Performance Analysis of a Low-Power Magnetically Shielded Hall Thruster: Experiments

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The successful application of a fully shielding magnetic field topology in a low-power Hall thruster is demonstrated through the testing of the MaSMi-60 Hall thruster (an improved variant of the original Magnetically Shielded Miniature Hall thruster). The device was operated at discharge powers from 160 to 750 W at discharge voltages ranging from 200 to 400 V. Several techniques were used to determine the effectiveness of magnetic shielding achieved by the MaSMi-60 and to estimate the reduction in discharge channel erosion rate enabled by the shielding field topology. This ultimately suggested an improvement in discharge channel life by a factor of at least 10 times, and likely greater than 100 times, when compared to unshielded devices. Thruster performance, measured both directly by a thrust stand and indirectly by plume diagnostics, was lower than expected when compared to results from high-power magnetically shielded Hall thrusters. However, the plume diagnostic measurements enabled the identification of the primary causes for the MaSMi-60’s moderate performance.

Nomenclature

\[ B = \text{magnetic field, G} \]
\[ e = \text{electron charge, C} \]
\[ f_i = \text{current fraction of the } i\text{th ion species} \]
\[ g = \text{acceleration due to gravity on Earth, } \text{m/s}^2 \]
\[ I_b = \text{beam current, } A \]
\[ I_d = \text{discharge current, } A \]
\[ I_i = \text{current of the } i\text{th ion species, } A \]
\[ I_{sp} = \text{specific impulse, s} \]
\[ F_{+,+,\ldots} = \text{current of each ion charge species, } A \]
\[ M = \text{xenon atomic mass, kg} \]
\[ m_{BN} = \text{particle mass of boron nitride, kg} \]
\[ m_c = \text{particle mass of carbon, kg} \]
\[ m_a = \text{anode mass flow rate, kg/s} \]
\[ m_b = \text{beam mass flow rate, kg/s} \]
\[ m_i = \text{ion mass flow rate, kg/s} \]
\[ P_d = \text{discharge power, } W \]
\[ R_C = \text{carbon backspatter rate, } \mu\text{m/h} \]
\[ T = \text{thrust, } N \]
\[ T_e = \text{electron temperature, eV} \]
\[ V_b = \text{beam voltage, } V \]
\[ V_d = \text{discharge voltage, } V \]
\[ v_i = \text{ion velocity, } m/s \]
\[ Y_{Xe-BN} = \text{sputter yield of boron nitride under xenon ion bombardment} \]
\[ Y_{Xe-C/BN} = \text{sputter yield of carbon-coated boron nitride under xenon ion bombardment} \]
\[ Z_i = \text{charge state of the } i\text{th ion species} \]
\[ \alpha = \text{sticking coefficient} \]

\[ \epsilon_{Xe-BN} = \text{erosion rate of boron nitride under xenon ion bombardment, } \mu\text{m/h} \]
\[ \eta_a = \text{anode efficiency} \]
\[ \eta_b = \text{beam current utilization efficiency} \]
\[ \eta_d = \text{plume divergence efficiency} \]
\[ \eta_m = \text{mass utilization efficiency} \]
\[ \eta_i = \text{charge utilization efficiency} \]
\[ \theta = \text{beam divergence half-angle, rad} \]
\[ \rho_{BN} = \text{boron nitride mass density, } \text{kg/m}^3 \]
\[ \rho_c = \text{carbon mass density, } \text{kg/m}^3 \]

I. Introduction

An efficient long-life low-power Hall thruster represents an enabling technology for a new class of low-mass spacecraft (~100–300 kg), offering the capability of performing challenging scientific near-Earth and deep-space missions. Although numerous high-performance low-power Hall thrusters have been developed, few are capable of sufficient propellant throughput for multiyear (greater than 10,000 h of operation) solar electric propulsion (SEP) missions. The BHT-200, for example, is a 3 cm Hall thruster capable of 11.4 mN of thrust at a specific impulse of 1570 s and an anode efficiency of 42%; however, the BHT-200’s operational life is limited to under 2000 h [1–5]. The Russian SPT-50 employs a 5 cm discharge channel outer diameter and demonstrates a maximum anode efficiency of nearly 40% with a thrust of between 20 and 30 mN and a specific impulse of between 1300 and 2000 s over discharge powers of 350–500 W; a flight-demonstrated lifetime of approximately 2500 h has been reported [6,7]. Recently, thrusters such as the Plas-40, CAM200, and HTI100 have been developed and tested, yet no published data have shown operational lifetimes greater than a few thousand hours [8–10]. In addition to operational lifetime, thruster efficiency is a critical performance metric for small satellites. Because the SEP system is the primary driver for solar array and power subsystem size, higher SEP system efficiencies directly translate to lower power, and therefore less massive, solar arrays and power processing systems.

It is well understood that the primary challenges for Hall thrusters at small scales (less than 500 W and less than 7 cm diameter) are poor life and low efficiency due to rapid erosion of and high electron losses to the discharge channel walls resulting from the inherently higher surface-to-volume ratio of small thrusters. The advent of
magnetic shielding has virtually eliminated these mechanisms as life-limiting factors for high-power Hall thrusters through a unique magnetic field topology that maintains both a low electron temperature and a near-constant plasma potential equal to that of the discharge voltage along the discharge channel walls [11–13]. The application of magnetic shielding to low-power Hall thrusters therefore appears promising as a means to extend their operational lifetimes.

This paper describes the experimental testing and characterization of the MaSMi-60, which is an improved variant of the original Magnetically Shielded Miniature (MaSMi) Hall thruster: the MaSMi-40 [14–16]. The paper begins by briefly reviewing the performance and design shortcomings of the MaSMi-40. The relevant Hall thruster theory used to analyze the performance of the MaSMi thruster follows. The vacuum facility, performance and plasma diagnostics, and supporting equipment used in the testing of the MaSMi-60 are then described. An assessment of the magnetic shielding effectiveness achieved by the MaSMi-60 as well as results from the performance and characterization experiments are presented. The paper ends with a discussion of the primary mechanisms responsible for the lower-than-desired efficiency observed in the MaSMi-60, and then concluding remarks. A companion paper uses the experimental results collected here along with a thorough computational investigation to provide a detailed discussion about the physical causes for these performance-limiting mechanisms [17].

II. Previous Work

The MaSMi Hall thruster investigation is focused on the design, development, and operation of low-power magnetically shielded (MS) Hall thrusters [14,15,18,19]. An image of the first generation MaSMi Hall thruster, the MaSMi-40, is shown in Fig. 1 before and during operation. Testing of this device was executed at two vacuum facilities: the University of California, Los Angeles (UCLA) Electric Propulsion Test Facility and the Jet Propulsion Laboratory (JPL) High Bay facility. Testing at UCLA focused on the nominal operating power of 325–330 W, whereas testing at the JPL facility spanned a range of power levels from 130 to 640 W. A complete characterization of the thruster’s performance at 330 W was completed by using a thrust stand and the full plume diagnostic suite at the JPL. A thrust of 13 mN at an anode efficiency of 24% was measured at the nominal operating point; a range of thrust from less than 5 mN to over 20 mN was measured over the full operating power range [15,19]. Several operation modes were observed, each corresponding to different performance levels and related to the thruster’s operating temperature [15,19]. The performance and behavior exhibited by the MaSMi-40 was found to be limited by the thruster’s small size and magnetic circuit design, as described in [18]. The findings from the MaSMi-40 led to the development of an improved version of the MaSMi thruster, the MaSMi-60. Details on the design of this device can also be found in [18].

![MaSMi-40 Hall thruster before and during operation at 330 W.](image)

III. Hall Thruster Performance Theory

The equations used to analyze the data collected from the MaSMi-60 experiments are described here to show the method by which the thruster performance was evaluated [20]. Thrust $T$ is given by

$$T = \sum_i \dot{m}_i \langle v_i \rangle = \eta_0 I_d \left( \frac{2MV_d \eta_d \eta_b}{e} \right) \sum_i \sqrt{\frac{f_i}{Z_i}}$$

(1)

where $\dot{m}_i$ is the ion mass flow rate, $\langle v_i \rangle$ is the average ion velocity, $I_d$ is the discharge current, $M$ is xenon’s atomic mass, $V_d$ is the discharge voltage, $e$ is the charge of an electron, and $Z_i$ is the charge state of the $i$th ion species. The beam current utilization $\eta_b$, beam voltage utilization $\eta_b$, and plume divergence $\eta_d$ efficiencies are given by

$$\eta_b = \frac{V_b}{V_d}, \quad \eta_b = \frac{I_b}{I_d}, \quad \eta_d = (\cos \theta)^2$$

(2)

where $V_b$ is the beam voltage, $I_b$ is the beam current, and $\theta$ is the beam divergence half-angle containing 95% of the momentum-weighted beam ions. The current fraction of the $i$th ion species $f_i$ is given by

$$f_i = \frac{I_i}{I_b}$$

(3)

where $I_i$ is the current of the $i$th ion species. It is important to note that $I_d$ is the current input to the thruster’s plasma discharge, whereas $I_b$ is the ion current produced by the thruster that generates thrust. The thrust correction term in Eq. (1) accounts for the presence of multiply charged species in the ion beam and is calculated for any number of ion charge states as

$$\sum_i f_i = \frac{I^+ + \sqrt{1/2}I^{++} + \sqrt{1/3}I^{+++} + \cdots}{I_b}$$

(4)

where $I^+$, $I^{++}$, and $I^{+++}$ are the currents of singly, doubly, and triply ionized particles in the beam.

The anode specific impulse is given by

$$I_{sp} = \frac{T}{m_a g} = \frac{\eta_m}{g} \left( \frac{2eV_d \eta_d \eta_b}{M} \right) \left( \sum_i \frac{f_i}{Z_i} \right)$$

(5)

where $\dot{m}_a$ is the thrust anode mass flow rate, $g$ is the Earth’s gravity acceleration, and $\eta_m$ is the mass utilization efficiency given by

$$\eta_m = \frac{m_{i_b}}{m_{i_a}} = \frac{M_i I_d}{m_{i_a} e} \left[ \eta_b \sum_i \frac{f_i}{Z_i} \right]$$

(6)

where $m_{i_b}$ is the beam propellant mass flow rate. The correction to the mass utilization for multiply charged ions is

$$\sum_i \frac{f_i}{Z_i} = \frac{I^+ + (1/2)I^{++} + (1/3)I^{+++} + \cdots}{I_b}$$

(7)

The anode efficiency $\eta_a$, which can be broken into the product of five utilization efficiencies, is given by

$$\eta_a = \frac{T^2}{2m_a P_d} = \eta_b \eta_d \eta_0 \eta_m \eta_q$$

(8)

where $P_d$ is the discharge power ($P_d = V_d I_d$). The charge utilization efficiency $\eta_q$ is

$$\eta_q = \left( \sum_i \frac{f_i}{Z_i} \right)^2 \sum_i \frac{f_i}{Z_i}$$

(9)
IV. Experimental Setup

A. Vacuum Facility and Supporting Equipment

Experiments were conducted at the High Bay vacuum facility at the NASA Jet Propulsion Laboratory. The High Bay facility consists of a 2.6-m-diam by 5.2-m-long cylindrical vacuum chamber. All internal surfaces of the chamber with line of sight to the thruster’s discharge channel are covered with either graphite panels or carbon felt. Three cryopumps provide a combined xenon pumping speed of approximately 40,000 1/s. The chamber pressure is monitored by two ionization gauges, which are both calibrated for xenon. The first gauge is located in the thruster exit plane approximately 1 m radially from the thruster axis and is used as the primary indication of chamber pressure. The second gauge is mounted along the chamber wall just downstream of the thruster exit plane. The base pressure of the system is less than 1.5 × 10⁻⁷ torr and, during operation with xenon flow of 1.0–3.0 mg/s, the chamber pressure remains in the low-to-middle 10⁻⁶ torr range.

Commercially available power supplies and propellant flow controllers were used for all experiments. Research-grade xenon was supplied to the thruster via electropolished stainless-steel propellant lines. The mass flow controllers were calibrated before testing and digitally controlled to an accuracy of ±1% of the set point. A 1/4 in. barium-oxide impregnated cathode (BaO-W), based on the International Space Station plasma contactor and NASA Solar Technology Application Readiness program ion thruster cathodes, was used for these experiments. The cathode was mounted at a 45 deg angle with respect to the thruster axis with the cathode orifice at the thruster exit plane approximately 50 mm above the thruster centerline, in a similar manner as shown in Fig. 1.

B. Thruster and Plasma Diagnostics

1. Thrust Measurements

A water-cooled inverted-pendulum thrust stand was used to directly measure the thrust of the MaSMi-60. The thrust stand was calibrated by the lowering and raising of a series of precision masses and correlating the displacement to a force measurement. The calibration was performed before and after each experimental run, with thrust stand zeros performed after each thrust measurement. The thrust stand demonstrated a resolution of 0.1 mN with an estimated uncertainty of 2.0%. Combined with the other thruster system uncertainties (power supplies, flow controllers, etc.), the estimated uncertainty in the \( I_{q} \) and efficiency were 2.2 and 4.2%, respectively.

2. Plume Measurements

Ion current density measurements were taken using a 24-mm-outer-diameter cylindrical graphite Faraday probe with a 19 mm collector diameter. The probe was biased to −28 V and was placed five discharge channel lengths downstream of the thruster exit and swept ±35 cm laterally across the beam using a commercial probe drive stage. Measurements were taken at 19 mm intervals, with reported value at each point consisting of an average of 2000 measurements recorded at 200 kHz. Integrating the ion current density profile yielded the total ion beam current, which was corrected for charge-exchange collisions as shown in [21]. The beam divergence half-angle was determined by finding the beam angle containing 95% of the momentum-weighted ion current. The uncertainty of the ion current density and beam divergence half-angle were estimated to be ±0.05 mA/cm² and ±2.5 deg, respectively [19].

A four-grid retarding potential analyzer (RPA) with a 19-mm-diam entrance orifice provided the most probable ion potential measurements. The RPA was mounted on a rotary stage 0.5 m downstream of the thruster exit along the thruster centerline axis. The four grids included a plasma grid, an electron repelling grid, and a double-grid ion discriminator. A double-grid ion discriminator, consisting of two closely spaced grids at the bias potential, provides a flatter potential across the grid holes than is found in single discriminator grids. It is therefore better at preventing ions at lower potentials than the bias voltage from passing through the potential “wells” found in the center of each grid hole. The electron repelling grid was biased to −28 V, whereas the ion double-discriminator voltage was swept from 0 to 400 V with a bipolar power supply. The uncertainty of the most probable ion potential was estimated to be ±10 V [19].

An emissive probe was used to determine the plasma potential local to the RPA. The probe held a 0.13-mm-diam tungsten filament between two 0.51 mm tantalum rods, each sheathed in alumina insulators. The emissive probe was mounted adjacent to the RPA on the rotary stage 0.5 m downstream of the thruster exit. The plasma potential was subtracted from the RPA measurements to determine the actual potential drop experienced by beam ions, yielding the corrected most probable ion potential. The uncertainty in the plasma potential was estimated to be ±1 V based on a local electron temperature of 3 eV measured by a far-field Langmuir probe [17].

A custom-built electric field crossed with magnetic field (\( E \times B \)) probe was used to measure the ion species mix in the MaSMi-60 beam. The probe was mounted to the rotary stage 0.5 m downstream of the thruster and next to the RPA and emissive probe. Details of the probe’s geometry can be found in [19]. Gaussian curves were fit to the peaks of the \( E \times B \) probe traces corresponding to single-, double-, and triple-charged ions; the relative areas under these curves are directly proportional to each ion species’ fractional contribution to the total beam current. The uncertainty in ion species fraction was estimated at ±0.05% [19].

A commercial uncollimated quartz-crystal microbalance (QCM) sensor was used to measure carbon backspatter from the graphite beam dump and graphite panels covering the vacuum chamber’s interior surfaces. The QCM was mounted approximately 0.2 m radially from the thruster centerline in the plane of the thruster exit facing downstream. Measurements were taken over 20 min intervals with a minimum of 1 h between each measurement to confirm constant deposition rates. Uncertainty was reported as ±5% of the measurement according to the manufacturer.

A commercial current probe was used to provide discharge current oscillation data. The probe was attached to the thruster’s anode power cable and connected to a high-speed oscilloscope. The uncertainty of the current probe measurements was estimated to be less than 3% based on the product manual.

V. Results and Discussion

A. Thruster Operating Conditions

A summary of the operating conditions examined by thrust stand measurements is presented in Table 1, which shows the optimum discharge power level as a function of discharge voltage and anode propellant flow rate. Testing of the MaSMi-60 was conducted at discharge voltages ranging from 200 to 400 V in increments of 50 V. At each of the five discharge voltages, the anode propellant flow rate was varied from 1.18 to 2.75 mg/s in increments of 0.197 mg/s; the flow rate was increased until 2.75 mg/s was achieved with stable thruster operation or until the thruster demonstrated unfavorable behaviors, such as localized wall heating or unstable discharge oscillations (these conditions are marked with an “X” in Table 1). Discharge powers of 160 W to nearly 750 W were observed. A total operation time in excess of 83 h was logged during this testing campaign.

<table>
<thead>
<tr>
<th>Anode flow rate, mg/s</th>
<th>Discharge voltage, V</th>
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<tbody>
<tr>
<td>200</td>
<td>250</td>
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<tr>
<td>1.18</td>
<td>160 W</td>
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<tr>
<td>1.38</td>
<td>200 W</td>
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<tr>
<td>1.57</td>
<td>242 W</td>
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<tr>
<td>1.77</td>
<td>290 W</td>
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<tr>
<td>1.97</td>
<td>346 W</td>
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<tr>
<td>2.16</td>
<td>436 W</td>
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<tr>
<td>2.36</td>
<td>502 W</td>
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<tr>
<td>2.56</td>
<td>564 W</td>
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<tr>
<td>2.75</td>
<td>628 W</td>
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</tbody>
</table>

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The cathode flow rate was held to 7–9% of the anode flow rate. The thruster was operated both with and without an applied keeper current of 2 A, resulting in no observed sensitivities of the thruster operation to the application of keeper current. The cathode-to-ground potential remained between −8 and −20 V, depending on the operating condition. During all tests, the thruster body was allowed to float from chamber ground to enable measurements of the thruster floating potential and current to the thruster body. No changes in performance were observed between a grounded and floating electrical configuration. The inner and outer magnet coils were operated at up to 4.2 and 2.2 A, respectively, corresponding to a total magnet power of 60–75 W. These high powers relative to the discharge power were attributed to temperature-related increases in the magnet coil’s resistance and are one of several areas identified for improvement on future MaSMi designs. The discharge channel length could be varied based on anode placement, and was set to twice the discharge channel width. Temperatures recorded by K-type thermocouples at the front outer pole and near the center core at the back pole remained below 250 and 220°C, respectively, for all tests; the temperature gradient along the radius of the back pole remained below 30°C.

The MaSMi-60 exhibited various discharge current oscillations, depending on how a specific operating condition was approached (i.e., ramping the coil currents up vs down, beginning from a lower vs higher discharge voltage or current, etc.). The oscillations ranged from very quiet modes (peak-to-peak currents less than 30% of the mean discharge current) to highly oscillatory modes (peak-to-peak currents greater than 200% of the mean discharge current) across a frequency range of 20–40 kHz. The measured performance of the thruster appeared to be unaffected by the characteristics of these oscillations within the measurement uncertainty; however, they may affect other aspects of the device such as the observed pole face erosion (discussed in the following).

Nominal Hall thruster operation is defined as the minimum discharge current as a function of magnetic field strength for a given discharge voltage and propellant flow rate. This operating point is found by fixing both the discharge voltage and propellant flow rate, and then ramping the magnetic field strength across the available range until a minimum in the discharge current is observed (indicated by the inflection point of the \( I_d \) vs \( B \) curve). Nominal operation of the MaSMi-60 was only achievable at a discharge voltage of 200 V and a propellant flow rates of 1.18 or 1.38 mg/s. For all other conditions presented in Table 1, the thruster was operated at the highest possible magnetic field setting, which corresponded to the lowest possible discharge current. Note that these points were not the nominal operating points (i.e., the absolute discharge current minimum) because the trend in \( I_d \) vs \( B \) was still decreasing at the maximum available magnetic field setting. A plot of discharge current against inner magnet coil current for the 200–300 V and 250 W operating conditions presented in Table 1 are shown in Fig. 2. The discharge current approaches a minimum value at the maximum available field setting, but additional field strength appears to be required to achieve true nominal operation. This trend was consistent for nearly all other operating points, as shown in the plots for the 400 and 550 W operating conditions found in [19]. The variable discharge current oscillations and the thruster’s inability to achieve nominal operation across most of its operating envelope appear to be related to the magnetic field strength in the MS configuration. This represents another important area for future improvement of the MaSMi-60’s performance and life.

B. Magnetic Shielding Assessment

Three experimental methods were used to assess the effectiveness of magnetic shielding in the MaSMi-60: 1) visual observations of the plasma discharge near the channel walls, 2) examination of the sputter-deposited carbon on the discharge channel surfaces after thruster operation, and 3) erosion calculations based on carbon backspatter measurements.

Images of the MaSMi-60’s plasma discharge (Fig. 3) show visible gaps between the plasma and the discharge channel walls. These darker zones between the plasma and channel walls are associated with low local electron temperatures corresponding to lower local xenon excitation rates near the channel walls in MS Hall thrusters. The gaps, extending fully along the channel length, suggest that the MaSMi-60 is magnetically shielded [13]. This is normally validated by local probe measurements of the electron temperature at the channel walls, but the small size of the MaSMi-60 prevented internal probing.

An image of the MaSMi-60 discharge channel before and after thruster operation is presented in Fig. 4. The boron nitride (BN) channel walls were uniformly coated by a carbon-film sputter-deposited from the graphite panels found in the beam dump and along the walls of the vacuum chamber. As shown in previous publications discussing magnetically shielded Hall thrusters, these observations are supporting, but not conclusive, evidence of a fully shielding magnetic field topology [13,22].

Erosion of both the inner and outer poles, shown in Fig. 4 by the roughening of these components, was observed after ~20 h of operation with similar observations made throughout the test campaign. This feature is known to affect both high- and low-power magnetically shielded Hall thrusters; its appearance after short-duration operation of the MaSMi-60 may be caused by the thruster’s nonoptimized magnetically shielded field topology, thruster body electrical configuration, energetic ions from cathode plume oscillations (observed in ion thruster and cathode life tests), or other mechanisms [23–25]. For example, though the MaSMi-60 achieves symmetric shielding of the inner and outer walls, it also
imposes a topology around the chamfered regions of the discharge channel with exceedingly high field curvature (termed “over-shielded” because the degree of field curvature is much higher than in the designs of high-power MS Hall thrusters). This is shown in Fig. 5 [12,19,23,26] through electron temperature profiles of the 6 kW H6MS Hall thruster operating at 300 V and 6 kW and the MaSMi-60 operating at 300 V and 400 W (a detailed discussion of the electron temperature magnitudes and profiles can be found in [17]). The shape of the magnetic field is indicated by the $T_e$ profiles because of the isothermally of the magnetic field lines in Hall thrusters [12,27]. The oversheilded field topology may lead to higher angular divergence of beam ions, and therefore increased pole erosion. Alternatively, a combination of the magnetic field structure and the floating electrical configuration may lead to large (greater than 100% of the mean discharge current) plasma oscillations, which could enhance erosion. These and other possible physical mechanism(s) of ion bombardment impose constraints on the useful life of the discharge channel (and to some extent, the thruster) can be estimated.

Equation (10) can be bounded by

$$\varepsilon_{Xe-BN} \leq a R_e \left( \frac{p_{BN} m_B}{p_{Xe-BN} m_{Xe-BN}} \right) \frac{Y_{Xe-BN}}{Y_{Xe-C/BN}} \approx 2 R_e \left( \frac{Y_{Xe-BN}}{Y_{Xe-C/BN}} \right) \quad (10)$$

where $\alpha$ is the sticking coefficient (assumed to be unity), $R_e$ is the carbon backsputter rate, $p_{BN}$ is the mass density of carbon, $m_{BN}$ is the particle mass of BN, $p_{Xe-BN}$ is the mass density of BN, $m_{Xe-BN}$ is the particle mass of carbon, $Y_{Xe-BN}$ is the sputter yield of BN under xenon ion incidence, and $Y_{Xe-C/BN}$ is the sputter yield of carbon-coated BN under xenon ion incidence [13]. The yield ratio is conservatively estimated to be 10 based on the findings of Hofer et al. [13]. By dividing a Hall thruster’s discharge channel wall thickness by the erosion rate calculated from Eq. (10), a conservative lower bound on the useful life of the discharge channel (and to some extent, the thruster) can be estimated.

To approximate the MaSMi-60’s discharge channel erosion (and therefore channel life), carbon backsputter measurements were taken using a QCM at discharge voltages of 200 and 300 V. Deposition rates of approximately 0.03 and 0.06 $\mu m/h$ were observed for the 200 and 300 V conditions, respectively. Applying these values to Eq. (10) suggests a maximum discharge channel erosion rate of approximately 0.63 $\mu m/h$ at 200 V and 1.13 $\mu m/h$ at 300 V. Because the discharge channel walls were completely coated in a layer of backsputtered carbon after operation of the MaSMi-60 (a required feature for this analysis), the discharge channel erosion rate was bounded by 0.03–0.63 $\mu m/h$ for operation at 200 V and 0.06–1.13 $\mu m/h$ for operation at 300 V [13]. These erosion rates represent at least a factor of 10 (and likely greater than a factor of 100) reduction in discharge channel wall erosion rates compared to unshielded Hall thrusters (both low-power and high-power Hall thrusters show similar erosion rates), suggesting that increased discharge channel lifetimes of 10–100 times may be realized [13,22].

Interestingly, the carbon deposition rates measured for the MaSMi-60 were approximately an order of magnitude greater than those observed during testing of the H6MS conducted at JPL’s Owens (Patio) chamber [13,22]. These observations appear to be related to the relative sizes of the two vacuum chambers. Despite the higher ion flux generated by the H6MS compared to the MaSMi-60, a factor of ~10 increase in carbon backsputter was observed during MaSMi-60 testing in the High Bay chamber, likely due to the shorter distance from the thruster to the beam dump (~1/2 that of the Owens chamber). A shorter distance from the thruster to the beam dump reduces the distance over which the beam energy can be attenuated, yielding more high-energy ion bombardment at the beam dump and increased backsputter rates. This is significant because, as shown in Eq. (10), the upper bound of the channel erosion rate is directly proportional to the carbon backsputter rate. Testing in a lower backsputter facility while still observing carbon-coated discharge channel walls after operation due to the presence of magnetic shielding (MaSMi-60 operated in JPL’s Owens chamber, for example) would provide a more accurate estimate of the channel wall erosion rate upper bound. This suggests that the above 10–100 times reduction in the MaSMi-60’s channel wall erosion compared to unshielded thrusters is a conservative estimate.

C. Performance Measurements: Thrust Stand

Thrust as a function of discharge power is shown in Fig. 6 for each of the 30 operating conditions presented in Table 1. Increases in discharge power yielded proportional increases in thrust, generating nearly linear trends for each discharge voltage. Thrust values ranging from 8 to over 33 mN were observed, demonstrating a favorable throttling range for the MaSMi-60.

The anode specific impulse as a function of discharge power is shown in Fig. 7. All curves followed the expected trends of increasing $I_{sp}$ with both discharge voltage and discharge power, and anode specific impulse values of between 730 s and 1370 s were observed. The MaSMi-60 achieved slightly lower $I_{sp}$ values at a given power level than conventional low-power Hall thrusters of a similar scale. This is likely due to the ionization and acceleration regions being

![Fig. 4 Comparison of the MaSMi-60’s discharge channel and poles before and after ~20 h of operation.](Image)

![Fig. 5 Electron temperature contours for the H6MS (left) [12] and the MaSMi-60 (right) [19,23] predicted by Hall2De [26] (note that these plots do not share a common scale).](Image)

![Fig. 6 Thrust vs discharge power.](Image)
D. Performance Measurements: Plume Diagnostics

Anode efficiency as a function of discharge power is presented in Fig. 8. In general, all operating conditions yielded increased efficiency as the discharge power was increased. In every case except the 400 V conditions, however, there appeared to be a peak efficiency maximum at 29%. This efficiency maximum is also likely caused by the overshielded topology that forces the ionization and acceleration regions downstream of the discharge channel exit, reducing plasma confinement and beam focusing while enabling increased neutral leakage [17].

The normalized ion current measured by the four-grid RPA at discharge voltages of 200, 250, and 300 V are shown in Fig. 10a (left), whereas a plot of normalized \( dI/dV \) for each of these discharge potentials is presented in Fig. 10b (right). One representative curve is shown for each discharge voltage, as the variation of the RPA traces was minimal between the three power levels at each discharge voltage. A full-width at half-maximum (FWHM) value of between approximately 65 and 70 V was observed for all but one of the RPA traces (the one exception had an FWHM value in excess of 100 V), suggesting a relatively wide distribution of ion energies in the beam. The plasma potential, measured directly from the emissive probe local to the RPA, was between 9 and 10 V for all operating conditions. Details of the emissive probe measurements were presented in [19].

The electron temperature \( (T_e) \) local to the RPA was 3 eV based on far-plume Langmuir probe measurements [17]. The far-field plasma potential was therefore \( 11 \pm 1 \) V at the RPA, which is calculated as the sum of emissive probe plasma potential and \( T_e/2 \). The most probable ion energy was then calculated as the peak of the RPA measurements less this local plasma potential. Table 3 summarizes the peak value of \( dI/dV \) \((V_{peak,RPA})\), the local plasma potential \((V_{plasma})\), the most probable ion potential \((V_{mp})\), and the approximate RPA measurement uncertainty.

2. Retarding Potential Analyzer and Emissive Probe Results

The normalized ion current measured by the four-grid RPA at discharge voltages of 200, 250, and 300 V are shown in Fig. 10a (left), whereas a plot of normalized \( dI/dV \) for each of these discharge potentials is presented in Fig. 10b (right). One representative curve is shown for each discharge voltage, as the variation of the RPA traces was minimal between the three power levels at each discharge voltage. A full-width at half-maximum (FWHM) value of between approximately 65 and 70 V was observed for all but one of the RPA traces (the one exception had an FWHM value in excess of 100 V), suggesting a relatively wide distribution of ion energies in the beam. The plasma potential, measured directly from the emissive probe local to the RPA, was between 9 and 10 V for all operating conditions. Details of the emissive probe measurements were presented in [19].

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3. \( E \times B \) Probe Results

The normalized ion current measured by an \( E \times B \) probe for the MaSMi-60 operating at 300 V and 250 W is presented in Fig. 11. The peaks of the three primary ion species were easily distinguishable in the \( E \times B \) traces. A small peak before the \( \text{Xe}^+ \) peak at around 40 V was observed in several of the \( E \times B \) probe datasets and is attributed to charge–exchange collisions within the plasma. Similar peaks appearing at lower bias potentials than the \( \text{Xe}^+ \) peak have been observed and described by both Ekholm and Kargus [28] and King [29].

### Table 2

<table>
<thead>
<tr>
<th>( V_e ) (V)</th>
<th>( P_d ) (W)</th>
<th>( I_b ) (A)</th>
<th>Divergence (deg)</th>
<th>Uncertainty ( I_b )</th>
<th>Uncertainty (divegence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>250</td>
<td>0.765</td>
<td>33</td>
<td>+8% / -4%</td>
<td>+ / -8%</td>
</tr>
<tr>
<td>200</td>
<td>400</td>
<td>1.237</td>
<td>33</td>
<td>+5% / -3%</td>
<td>+ / -8%</td>
</tr>
<tr>
<td>200</td>
<td>550</td>
<td>1.737</td>
<td>33</td>
<td>+4% / -2%</td>
<td>+ / -8%</td>
</tr>
<tr>
<td>250</td>
<td>250</td>
<td>0.615</td>
<td>31</td>
<td>+10% / -5%</td>
<td>+ / -8%</td>
</tr>
<tr>
<td>250</td>
<td>400</td>
<td>1.024</td>
<td>31</td>
<td>+6% / -3%</td>
<td>+ / -8%</td>
</tr>
<tr>
<td>250</td>
<td>550</td>
<td>1.405</td>
<td>34</td>
<td>+5% / -2%</td>
<td>+ / -7%</td>
</tr>
<tr>
<td>300</td>
<td>250</td>
<td>0.524</td>
<td>31</td>
<td>+12% / -6%</td>
<td>+ / -8%</td>
</tr>
<tr>
<td>300</td>
<td>400</td>
<td>0.791</td>
<td>33</td>
<td>+7% / -4%</td>
<td>+ / -8%</td>
</tr>
<tr>
<td>300</td>
<td>550</td>
<td>1.089</td>
<td>33</td>
<td>+5% / -3%</td>
<td>+ / -8%</td>
</tr>
</tbody>
</table>
Both high- and low-power unshielded Hall thrusters tend to produce beams that are strongly dominated by singly charged ions (~80–90% of the total beam content), as shown in published results for the 6 kW H6MS and 200 W BHT-200 [13,22,28]. Although the MaSMi-60’s beam is clearly dominated by singly charged ions, 30–45% of the beam ions consists of multiply charged ion species. In general, the MaSMi-60’s beam composition matches more closely with measurements made on the H6MS than on the BHT-200, offering further evidence of a fully shielding topology [22]. The wide ion energy distribution noted during the RPA measurements was also observed in the $E \times B$ probe spectra, where relatively wide Gaussian curves (corresponding to a large spread in ion energies) were required to fit the data. The results presented in Fig. 11 show the same trends observed for the other eight operating conditions considered during this investigation (the complete set of $E \times B$ probe traces can be found in [19]). A summary of the beam composition at each of the nine operating conditions and their associated uncertainties is shown in Table 4.

### E. Performance Summary

A summary of the anode efficiency measured by the thrust stand ($\eta_{a,\text{meas}}$) compared to the voltage utilization, current utilization, mass utilization, divergence, charge utilization, and anode efficiencies calculated from the plume diagnostics is presented in Table 5. The approximate uncertainty in the calculated anode efficiency ($\eta_{a,\text{calc}}$) is also included. Good matching was observed between the calculated and measured anode efficiencies, with all performance values falling well within the uncertainty of the plume measurements.

Insight into the behavior of the MaSMi-60 can be obtained by comparing its performance to that of the high-performing H6MS Hall thruster. The measured anode efficiency of the MaSMi-60 ranged from 24 to 28%, whereas the H6MS demonstrated an anode efficiency of 67% at a discharge voltage of 300 V [22]. Although the high efficiencies observed in high-power Hall thrusters have not yet been observed in low-power devices, the efficiency demonstrated by the MaSMi-60 is less than that of many comparably sized devices and warrants investigation. An examination of the individual efficiency contributions to the MaSMi-60’s anode efficiency clearly shows the primary causes of the thruster’s lower-than-expected performance. The MaSMi-60’s voltage utilization and charge utilization efficiencies were, in general, in the mid-90% range and matched well with the H6MS [22]. The current and mass utilization efficiencies were the two lowest components of the MaSMi-60’s anode efficiency, with an average value of 62% over all thruster operating conditions and no value greater than 67%. The beam divergence efficiency was only slightly better, with values peaking at 73%. By contrast, the H6MS demonstrated 87% current utilization efficiency, 98% mass utilization efficiency, and 89% divergence efficiency [22].

Three physical mechanisms were identified during this investigation as the primary factors responsible for the low-efficiency values observed in the MaSMi-60 [17,19]:

1) The first factor was low current utilization efficiency. An insufficient magnetic field strength prevented adequate confinement of electrons, enabling excessive electron streaming to the anode. This

### Table 3 Summary of the peak RPA-measured potential, most probable ion potential, far-field plasma potential, and the associated uncertainty

<table>
<thead>
<tr>
<th>$V_{dc}$ V</th>
<th>$V_{\text{peak,RPA}}$</th>
<th>$V_{\text{plasma}}$</th>
<th>$V_{mp}$</th>
<th>$V_{\text{uncertainty}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>186</td>
<td>11</td>
<td>175</td>
<td>+/− 6%</td>
</tr>
<tr>
<td>250</td>
<td>237</td>
<td>11</td>
<td>226</td>
<td>+/− 4%</td>
</tr>
<tr>
<td>300</td>
<td>290</td>
<td>11</td>
<td>279</td>
<td>+/− 4%</td>
</tr>
</tbody>
</table>

### Table 4 Summary of ion species’ contributions to the beam current and the associated uncertainty

<table>
<thead>
<tr>
<th>$V_{dc}$ V</th>
<th>$P_{dc}$ W</th>
<th>$I^+$</th>
<th>$I^{++}$</th>
<th>$I^{+++}$</th>
<th>Uncertainty ($I^+, I^{++}, I^{+++}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>250</td>
<td>0.613</td>
<td>0.245</td>
<td>0.142</td>
<td>+/− 8%</td>
</tr>
<tr>
<td>200</td>
<td>400</td>
<td>0.569</td>
<td>0.275</td>
<td>0.156</td>
<td>+/− 9%</td>
</tr>
<tr>
<td>200</td>
<td>550</td>
<td>0.550</td>
<td>0.269</td>
<td>0.181</td>
<td>+/− 9%</td>
</tr>
<tr>
<td>250</td>
<td>250</td>
<td>0.623</td>
<td>0.259</td>
<td>0.118</td>
<td>+/− 8%</td>
</tr>
<tr>
<td>250</td>
<td>400</td>
<td>0.601</td>
<td>0.252</td>
<td>0.147</td>
<td>+/− 8%</td>
</tr>
<tr>
<td>250</td>
<td>550</td>
<td>0.572</td>
<td>0.257</td>
<td>0.171</td>
<td>+/− 9%</td>
</tr>
<tr>
<td>300</td>
<td>250</td>
<td>0.708</td>
<td>0.204</td>
<td>0.088</td>
<td>+/− 7%</td>
</tr>
<tr>
<td>300</td>
<td>400</td>
<td>0.648</td>
<td>0.214</td>
<td>0.137</td>
<td>+/− 8%</td>
</tr>
<tr>
<td>300</td>
<td>550</td>
<td>0.643</td>
<td>0.258</td>
<td>0.099</td>
<td>+/− 8%</td>
</tr>
</tbody>
</table>
increased the measured discharge current relative to the beam ion current, leading to poor current utilization.

2) The second factor was low mass utilization efficiency. The combination of the thruster’s short discharge channel and anode design (which strongly influenced the axial vs radial transit direction of the injected neutral propellant) yielded ionization mean free paths that, on average, were longer than the discharge channel. This enabled a large population of neutral particles to escape the discharge channel unionized.

3) The third factor was low beam divergence efficiency. The convex curvature in an MS Hall thruster’s magnetic field topology local to the discharge channel walls directed the electric field vector off-axis relative to the channel centerline (yielding beam divergence), whereas the concave curvature near-channel centerline directed the electric field vector toward the channel centerline (yielding beam focusing). The high degree of field curvature observed in the MaSMi-60 resulted in higher beam divergence than has been observed in high-power MS Hall thrusters, leading to decreased performance.

VI. Conclusions

The performance of the MaSMi-60 was investigated to analyze the effects of applying magnetic shielding to low-power Hall thrusters. The device achieved a fully shielding magnetic field topology, which appeared to produce at least a 10–100 times increase in the useful life of the discharge channel compared to unshielded devices. The thruster demonstrated moderate performance, with peak thrust, anode specific impulse, and anode efficiency values of 33 mN, 1370 s, and 29%, respectively, for discharge powers up to 750 W. Plume diagnostics identified the primary contributors to this lower-than-expected performance: current utilization efficiency, mass utilization efficiency, and beam divergence. Investigating the physical causes for these performance limiters revealed three design improvements that would lead to improved performance: increasing the magnetic field strength, improving the anode design, and reducing the magnetic field curvature downstream of the channel walls (i.e., the level of magnetic shielding).

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Associate Editor