an ionization length and would thus not create the ideal trapping conditions. As such, propellants with lower ionization potential were considered. In this paper we present our results on the plume distribution of Xenon and demonstrate operation of the thruster with Bismuth.

II. Propellant Utilization and Plume Angle

One key aspect of the MET thruster was whether the plume would be accelerated axially and to what degree. Without any walls and with such high axial magnetic field components, there is some concern the propellant would simply leave the thruster without contributing to thrust. A first-order study was performed to determine both the ionization length of the thruster and the basic plume angle of the plasma given that ionization length. The plume angle was determined by assuming that the angle of the electric field at 99% ionization length was the angle with which the ions would be accelerated. Equipotentiality of the magnetic field lines was assumed in this case, as has been done previously for similar thrusters.[8]

The ion fraction is defined as

$$Ion\ Fraction = 1 - exp\ (-\frac{L}{\lambda_i}) \tag{1}$$

Where L is the axial length and λ_i is the mean free path of ionization of the propellant, which is

$$\lambda_i = \frac{V_{tn}}{n_e V_e \sigma_{ie}} \tag{2}$$

Where V_{tn} is the thermal velocity of the neutral propellant, n_e is the electron density, V_e is the electron thermal velocity, and σ_{ie} is the cross section of electron ionization collisions with the neutral propellant. Neutral thermal velocity is defined as

$$V_{ti} = \sqrt{\frac{8\ kT_n}{\pi m}} \tag{3}$$

Where k is Boltzmann constant, T_n is the neutral velocity (assumed to be 1000K for Xenon and vaporization temperature of ~800 C for Bismuth) and m is the atomic mass. To calculate electron density quasineutrality is assumed to derive it from the thrust.

$$n_e = n_i = \frac{Thrust}{Area <m\, V_{tn}> I_{sp}\ g} \tag{4}$$

Where thrust is assumed to be about 2mN, area is the cross-sectional area of the plasma by the anode and is taken to be 6.28 cm^2, I_{sp} is the specific impulse and is taken to be 1500 s, and g is the gravitational constant 9.8 m/s^2. The ionization length can then be calculated for an ionization fraction of 99% for any propellant and is found to be 18.6mm for Xenon and 2.7 mm for Bismuth. These lengths were then fed into the magnetic field simulations over an arc about the midpoint of the anode, as shown in Figure 4. The electric field angle about that arc was then found, where 0º points axially, also shown in Fig. 4. The mean plume angle of the Bismuth and Xenon are 14º and 53º respectively. This is somewhat encouraging as the 90% plume angle of the Cylindrical Hall thruster with Xenon was experimentally found to be about 60º.

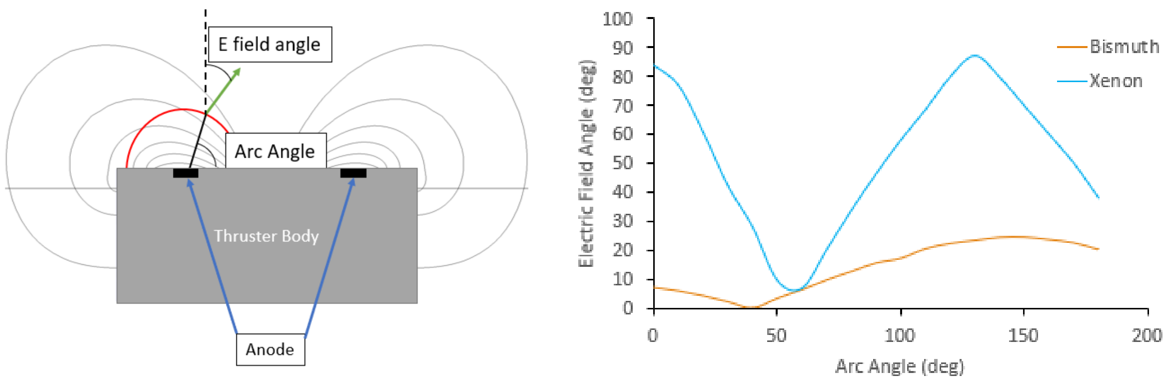

Figure 4. (left) Geometry of the electric field and (right) electric field angle vs arc angle for both Bismuth and Xenon

III. Experimental Diagnostics

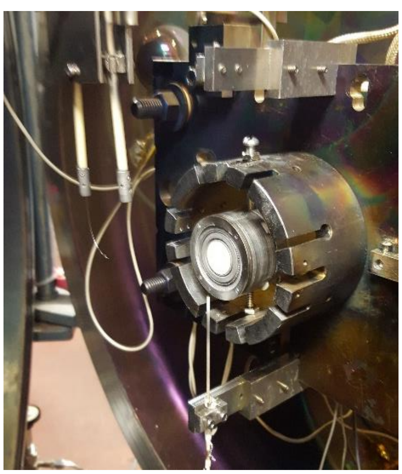

Figure 5. MET Thruster with Tungsten Filament Cathode

The thruster was operated in the Small Thruster Facility at PPPL HTX, which is outlined in Ref. 5 The plume was measured with a -40V negatively biased planar probe 17cm from the thruster face. The probe has the ability to sweep an arc across ±90º and has been discussed in detail in Ref. 5. A thoriated tungsten filament was used as the cathode for the experiment, following the approach used for Cylindrical Hall Thruster cathodes by Granstedt.[9] This cathode was placed 3cm from the thruster face and was located 5cm off-axis and out of plane of the plume measurement plane. A base pressure of 0.5 µTorr was achieved for all measurements.

While the mass flow in the gas-fed thruster could be monitored and changed with a mass-flow controller, it was very difficult to determine the instantaneous mass flow of the Bismuth fuel thruster. As such, the thruster was weighed before and after measurements, and the average mass flow was determined from the operating time. This caused great uncertainty in the mass flow measurements. For Bismuth operation the thruster was initially operated vertically and new diagnostics had to be used to avoid contamination by the Bismuth film that proceeded thruster operation. A simple negatively biased collector plate was used then to collect ion current over a large area with angle θ=24º as seen in Figure 6.

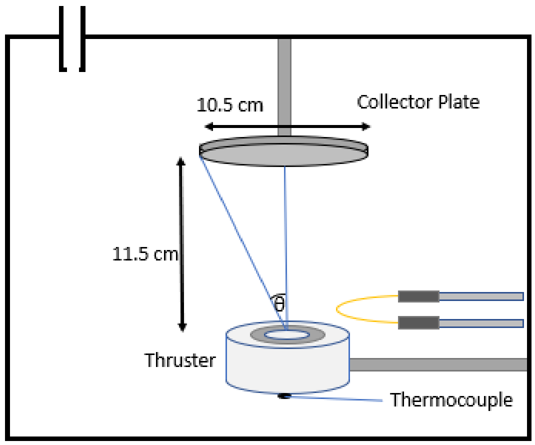

Figure 6. Experimental setup of Bismuth MET

The HTX "see-saw" thrust stand was developed in 2019. This thrust stand measures thrusts up to 20 mN with resolutions down to 0.02 mN. Thrust is measured by detecting the displacement of an arm as the thruster applies a torque which is resisted by a flex-pivot, as seen in Fig. 6.

A Micro-Epsilon optoNCDT 1420 laser sensor was used to measure displacement, while a Riverhawk 6032-800 Flex Pivot provides the restoring force. Damping was achieved with a permanent magnet below an aluminum block on the arm, which provided a small friction force by eddy-damping. Calibration of the thrust stand was achieved with electrostatic fins, following the work in Ref 10. The fin voltage-force response was measured using a precision balance over a range of fin separation distances. Once the thrust stand was assembled inside the chamber, this voltage-force response was confirmed by comparing the resulting arm displacement to the torque due to hanging a known mass. Agreement was found within 1%. A detailed overview of the electrostatic fin calibration process followed can be found in Ref 10.

To measure thrust the following procedure was followed: the thruster was ignited and allowed to run for several minutes to allow the thrust stand to settle. The arm displacement was then measured and the thruster was turned off. The displacement with time was measured as the arm returned to equilibrium. A damped sine wave was fitted to the displacement to determine the equilibrium displacement at the time before the thrust was turned off, and the total displacement due to thrust was calculated.

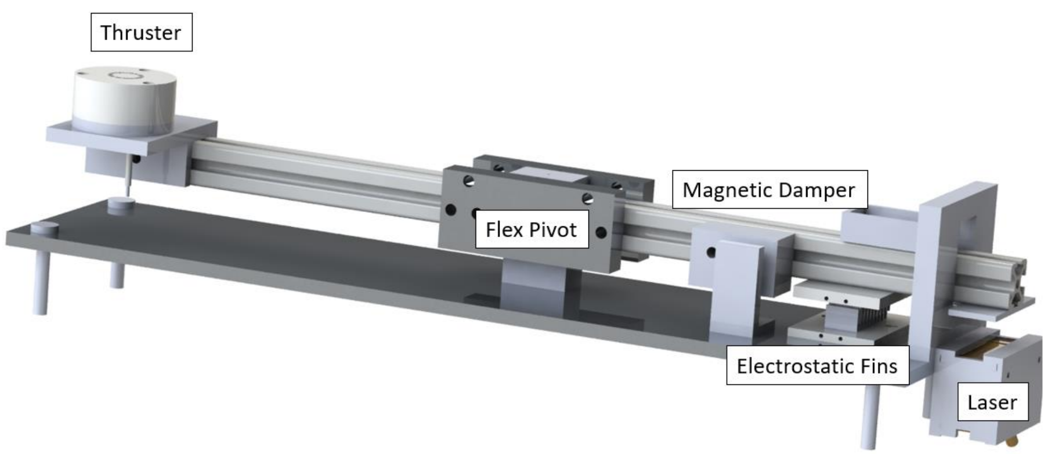

Figure 7. Torsion Balance Thrust Stand

IV.Results and Analysis

The VI Characteristics (Figure 7) for the Xenon version was relatively flat, operating at similar discharge currents as the Cylindrical Hall Thruster for the mass flow rate. It was found that by increasing electron current supply (by increasing filament current) the thruster would become unstable and lose plasma. These cathode current induced oscillations in discharge current did not occur with Bismuth operation. For Xenon the discharge was stable and quiet

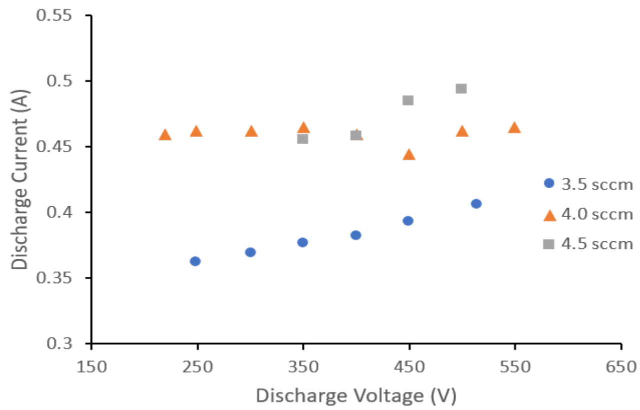

Figure 8. VI Characteristics for Xenon MET Thruster for mass flow of 3.5sccm, 4.0sccm, and 4.5 sccm

at lower filament currents, however contained large asymmetries, as shown in Figure 8. Oddly enough, for both saturated and unsaturated current the 90% plume angle was the same at 60º.

The plume distribution of the Xenon MET thruster was compared to a 2.6cm CHTpm2 (outlined in Ref. 11) at the same regime of 220V and 3.5sccm and saturated discharge current, which is shown in Figure 9. It was found that the thruster achieves roughly the same plume angle as the CHT (64º vs 61º respectively), but has worse ionization – propellant utilization is 48% compared to 87% of the CHT. This presents the case for the need of a lower ionization potential fuel for the MET thruster.

Operation of the Bismuth MET thruster with the collector plate resulted in unusually high ion current efficiency (ion current / discharge current). Figure X. shows the current efficiency trace with time over the experiment as well as the thruster temperature. Current efficiency stayed high over a variety of voltages and discharge currents during the course of the 35-minute experiment. Measurements of performance of the thruster were unfortunately not as encouraging, as thrust appeared invariant to voltage but closely correlated to discharge current, as seen in Figure X. However it is unknown if the thruster was operating in the same regime as seen in Figure X, as the implied mass flow due to 80% current efficiency and the mass flow by measuring the actual mass are off by an order of magnitude, suggesting much lower current efficiency for the thrust measurement experiment. It is

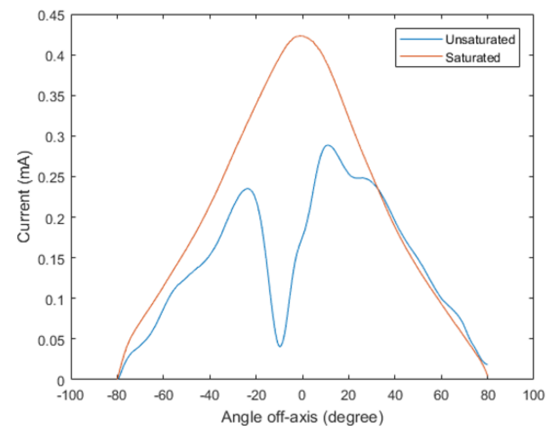

Figure 9. Saturated and Unsaturated Plume distribution of the Xenon MET thruster at 220V and 3.5 sccm

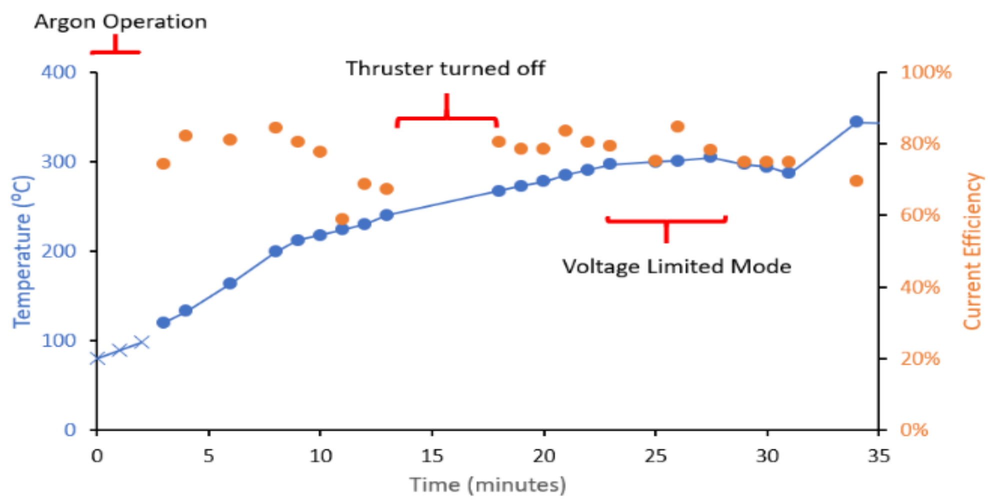

Figure 10. Current efficiency and Temperature of the Bismuth MET Thruster vs time

very uncertain what the instantaneous mass flow was for the thrust measurements and so we cannot draw any particular performance. If the time-averaged mass flow of 0.17 mg/s is taken for all measurements then the performance would be 20% for when the discharge current was saturated at 200V, otherwise efficiency was below 10%.

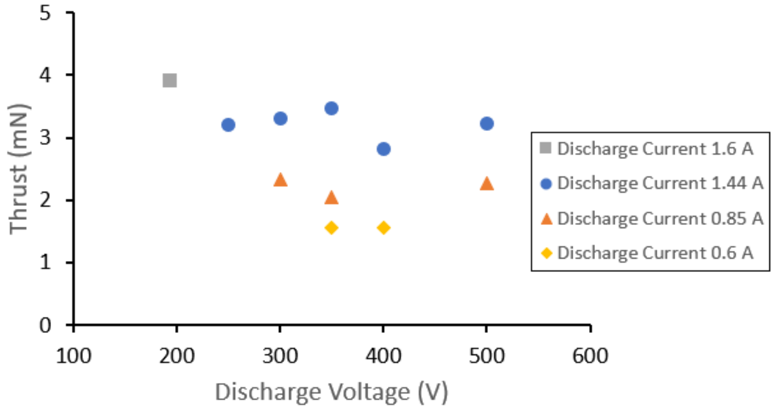

Figure 11. Thrust vs Discharge Voltage for several discharge currents of the Bismuth MET thruster

V. Conclusion

A magneto-electrostatic trap thruster was developed to investigate thrusters with low wall erosion for miniaturization. Several features of the thruster make it interesting for study – particularly the high mirror ratio, the high magnetic field, and the potential for plasma focusing when used with low ionization energy fuels. Early theoretical work shows potentially high propellant utilization with Bismuth propellant due to the very small ionization length. Analysis of plume distribution shows plume angles similar to Cylindrical Hall Thrusters for Xenon, which was supported by experimental measurements. Plume angle was shown to be much smaller for propellant such as Bismuth and early experimental work showed high current efficiency with Bismuth operation. Low performance measurements and difficulties with measuring instantaneous mass flow with metal fuels indicate more development is needed for comprehensive diagnostics. Despite these challenges, wall-less hall thrusters with metal propellant may aid in miniaturizing thruster size while keeping lifetime and efficiency high.

Acknowledgments

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References

[1] Y. Raitses and N. J. Fisch, "Parametric investigations of a nonconventional Hall thruster," *Physics of Plasmas*, Vol. 8, pp. 2579, 20 Apr. 2001.

[2] K. D. Diamant et al., "Ionization, Plume Properties, and Performance of Cylindrical Hall Thrusters", *IEEE Transactions on Plasma Science*, Vol. 38, 1052, 2010,

[3] "SpaceWorks Nano/Microsatellite Market Forecast, 9th edition", SpaceWorks Enterprises, Jan. 2019

[4] V. Khayms and M. Martinez Sanchez, "Design of a miniaturized Hall Thruster for Microsatellites", AIAA, ASMA, SAE, and ASEE, Joint Propulsion Conference and Exhibit, 32nd, Lake Buena Vista, FL, July 1-3 1996

[5] A. Smirnov, Y. Raitses, and N. J. Fisch, "Parametric investigations of miniaturized cylindrical and annular Hall thrusters," *Journal of Applied Physics*, Vol. 92, No. 10, 15 Nov. 2002.

[6] Kapulkin A. M., Grishkevich A. D. and Prisnyakov V. F., "Outside electric field thruster," Proceedings of the 45th IAF congress, Space Technol. Vol. 15, Pergamon, UK, 1995, pp. 391-394.

[7] S. T. a. J. V. S. Mazouffre, "Development and characterization of a wall-less Hall thruster," *AIAA Propulsion and Energy Forum*, 2014.

[8] A. Smirnov, Y. Raitses, and N. J. Fisch, "Enhanced Ionization in the Cylindrical Hall Thruster" *Journal of Applied Physics*, Vol. 94 (2), 852, 2003

[9] E. M. Granstedt, Y. Raitses, and N. J. Fisch, "Cathode effects in cylindrical Hall thrusters," *Journal of Applied Physics*, Vol. 104, 103302, 2008.

[10] J. Kolbeck, T. Porter, and M. Keidar, IEPC Proceedings (2017).

[11] Y. Raitses, E. Merino, and N. J. Fisch, "Cylindrical Hall thrusters with permanent magnets", *Journal of Applied Physics*, Vol. 108, 093307, 2010.