

Magnetically Shielded Miniature Hall Thruster: Development and Initial Testing

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The scaling of magnetically shielded Hall thrusters to low-power is investigated through the development and fabrication of a 4 cm Hall thruster. During initial testing, the magnetically shielded miniature Hall thruster was operated at 275 V discharge voltage and 325 W discharge power. Inspection of the channel walls after testing suggests that the outer discharge channel wall was successfully shielded from high-energy ion erosion while the inner channel wall showed evidence of weaker shielding, likely due to magnetic circuit saturation. Scanning planar probe measurements taken at 4.4 cm and 10.8 cm downstream of the thruster face provided ion current density profiles. The ion current calculated by integrating these data was 1.04 A with a plume divergence half-angle of 30°. Swept retarding potential analyzer measurements taken at 80 cm axially downstream of the thruster measured the most probable ion voltage to be 252 V. The total thruster efficiency was calculated from probe measurements to be 43% (anode efficiency of 59%) corresponding to a thrust of 19 mN at a specific impulse of 1870 s. Discharge channel erosion rates were found to be approximately three orders of magnitude less than unshielded Hall thrusters, suggesting a significant increase in projected operational life.

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Nomenclature

A_{en}	entrained neutral mass flow area [m ²]	P_T	total power [W]
A_p	probe area [m ²]	$P_{T,true}$	vacuum total power [W]
A_R	radiation surface area [m ²]	P_w	power deposited to the channel wall [W]
A_{RPA}	RPA orifice area [m ²]	Q_{int}	plasma heating power loss [W]
A_w	channel area in contact with plasma [m ²]	R	probe radius from thruster centerline [m]
b	channel width [mm]	R_C	carbon deposition rate [μm/h]
d_m	channel mean diameter [mm]	T	thrust [N]
e	charge of an electron [C]	T_{true}	vacuum thrust [N]
F	view factor	$T_{e,eV}$	electron temperature [K, eV]
f	ion species current fraction	T_{e0}	centerline electron temperature [K]
g	acceleration due to gravity [m/s ²]	T_M	MaSMi thruster temperature [K]
$I^{+,++,...}$	ion charge species currents [A]	T_n	neutral gas temperature [K]
I_a	anode current [A]	T_S	local space temperature [K]
I_b	beam current [A]	U^+	ionization potential [V]
I_d	discharge current [A]	V_b	beam voltage [V]
$I_{d,true}$	vacuum discharge current [A]	V_d	discharge voltage [V]
I_{en}	entrained ion current [A]	V_p	volume of high-temperature plasma [m ³]
I_{ew}	electron current to channel walls [A]	v_e	electron thermal velocity [m/s]
I_i	i th ion species' current [A]	v_i	ion velocity [m/s]
I_{iw}	ion current to channel walls [A]	w	probe scan resolution [m]
I_p	probe collected current [A]	Y	sputter yield
I_{sp}	specific impulse [s]	Z_i	i th ion species' charge state
$I_{sp,true}$	vacuum specific impulse [s]		
J_i	ion current density [A/m ²]	α	sticking coefficient
k	Boltzmann constant [m ² kg/s ² K]	γ	secondary electron yield
M	xenon mass [kg]	ε	pre-sheath energy [J]; erosion rate [μm/h]
m	electron mass [kg]	ε_R	surface emissivity
m_{BN}, m_c	particle mass of BN & carbon [kg]	ζ_{en}	entrained neutral utilization factor
$\dot{m}_a$	anode propellant mass flow rate [kg/s]	η_a	anode efficiency
$\dot{m}_{a,true}$	vacuum anode mass flow rate [kg/s]	η_b	beam current utilization efficiency
$\dot{m}_b$	beam propellant mass flow rate [kg/s]	η_c	cathode efficiency
$\dot{m}_c$	cathode propellant mass flow rate [kg/s]	$\eta_{c,true}$	vacuum cathode efficiency
$\dot{m}_{en}$	entrained neutral mass flow rate [kg/s]	η_d	plume divergence efficiency
$\dot{m}_i$	ion mass flow rate [kg/s]	η_m	mass utilization efficiency
$\dot{m}_T$	total propellant mass flow rate [kg/s]	η_o	electrical efficiency
n_e	electron density [m ⁻³]	$\eta_{o,true}$	vacuum electrical efficiency
n_{e0}	centerline electron density [m ⁻³]	η_q	beam charge efficiency
$n_{i,fast}$	fast (beam) ion density [m ⁻³]	η_T	total efficiency
$n_{i,slow}$	slow (charge exchange) ion density [m ⁻³]	$\eta_{T,true}$	vacuum total efficiency
n_o	neutral density [m ⁻³]	η_{tc}	effective thruster efficiency
P	chamber pressure [Pa]	η_v	beam voltage utilization efficiency
P_a	power deposited to the anode [W]	θ	beam divergence angle [°]
P_b	beam power [W]	ρ_{BN}, ρ_c	mass density of BN & carbon [kg/m ³]
P_d	discharge power [W]	σ	Stefan-Boltzmann constant [W/m ² K ⁴]
P_i	power to produce ions [W]	σ^*	excitation cross section [m ²]
P_{jet}	jet power [W]	Φ_s	sheath potential [V]
P_k	keeper power [W]	Φ	plasma potential [V]
P_{mag}	magnet power [W]	Φ_o	centerline plasma potential [V]
P_R	plasma radiative power loss [W]		

I. Introduction

An efficient, high ΔV , low-power Hall thruster would be attractive for a wide range of NASA missions. Such a thruster would provide deep space and near Earth mission planners with the combined advantages of high specific impulse (>1500 s) and high thrust-to-power ratio at a reduced scale. Numerous miniature Hall thrusters have been developed in an effort to meet this demand. The BHT-200, for example, employs a 3-cm discharge channel diameter and generates up to 12.8 mN of thrust at a specific impulse of 1390 s and an anode efficiency of 44% (nominally 11.4 mN, 1570 s, and 42%); however, the BHT-200's operational life is limited to approximately 1000 hours [1-5]. The SPT-30, also a 3-cm Hall thruster, produces a thrust of 11.3 mN at a specific impulse of 1170 s and an anode efficiency of 32%, and is limited to approximately 600 hours of total operation [6]. The primary challenges for Hall thrusters at small scales (<500 W and <7 cm dia.) 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. To combat low performance and efficiency caused by high surface-to-volume ratios, miniature Hall thrusters are often designed with large discharge channels relative to the size of the thruster. This corresponds to an increased channel volume compared to the channel surface area, thereby reducing the surface-to-volume ratio at reduced scales. The discharge channel width-to-mean-diameter ratio (b/d_m) of several well-known Hall thrusters is plotted in Figure 1 against their power level, showing an increasing trend of b/d_m as a Hall thruster's scale is reduced.

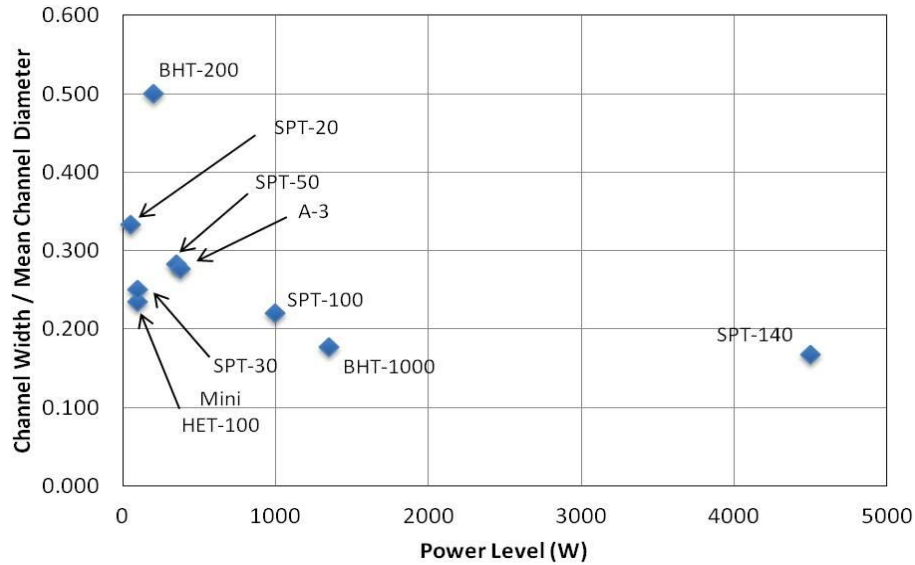


Figure 1. Trends of discharge channel width-to-mean-diameter ratio as a function of input power for a range of Hall thrusters [3-9].

II. Background and Motivation

A. Hall Thruster Life Limiting Factors

The primary life-limiting factor of conventional Hall thrusters is erosion of the discharge channel walls due to ion bombardment. Due to the zero net current condition at the insulating walls, a large sheath potential forms to reject the bulk of the electron population. In turn, the electron repelling sheath adds to the radial electric field component from the bulk plasma that accelerate nearby ions into the walls [10,11]. The resultant sputter erosion is concentrated near the exit plane and can wear through the discharge channel walls, exposing the thruster's pole pieces to ion bombardment. Degradation of the pole pieces alters the interior magnetic circuit of the device, eventually degrading the performance of the thruster and ending its useful life [12].

Another key performance-limiting factor in Hall thrusters is high-energy electron power loss to the discharge channel walls. In conventional Hall thrusters, the radial magnetic field lines near the exit plane intersect the channel walls. High-energy electrons flow along these field lines, and the most energetic ones bombard the discharge channel walls while the bulk of the distribution is reflected back into the plasma by either the plasma

sheath or the magnetic mirror created at the pole pieces. This electron power deposition results in performance-robbing heating of the Hall thruster that can also affect operational lifetime due to temperature limitations of the thruster's materials and construction [13,14].

Ion bombardment and electron power loss effects increase rapidly in low power Hall thrusters primarily due to their characteristically larger surface-to-volume ratios. The erosion rates of conventionally sized and miniature Hall thrusters are comparable; however, shorter operational lifetimes are always observed in miniature devices due to their reduced channel wall thickness. Operational lifetimes of miniature Hall thrusters are generally low, ranging from tens of minutes to hundreds of hours with few devices surviving beyond 1,000 hours [5,6,15].

B. Magnetic Shielding Theory

Magnetic shielding is a method of dramatically increasing the operational life of Hall thrusters by significantly reducing the aforementioned life and performance limiting factors through careful design of the magnetic circuit. The physics of magnetic shielding were first described by JPL after Aerojet-Rocketdyne's BPT-4000 reached a zero-erosion state 5,600 hours into a 10,400 hour wear test [16,17]. Subsequently, magnetic shielding was shown to reduce erosion rates by three orders of magnitude in a series of simulations and experiments specifically designed to validate the physics of magnetic shielding through modification of the H6 Hall thruster (called the H6MS) [10,11,18,19]. Through nearly 5,000 hours of wear testing in a zero-erosion configuration with the BPT-4000 and detailed simulations and experiments with the H6MS, the physics of magnetic shielding have been established for thrusters operating at 4.5-6 kW and 2000 s specific impulse. The extensibility of magnetic shielding to higher specific impulse, high power density, higher power, lower power, and alternate wall materials are key questions now being addressed by NASA as the limits of magnetic shielding are explored [20-23].

Magnetically shielded Hall thrusters benefit from a unique magnetic field topography that prevents the magnetic field lines from intersecting the discharge channel walls in the acceleration region. Instead, the lines of force curve around the downstream edges of the discharge channel and follow the channel walls, eventually curving back towards the exit plane near the anode, as illustrated in Figure 2. This unique field topography provides low electron temperature at the discharge channel wall while eliminating any significant electric field components that may accelerate ions into the channel walls.

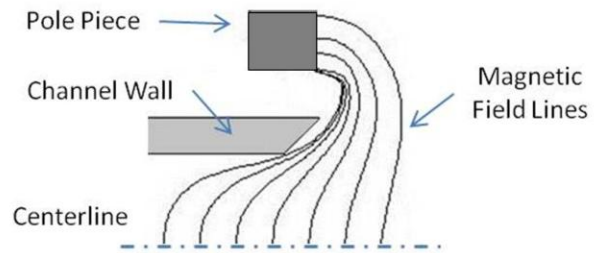


Figure 2. Illustration of the lines of force in a magnetically shielded Hall thruster.

Several well known properties of Hall thrusters are exploited in a magnetically shielded field topography [24-26]. The isothermality of magnetic lines of force requires that the electron temperature (T_e) along a field line is essentially constant, or $T_e \approx T_{e0}$. This property allows the deep-penetrating magnetic field lines to capture cold (~ 5 eV) electrons near the anode and transport these electrons adjacent to the discharge channel walls, maintaining a low average electron temperature near the wall [10,11,17,27]. Because the sheath potential is a function of electron temperature for a given material, the low electron temperature yields lower sheath potentials at the discharge channel walls. Through the thermalized potential equation, $\Phi \approx \Phi_0 + T_{e0} \ln \times (n_e / n_{e0})$, another byproduct of the cold field lines is that the assumption of magnetic-force-line equipotentialization will hold to a greater extent near the walls than in conventional Hall thrusters, maintaining a plasma potential close to that of the discharge voltage along the length of the discharge channel [10,11]. Here, Φ is the plasma potential, n_e is the electron density, and the subscript 0 denotes the centerline reference values. Additionally, proper channel geometry and magnetic field design forces the electric field to point nearly perpendicular to the discharge channel surfaces [10,11]. These factors significantly reduce the kinetic energy gained by ions passing through the potential drop along the channel walls, thereby decreasing sputter erosion of the channel. Because the field lines do not intersect with the thruster walls, high-energy electron confinement is improved while power deposition to the walls is reduced. The result is an increase of thruster lifetimes by as much as a factor of 1000 compared to unshielded Hall thrusters [10,11]. In terms of performance, implementation of magnetic shielding on the H6 Hall thruster resulted in a slight drop in efficiency (1.7%), a significant drop in insulator ring (discharge channel downstream edge) temperature (12-16%), and an increase in specific impulse (2.9%) primarily due to an increase in multiply charged ions from the decreased electron wall losses and resulting higher electron temperature [10,11].

C. Objective

The goal of this investigation is to develop a miniature (~ 4 cm diameter) Hall thruster operating in the 300 to 400 W range that demonstrates significantly increased operational lifetimes and improved performance compared to existing low-power Hall thrusters. We aim to develop a detailed understanding of the physical mechanisms of magnetic shielding as it is applied to miniature Hall thrusters and to determine to what extent magnetically shielding a miniature Hall thruster can result in:

- Significantly increased lifetimes resulting from nearly eliminating wall erosion
- Improved performance resulting from the reduction of wall power losses

The thruster designed, fabricated, and tested for this investigation will herein be called the MaSMi (*Magnetically Shielded Miniature*) Hall thruster. An analysis of the MaSMi Hall thruster's dimensions and predicted performance is presented in Section III, followed by a discussion of the experimental investigation in Sections IV and V.

III. Thruster Design and Predicted Performance

A. Scaling Method and Results

Hall thrusters present unique design challenges as they are scaled to the sub-7 cm channel diameter regime. As the scale is reduced, the increase in the thruster's surface-to-volume ratio significantly contributes to the non-linear scaling of miniature Hall thrusters [7,8]. Additionally, no scaling laws exist yet for magnetically shielded thrusters. As a means to roughly approximate MaSMi's performance, a proven scaling method for conventional Hall thrusters presented in the literature was applied [7,8]. Using the BHT-200 (30 mm channel outer diameter), the A-3 (60 mm channel outer diameter) and the SPT-100 (100 mm channel outer diameter) as the reference thrusters, a 44 mm (channel outer diameter) thruster model was generated [4-9]. The discharge power, thrust, and specific impulse were calculated and plotted against the reference thrusters' channel diameters, as shown in Figure 3. The non-linear scaling trends result from the many variables changing in the optimization of each design. The applied scaling laws predict a discharge power of approximately 320 W, a thrust of approximately 19 mN, and a specific impulse of approximately 1380 s.

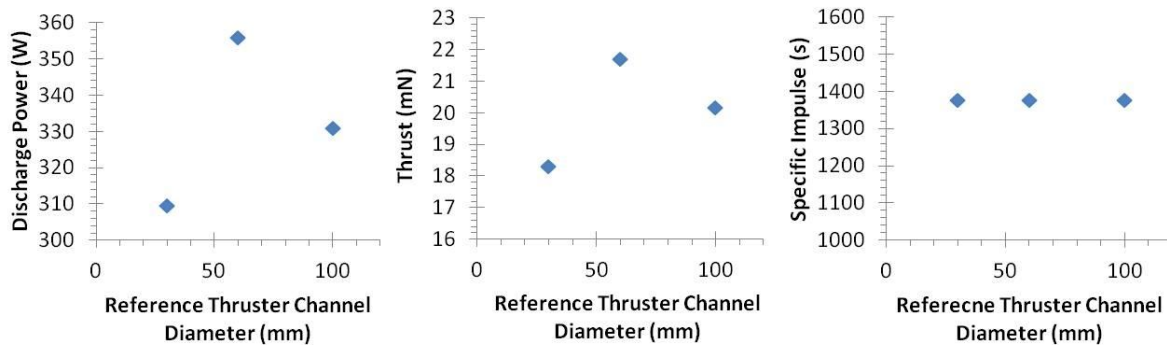


Figure 3. Predicted discharge power, thrust, and specific impulse for MaSMi based on scaling laws.

B. Key Dimensions

The MaSMi Hall thruster employs an outer channel diameter of 44 mm and a mean channel diameter of 36 mm. A model of the thruster's magnetic circuit predicts a magnetically shielded field topography with no intersection of the magnetic field lines and the discharge channel walls. A maximum magnetic field strength of approximately 218 G is predicted along the discharge channel centerline, exceeding the required value of 213 G to constrain electron Larmor radii to 10% of the discharge channel width (assuming an electron temperature of 20 eV) as is generally deemed optimal [14].

Iron is conventionally used for Hall thruster magnetic cores due to its favorable magnetic properties and low cost; however, it displays severe magnetic saturation problems at small thruster scales. Hiperco (an iron-cobalt-vanadium alloy), which has a much higher magnetic saturation tolerance than iron, was therefore selected for MaSMi's magnetic core. A single inner coil and a single outer coil, wrapped from AWG-22 nickel-plated and fiberglass-insulated high temperature copper magnet wire (rated to over 400°C), provide the necessary fields to operate the thruster.

The discharge channel, machined from HP-grade boron nitride (BN), has an 8 mm channel width and chamfered downstream edges characteristic of magnetically shielded thrusters to avoid intersection with magnetic field lines. The thruster has a channel width-to-mean-diameter ratio of 0.222, placing it in line with the trends of conventional miniature Hall thrusters shown in Figure 1. According to conventional Hall thruster design theory, the discharge channel length should be no less than three times the ionization length to allow for proper thruster operation, as defined in the literature [14]. The mean free path is between 2 mm and 6 mm based on MaSMi's expected performance range. A maximum discharge channel length of 16 mm (providing a maximum discharge channel length-to-width ratio of 2) was selected to allow for variable anode placement within the channel to optimize propellant mixing and ionization. During testing, the full 16 mm discharge channel length was utilized.

The anode employs a two-chamber design: the first chamber is intended to choke the propellant flow while the second has an annular diffuser to encourage propellant mixing [28]. The dividing plate (between the two chambers) and the downstream diffuser rings face the discharge plasma during operation and are therefore machined from graphite to provide high emissivity and lower operational temperatures. The remaining parts of the anode are machined from stainless steel.

C. Performance Modeling

I. Power Balance

The total power deposition to the discharge channel walls and anode can be estimated based on the thruster's operational parameters. It should be noted that the equations used for this power deposition model apply only to unshielded Hall thrusters; therefore, the power deposition experienced by MaSMi is expected to be significantly less than the model predicts. A linear curve fit of the secondary electron yield of boron nitride is used to predict finite secondary electron yields at low incident energies [29]. The electron temperature at the thruster exit plane is then calculated using an iterative process outlined in the literature (Goebel & Katz, Chapter 7.3) based on the linear secondary electron yields and the thruster operating parameters [14]. The power input to the thruster to generate the beam (i.e. the discharge power, P_d), which by definition is equal to the total power out of the thruster, is modeled to the first order as

$$P_d = P_b + P_w + P_a + P_R + P_i \quad (1)$$

where P_b is the beam power, P_w is the power deposited to the discharge channel walls by electrons and ions, P_a is the power deposited to the anode by electrons, P_R is the plasma's radiative power loss, and P_i is the power to produce ions that either become the beam or bombard the channel walls. These power terms are presented in the literature as

$$P_b = V_b I_b \quad (2)$$

$$P_w = n_e e A_w \left[\left(\frac{kT_e}{e} \right)^{3/2} \left(\frac{2e}{\pi m} \right)^{1/2} e^{\frac{e\Phi_s}{kT_e}} + \frac{1}{2} \sqrt{\frac{kT_e}{M}} (\epsilon - \Phi_s) \right] \quad (3)$$

$$P_a = 2T_{ev} I_a \approx 2T_{ev} I_d \quad (4)$$

$$P_R = n_o n_e \langle \sigma_* v_e \rangle V_p \quad (5)$$

$$P_i = (I_b + I_{iw}) U^+ = [\eta_b + I_{ew}(1 - \gamma)] I_d U^+ \quad (6)$$

where V_b is the beam voltage, I_b is the beam current, e is the charge of an electron, A_w is the surface area of the inner and outer discharge channel walls in contact with the plasma, k is the Boltzmann constant, m is the mass of an electron, Φ_s is the sheath potential relative to the plasma, M is the mass of a xenon atom, ϵ is the pre-sheath ion energy, T_{ev} is the electron temperature in electron volts, I_a is the current to the anode, I_d is the discharge current, n_o is the neutral density, $\langle \sigma_* v_e \rangle$ is the excitation reaction rate coefficient including the excitation cross section and the electron velocity, V_p is the volume of the high-temperature plasma region, I_{iw} is the ion current to the walls, U^+ is the ionization potential, η_b is the beam current utilization efficiency, I_{ew} is the electron current to the walls, and γ is the secondary electron yield [14].

To complete this analysis, several assumptions were made. The anode-region electron temperature was assumed to be 4 eV and the axial depth of the high-density plasma near the exit-region of the thruster was assumed to be 3 mm. The current and voltage efficiencies were assumed to be 70% and 90%, respectively, and the magnetic

field strength at the peak field point was conservatively assumed to be 160 G. A discharge current of 1.3 A and a total propellant flow rate of 20 sccm were also assumed. Using these assumptions and the known MaSMi thruster dimensions, the various power loss terms presented in Equations 2-6, in addition to the beam power and the electron temperature, were calculated as functions of the discharge voltage.

The beam power, the net power carried by the plasma beam, is approximately 245 W according to the unshielded power model (Equations 1-6). The power deposited to the channel walls is broken into two terms: the first is the power deposition of electrons that overcome the repelling sheath potential and the second is the power deposition of ions that fall through the pre-sheath and sheath potentials (the cooling effect of emitted secondary electrons is neglected). Electron and ion heating of the walls account for approximately 115 W and 4 W, respectively, of the total 145 W of power dissipated to the discharge channel walls in an unshielded MaSMi thruster. The remaining 25 W are contributions from xenon ionization, electron power deposition to the anode, and radiation. The xenon ionization power is 12.56 W and is not sensitive to changes in the thruster model's operation conditions. The power deposited to the anode is calculated based on the assumption that the discharge current is effectively equal to the electron current collected at the anode and assumes that the plasma potential is equal or slightly higher than the anode potential. Electrons are assumed to deposit $2T_{ev}$ of energy from the plasma to the anode, totaling in approximately 10.5 W of power loss for the unshielded model. The radiative power loss is the thermal power radiated by the plasma volume (the product of the discharge channel cross-sectional area and the axial thickness of the high-temperature plasma region) based on the excitation of neutrals in the plasma. Radiative power losses for the unshielded thruster total to approximately 2.5 W. The power to produce ions is the sum of the power used to generate the beam ions (product of the beam current and the ionization potential) and the power used to create ions that will bombard the discharge channel walls (product of the ion current to the walls and the ionization potential). Alternatively, this power can be calculated based on the beam efficiency and the electron current to the discharge channel walls, accounting for emitted secondary electrons; the sum of these factors is multiplied by the discharge current and ionization potential. Ionization power to the beam and wall ions totals to approximately 17 W for the unshielded thruster model. Other terms, including the power electrons may carry into the beam, are generally small and can be neglected [14].

For MaSMi's original expected operating conditions (300 V, 1.3 A), the electron temperature is calculated to be approximately 18.3 eV with a total power deposition of approximately 145 W according to the power model (calculated for conventional unshielded Hall thrusters). Figure 4 shows the electron temperature and total power deposition to the discharge channel walls and anode for a variety of discharge voltages at the expected operation discharge current of 1.3 A. An additional 35 W of power is expected to be generated by the two magnetic coils during nominal operation based on a temperature-sensitive model relating applied current and resulting magnetic field strength. The 180 W of thermal power produced by MaSMi represents a significant challenge for long-duration operation.

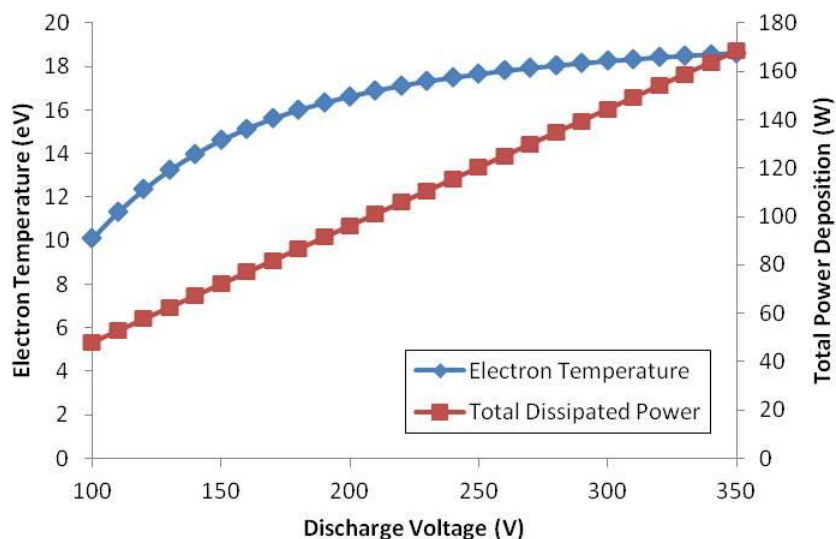


Figure 4. Electron temperature and total power deposition as a function of discharge voltage calculated for an unshielded 44 mm Hall thruster operating at 1.3 A discharge current.

II. Thermal Model

A thermal balance was performed to determine MaSMi's temperature during operation based on the power deposition model presented above. This balance, only accounting for thermal radiation, is represented by

$$Q_{int} = \sigma \varepsilon_R A_R F (T_M^4 - T_s^4) \quad (7)$$

where Q_{int} is the power lost from plasma heating of the thruster, σ is the Stephan-Boltzmann constant, ε_R is the surface emissivity, A_R is the radiation surface area, F is the free-space-facing view factor (assumed to be 1 in our case), T_M is MaSMi's temperature, and T_s is the temperature inside the vacuum chamber (assumed to be room temperature). Assuming no conduction, a total plasma heating power loss of 180 W, an emissivity of 0.3 (bare Hiperco), and a radiation area equal to the surface area of the thruster body, the predicted operation temperature is 450°C, which exceeds the thermal rating of the insulated magnet wire (~400°C). In order to efficiently dissipate the predicted 180 W, a thermal radiator is fitted over the thruster's outer core. The radiator is constructed from four 1/16" copper sheets with a quarter-circular bend in the center and bolted together tightly in the shape of an "X" to ensure thermal contact with the thruster body. The two upper fins are spread apart for greater surface area. The radiator, with a total space-viewing surface area of approximately 1000 cm², is oxidized (emissivity ~ 0.75) to yield a predicted thruster operation temperature of approximately 195°C. A photograph of the MaSMi Hall thruster mounted in its thermal radiator is presented in Figure 5.

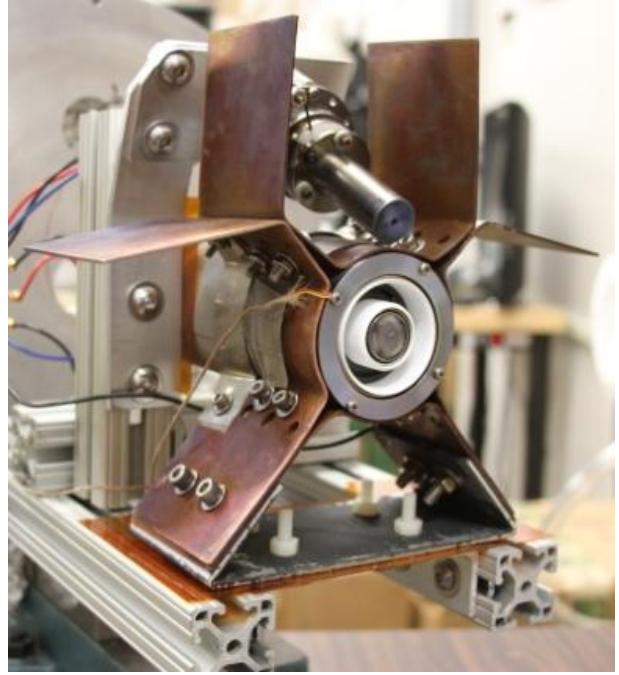


Figure 5. MaSMi Hall thruster fitted with thermal radiator and cathode.

III. Separatrix Analysis

Conventional Hall thrusters generally have one of two magnetic coil configurations to achieve the desired field topography. The first configuration uses discrete outer coils located at multiple, equally spaced azimuthal locations oriented parallel to the thruster's axis. These coils are magnetically coupled to the thruster's magnetic core to complete the thruster's magnetic circuit. The second thruster configuration uses a single outer coil, concentric with the thruster discharge channel and oriented along the thruster axis. This single coil is generally sheathed by the thruster's outer core to connect the coil to the thruster's magnetic circuit. In either thruster design, a single inner magnet coil located radially inward from the inner wall of the discharge channel may be implemented. Thrusters using discrete outer coils generate two species of field lines. The first circulates through the magnetic circuit and then extends from the inner pole to the outer pole. The second extends from the front of the outer coils and then reconnects at the back of the coils, traveling around the thruster body (not conducted by the magnetic circuit). Thrusters using a single outer coil generate only one magnetic field line species which circulates through the magnetic circuit and then extends from the thruster inner pole, reconnecting at the outer pole, sides, and rear of the thruster body.

The placement of the thruster's hollow cathode is a critical design feature depending on a thruster's magnetic coil configuration. Work is necessary for electrons born from the cathode to travel to the anode and ion beam, overcoming both strong magnetic fields

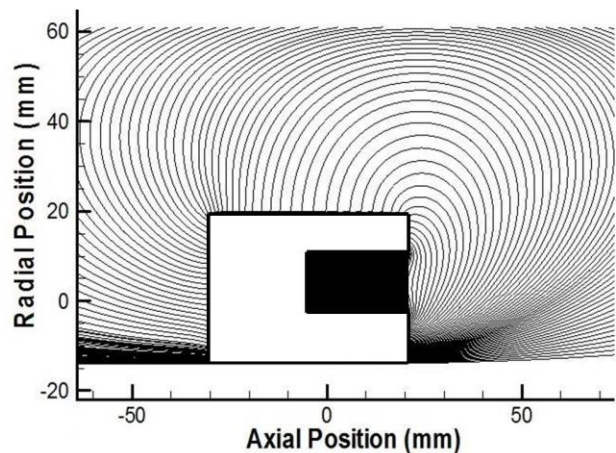


Figure 6. Simulation of MaSMi's magnetic field structure confirming that no separatrix exists.

and insufficient collision frequency, to maintain charge quasi-neutrality. The minimization of this work, which can be considered an energy loss mechanism, results in more effective cathode coupling with the thruster and improved thruster efficiency [30,31]. In the case of a Hall thruster with discrete outer coils, the magnetic field is divided into two regions of similarly connected flux lines (the two different species of flux lines discussed above); the boundary between these regions is called the separatrix. In a series of cathode coupling investigations using a BPT-2000 Hall thruster (which uses four discrete outer coils), Sommerville and King determined that placing a Hall thruster's hollow cathode orifice within the separatrix (towards the thruster's centerline) yielded significantly better thruster efficiency and improved cathode coupling [30,31].

In an effort to ensure good cathode coupling, MaSMi's far-field magnetic field structure was simulated to determine the location of the separatrix. Consistent with Sommerville's findings, the fields model suggests that that no separatrix exists in MaSMi's magnetic field structure, as shown in Figure 6 (note that the origin is located in the plane of the anode face along the inner wall of the discharge channel) [31]. It is therefore expected that cathode placement would be a minor concern for strong cathode coupling and efficient operation of the MaSMi Hall thruster.

IV. Experiment Configuration

A. Vacuum Facility and Supporting Equipment

Experiments were carried out in the Microthruster Test Facility in the Plasma and Space Propulsion Laboratory at UCLA. The UCLA Microthruster Test Facility, shown in Figure 7, uses a custom built cylindrical chamber measuring 2.8 m long with a diameter of 1.8 m. Two CTI CryoTorr 10 cryogenic pumps operate in parallel for a combined xenon pumping speed of about 1300 l/s. This system is capable of achieving a nitrogen base pressure of approximately 5×10^{-7} Torr, and during operation with a 15 sccm xenon flow the chamber pressure remains in the mid-high 10^{-5} Torr range (corrected for xenon).

The five power supplies required for normal operation of the MaSMi Hall thruster and supporting hollow cathode are installed on a power supply rack adjacent to the Microthruster Test Facility vacuum chamber. MaSMi's anode potential is provided by a Sorensen DLM 300-2 power supply while the inner and outer magnet coils are powered by a pair of Sorensen DLM 20-30 power supplies. Sorensen DLM 40-15 and DLM 150-4 power supplies are used for the hollow cathode's heater and keeper, respectively. Research grade xenon was supplied to the thruster by an Apex AX-DM 50 sccm mass flow controller and to the cathode by an Apex AX-DM 5 sccm mass flow controller.

MaSMi was coupled to a BaO-W cathode loosely based on the ISS plasma contactor cathode and the NSTAR ion thruster cathode. MaSMi's cathode has a 3/4 mm diameter cathode orifice and a tantalum keeper with a 3/16" diameter orifice. All other dimensions are similar to the NSTAR hollow cathode. During initial testing, the cathode was mounted parallel to the thruster axis with the cathode orifice approximately 6.6 cm (1.5 channel outer diameters) above the thruster centerline. In an effort to enhance cathode coupling, MaSMi's cathode was later mounted at a 22.5° angle relative to the thruster's centerline axis with the orifice approximately 10 mm above the thruster body in the plane of the thruster face and directed towards the beam. This second configuration yielded superior stability during thruster operation and was maintained throughout all ensuing performance characterization testing.

A high energy beam dump, consisting of a 1.25 m x 1.25 m square of 1/16" carbon felt mounted to a grounded aluminum frame, was mounted 80 cm downstream of the MaSMi Hall thruster. The close proximity of the beam dump to the thruster was selected to provide a short path for energetic carbon atoms ejected from the felt to easily backscatter onto the thruster discharge channel, enabling a visual verification of a successfully shielded thruster.

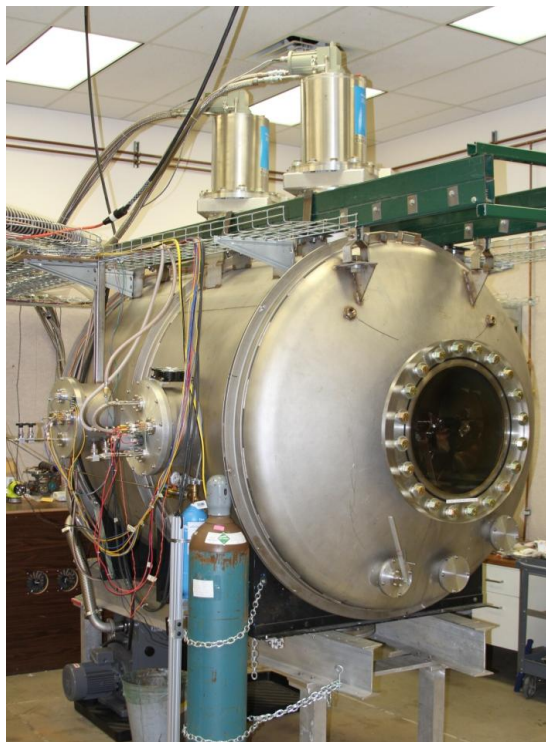


Figure 7. UCLA Microthruster Test Facility.

B. Diagnostics

In its current configuration, the UCLA Microthruster Test Facility employs two thruster plume characterization diagnostics: a retarding potential analyzer (RPA) and a scanning planar probe. Further diagnostics necessary to fully measure MaSMi's performance (i.e. ExB analyzer, emissive probe, Faraday probe, etc.) are under construction.

I. Scanning Planar Probe

A scanning planar probe, comprised of a flat, circular, single-sided electrode with a negative voltage bias, is used to determine the ion current density and integrated beam current. The current density (J_i) is calculated as $J_i = I_p / A_p$ where I_p is the ion current collected by the probe and A_p is the probe area. The total beam (ion) current is determined by integrating the current density azimuthally around the beam profile. Because a single probe scan measured the ion current from each side of the thruster, the ion current at each location is integrated around half of the azimuthal distance of the beam and then summed to account for any slight asymmetries in the beam profile. This simplifies to

$$I_b = \pi w \sum J_{i,n} R_n \quad (8)$$

where w is the width of the beam sampled by the probe (equal to the resolution of the scan) and R_n is the n th lateral distance of the probe from the thruster's centerline (in the plane of the probe trace).

The planar probe is an alumina-insulated 0.05" diameter tantalum wire with a 5/32" diameter, 0.005" thick molybdenum disk. The planar probe was scanned laterally +/-12 cm from the thruster's centerline and mounted 4.4 cm and 10.8 cm downstream of the thruster face (see Figure 8). The 4.4 cm probe scan was used for ion current density measurements because charge exchange effects are minimized near the thruster while the 10.8 cm scan offered insight into the evolution of the plume's properties downstream of the thruster. The probe's electron-repelling bias was measured as -28 V relative to the chamber potential. A Velmex single-axis mechanical translation stage with supporting Velmex VXM stepping motor controller provided horizontal motion across the thruster face at the set axial distance.

II. Retarding Potential Analyzer

A retarding potential analyzer (RPA) utilizes a series of biased grids to measure ion energy. The first grid is in contact with the plasma and floats relative to the plasma potential. The second grid is negatively biased to repel electrons, preventing them from entering the RPA and being collected by the ion collector electrode. The third (and sometimes fourth) grid is used as a positively biased ion discriminator, allowing only ions with energies greater than the applied voltage to reach the collector. The ion energy distribution is obtained by taking the first derivative of the current collected by the collector plate with respect to voltage [32].

The RPA built for this facility has a 3/8" diameter entrance orifice to the grid assembly. It uses stainless steel grids, each mounted to a 0.02" stainless steel ring; the individual plasma, electron repeller, and ion discriminator grid transparencies are 36%, 44%, and 40%, respectively. The RPA employs a four-grid design where the third and fourth grids make up the ion discriminator act as a double-discriminator (therefore, the effective grid transparency of the ion discriminator is 0.16). A four-grid design improves the energy resolution of the probe while preventing reductions in the discriminator potential at the centers of the ion grid orifices which may permit lower energy ions through the grid, leading to an over-estimate of collected ion current for a given discriminator potential [33]. At the end of the assembly is a 0.03" thick stainless steel disk as a simple collector plate. Each grid is separated by a 0.015" insulator ring, and the entire assembly is insulated from the aluminum RPA body by a cylindrical insulator. The RPA's electron repelling grid was biased to -28 V relative to ground while the ion discriminator grid's swept potential was provided by an Acopain P10HP60 high voltage power supply. The RPA was mounted on (and grounded to) the frame of the high-energy beam dump, fixed 80 cm axially downstream of MaSMi's centerline, as shown in Figure 8.

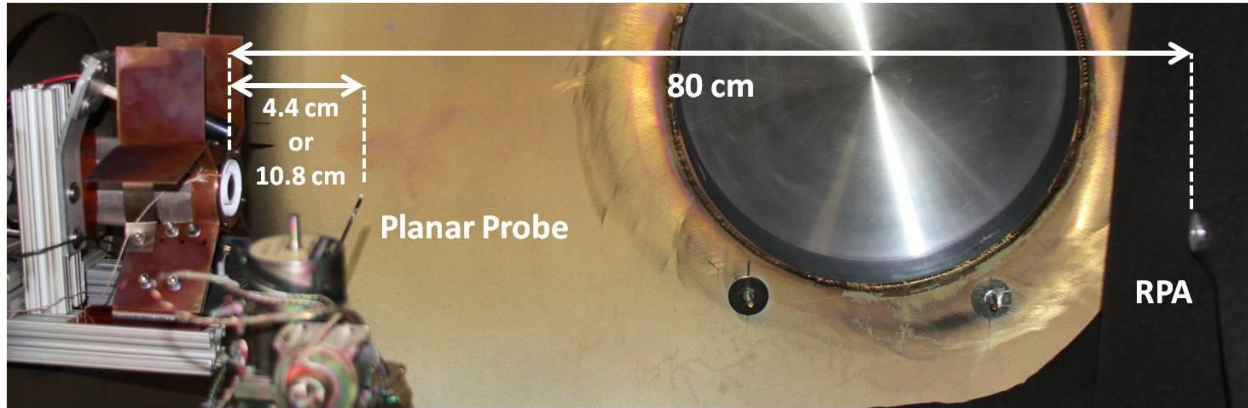


Figure 8. Planar probe and RPA locations downstream of the MaSMi Hall thruster.

III. Thermocouples

Four Omega K-type thermocouples were mounted on MaSMi to monitor operational temperatures. Three thermocouples were held at the base of the discharge channel and approximately equally spaced in the azimuthal direction (Figure 9, left); the fourth was mounted on the outer pole piece, below and to the left of the cathode (Figure 9, right). Temperatures were measured with Fluke digital multimeters.

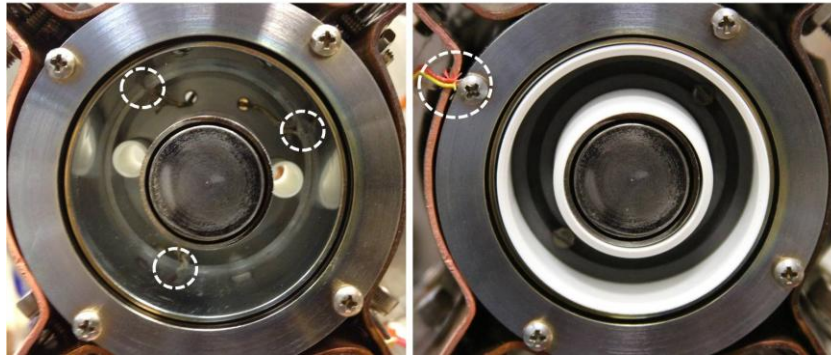


Figure 9. MaSMi thermocouple placement behind the discharge channel (left) and on MaSMi's outer pole piece (right).

V. Results and Discussion

The initial performance characterization experiments for the MaSMi Hall thruster were conducted at a discharge voltage of 275 V and a discharge power of 325 W. Early operation point optimization began at 300 V and 1.3 A in an effort to achieve the original design point of 390 W; however, testing revealed that the final operation conditions (275 V and 325 W) yielded a more stable discharge and constant temperatures throughout the duration of a given test. It should be noted that the nominal operation point is nearly identical to the predicted discharge power suggested by scaling laws utilized prior to thruster fabrication (Section III.A).

The anode propellant flow rate was set to 10.75 sccm of xenon while the cathode propellant flow rate was set to 1.1 sccm (10% of the anode flow rate). The inner and outer magnet coils were operated at 5.2 A and 1.5 A, respectively. Average operational temperatures of approximately 450 °C and 475 °C were measured at the base of the discharge channel and at the front pole piece, respectively. The Microthruster Test Facility vacuum chamber maintained a constant background pressure of 7×10^{-5} Torr, corrected for xenon, during all tests. The thruster performance was measured during eight experimental trials with a total run-time of approximately 4 hours during this initial testing period.

Two minor cracks in the thruster parts occurred during the final stages of testing (after the operation point was optimized to 325 W). The first was an axial crack along the outer wall of the discharge channel and the second

was a radial crack on the inner graphite ring of the anode (see Figure 11). Although their cause is still under investigation, it is likely due to anode thermal expansion that will be corrected during the next phase of performance testing. The operation of the MaSMi thruster at the nominal operation point was unaffected by these cracks and testing was concluded before the parts were replaced.

A. Magnetic Shielding

A photograph of the MaSMi Hall thruster during operation, with a magnified view of the upper discharge channel, is presented in Figure 10. To the naked eye, the plasma discharge appears to be slightly offset from the outer channel wall and more concentrated towards the center of the discharge channel. Similar to the visual observations with the H6MS, this was the first evidence suggesting that MaSMi achieved magnetic shielding [10]. The brightness of the discharge and the small scale of the thruster make it difficult to visually determine if the discharge was similarly offset from the inner channel wall.

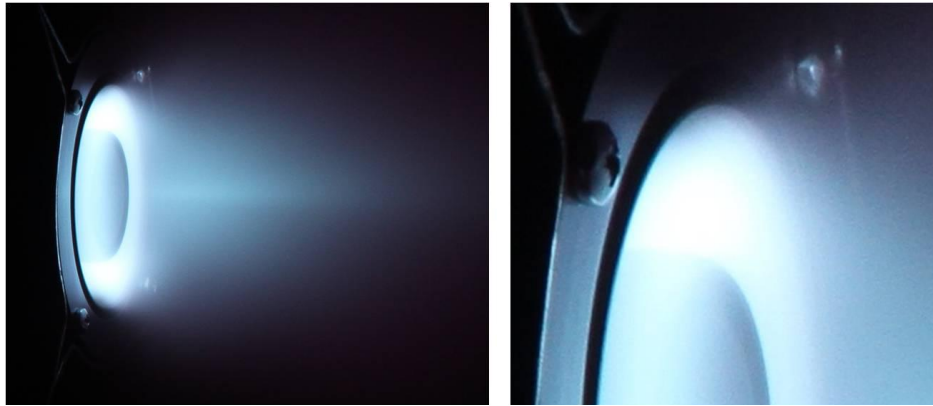


Figure 10. Operation of MaSMi at 275 V and 325 W with a magnified view of the upper region of the discharge channel showing a slight offset of the plasma from the wall typical of magnetic shielding.

A visual inspection of MaSMi's inner and outer discharge channel walls was conducted after each performance test. Figure 11 shows a comparison of MaSMi's discharge channel before and after testing. An even coating of carbon had been deposited on the outer wall of the discharge channel along its full axial length and covering the chamfered exit region; no exposed BN was visible anywhere on the outer channel wall. The inner wall of the discharge channel was found to be noticeably darker (more gray) in color than it was before testing, suggesting some carbon deposition in this region. Thin exposed rings of clean BN were found along the edges of the chamfers on the inner wall near the downstream edge; however, the remaining surface area near the thruster exit had an obvious dusting of carbon, suggesting that weaker magnetic shielding was present.

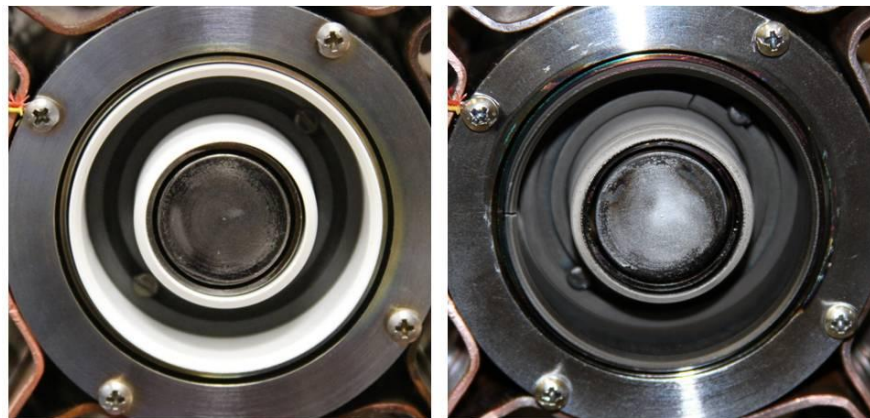


Figure 11. Comparison of MaSMi's discharge channel before and after testing. The layer of carbon back-sputter suggests the presence of magnetic shielding.

The thick carbon coating of the outer wall suggests that the backscatter rate of carbon from the high-energy beam dump exceeded the ion sputter rate of the outer wall material. The inner wall also showed evidence that plasma-wall interactions had been reduced; however, localized magnetic circuit saturation was likely the cause of the weaker shielding of the inner wall. In an effort to bound the erosion rate of the thruster's discharge channel, a back-sputter calculation was performed to determine the rate of carbon redeposition on the discharge channel downstream-facing edges (the area of the most concentrated ion bombardment erosion).

According to the literature, the erosion rate of the BN discharge channel under xenon-ion bombardment (ε_{Xe-BN}) is bounded by

$$\varepsilon_{Xe-BN} \leq \alpha R_C \left(\frac{\rho_C m_{BN}}{\rho_{BN} m_C} \right) \left(\frac{Y_{Xe-BN}}{Y_{Xe-C/BN}} \right) \approx 2 R_C \left(\frac{Y_{Xe-BN}}{Y_{Xe-C/BN}} \right) \quad (9)$$

where α is the sticking coefficient (assumed to be unity), R_C is the carbon backscatter rate, ρ_C is the mass density of carbon, m_{BN} is the particle mass of BN, ρ_{BN} is the mass density of BN, m_C 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. The sputter yield of carbon from the high energy beam dump was 7.2×10^{-2} atoms/ion, calculated using the methods for carbon material sputtering presented by Tartz and assuming perpendicular ion incidence to the beam dump [34]. The ion beam was assumed to strike the beam dump in a circular profile of radius 50 cm, calculated based on the beam divergence half-angle of 30° originating from the thruster channel's outer wall (the divergence half-angle calculation is shown in Section V.B.II below). An expected 4.7×10^{17} carbon atoms/s will be ejected from the beam dump, calculated by converting the measured ion current into number of ions incident on the dump per second and then multiplying by the sputter yield. A view factor was calculated from each of the discharge channel downstream edges' projected areas (two concentric annuli with thicknesses equal to that of the discharge channel walls) to the projected beam area, resulting in a view factor of 5.5×10^{-5} and 9.7×10^{-5} for the inner and outer edges, respectively. Multiplying these view factors by the number of carbon atoms ejected from the beam dump gives the total number of carbon atoms expected to be deposited on the channel's downstream edges, yielding 2.6×10^{13} atoms/s and 4.6×10^{14} atoms/s for the inner and outer edges, respectively. Assuming an average distance between the sputter-deposited carbon atoms' nuclei of 140 pm, the number of atoms required to yield a 1 μm thick layer on the inner and outer edges' projected areas are 5.6×10^{19} atoms/ μm and 9.7×10^{19} atoms/ μm , respectively. The product of the inverse of these values and the number of carbon atom deposited on the channel edges per second gives a total carbon deposition rate of approximately 1.7×10^{-3} $\mu\text{m/h}$ for both the inner and outer discharge channel edges.

Applying this result to Equation 9 gives a maximum channel erosion rate is approximately 3×10^{-2} $\mu\text{m/h}$ where the sputter yield ratio is conservatively assumed to be 10, as discussed in the literature [10]. Although the simplifying assumptions for these erosion rates yield a very large uncertainty, the reported values are approximately three orders of magnitude below common erosion rates of unshielded Hall thrusters [10,16,35]. Therefore, an error of several orders of magnitude in the calculated erosion rate still results in a significant improvement over unshielded Hall thrusters.

B. Performance

I. Theory

In addition to the useful life of the device (discussed above), the key figures of merit for the MaSMi Hall thruster are thrust, specific impulse, and efficiency. The thrust (T) is given by

$$T = \sum_i \dot{m}_i \langle v_i \rangle = \eta_b I_d \sqrt{\frac{2 M V_d \eta_v \eta_d}{e}} \sum_i \frac{f_i}{Z_i} \quad (10)$$

where $\dot{m}_i$ is the ion mass flow rate, $\langle v_i \rangle$ is the average ion velocity, V_d is the discharge voltage, η_v is the beam voltage utilization efficiency, η_d is the plume divergence efficiency, Z_i is the charge state of the i th ion species, and f_i is the current fraction of the i th species given by

$$f_i = \frac{I_i}{I_b} \quad (11)$$

where I_i is the current of the i th ion species (the efficiencies in Equation 10 are defined below). The correction term in Equation 10, which accounts for the presence of multiply charged species in the ion beam, can be calculated for any number of ion charge states as

$$\sum_i \frac{f_i}{Z_i} = \frac{I^+ + \frac{1}{2}I^{++} + \frac{1}{3}I^{+++} + \dots}{I_b} \quad (12)$$

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

The specific impulse (I_{sp}) is given by

$$I_{sp} = \frac{T}{\dot{m}_a g} = \frac{\eta_m}{g} \sqrt{\frac{2eV_d \eta_v \eta_d}{M}} \left(\frac{\sum_i \frac{f_i}{\sqrt{Z_i}}}{\sum_i \frac{f_i}{Z_i}} \right) \quad (13)$$

where $\dot{m}_a$ is the thruster anode mass flow rate, g is the acceleration of gravity at the Earth's surface, η_m is the mass utilization efficiency (defined below), and

$$\sum_i \frac{f_i}{\sqrt{Z_i}} = \frac{I^+ + \sqrt{\frac{1}{2}}I^{++} + \sqrt{\frac{1}{3}}I^{+++} + \dots}{I_b}. \quad (14)$$

The total efficiency (η_T) is the ratio of the jet power (P_{jet}) in the thruster exhaust to the total thruster input power:

$$\eta_T = \frac{P_{jet}}{P_T} = \left(\frac{T^2}{2\dot{m}_a P_d} \right) \left(\frac{P_d}{P_T} \right) \left(\frac{\dot{m}_a}{\dot{m}_T} \right) = \eta_a \eta_c \eta_o = \eta_{tc} \eta_o \quad (15)$$

where P_T is the total thruster input power (sum of the discharge, magnet, and keeper powers), $\dot{m}_T$ is the total propellant flow rate (sum of the anode and cathode flow rates), η_a is the anode efficiency, η_c is the cathode efficiency, η_o is the electrical utilization efficiency, and η_{tc} is an effective thruster efficiency consisting of the efficiency contributions of the thruster and cathode only. The anode efficiency can be broken into the product of five utilization efficiencies given by

$$\eta_a = \frac{T^2}{2\dot{m}_a P_d} = \eta_v \eta_b \eta_m \eta_d \eta_q \quad (16)$$

where the utilization efficiencies for the beam voltage, beam current, mass, plume divergence, and charge (η_q) are

$$\eta_v = \frac{V_b}{V_d}, \quad \eta_b = \frac{I_b}{I_d}, \quad \eta_m = \frac{\dot{m}_b}{\dot{m}_a} = \frac{M I_d}{\dot{m}_a e} \eta_b \sum_i \frac{f_i}{Z_i}, \quad \eta_d = (\cos \theta)^2, \quad \eta_q = \frac{\left(\sum_i \frac{f_i}{\sqrt{Z_i}} \right)^2}{\sum_i \frac{f_i}{Z_i}}. \quad (17)$$

In these equations, $\dot{m}_b$ is the beam propellant flow rate, and θ is the plume divergence half-angle. The cathode, electrical utilization, and effective thruster efficiencies are given as

$$\eta_c = \frac{\dot{m}_a}{\dot{m}_a + \dot{m}_c} = \frac{\dot{m}_a}{\dot{m}_T}, \quad \eta_o = \frac{P_d}{P_T} = \frac{V_d I_d}{V_d I_d + P_{mag} + P_k}, \quad \eta_{tc} = \eta_a \eta_c \quad (18)$$

where $\dot{m}_c$ is the cathode mass flow rate, P_{mag} is the magnet power, and P_k is the keeper power.

Due to the relatively high background pressures observed during thruster operation, a method for compensating for neutral gas entrained into the thruster channel was implemented [36]. The entrained mass flow ($\dot{m}_{en}$) is given by

$$\dot{m}_{en} = A_{en} \frac{n_n M}{4} \left(\frac{8kT_n}{\pi M} \right)^{1/2} = A_{en} P \left(\frac{M}{2\pi kT_n} \right)^{1/2} \quad (19)$$

where A_{en} is the entrainment area approximated as a hemisphere with a radius equal to the discharge channel outer diameter, T_n is the temperature of the background neutral particles, and P is the facility pressure. This entrained mass flow can then be converted to account for entrained discharge current (I_{en}) given by

$$I_{en} = \dot{m}_{en} \frac{e}{M} \quad (20)$$

where it is assumed that the neutral particles are singly ionized. These corrections can be applied to the measured discharge current and anode flow rate as

$$I_{d,true} = I_d - I_{en}, \quad \dot{m}_{a,true} = \dot{m}_a + \dot{m}_{en}. \quad (21)$$

where the subscript *true* represents the corrected value. The entrained mass correction for thrust (T) is given by

$$T_{true} = T \left(1 - \zeta_{en} \frac{\dot{m}_{en}}{\dot{m}_{a,true}} \right) \quad (22)$$

where ζ_{en} is the entrained mass utilization factor used to account for ingested neutrals that were ionized but that did not contribute to useful thrust. The value of the entrained mass utilization factor is 0.5 according to the literature [36]. The corrected specific impulse ($I_{sp,true}$) can then be calculated from Equation 13 using the corrected thrust (Equation 22) and the measured anode propellant flow rate because only the thrust term is dependent on the facility pressure. Using the corrected thrust and specific impulse, a corrected total efficiency ($\eta_{T,true}$) can be calculated using a modified form of Equation 15 given as

$$\eta_{T,true} = \left[\frac{g}{2} \left(\frac{I_{sp,true} T_{true}}{P_{T,true}} \right) \right] \eta_{o,true} \eta_{c,true} \quad (23)$$

where $P_{T,true}$, $\eta_{o,true}$, and $\eta_{c,true}$ are given by

$$P_{T,true} = V_d I_{d,true} + P_{mag} + P_k, \quad \eta_{o,true} = \frac{V_d I_{d,true}}{P_{T,true}}, \quad \eta_{c,true} = \frac{\dot{m}_{a,true}}{\dot{m}_{a,true} + \dot{m}_c}. \quad (24)$$

II. Planar Probe Results

The current density measured by the planar probe at both the 4.4 cm and 10.8 cm downstream locations as a function of the probe's lateral position from the thruster centerline is presented in Figure 12. Both the forward and return sweeps are shown for each axial distance to demonstrate repeatability of the measurement.

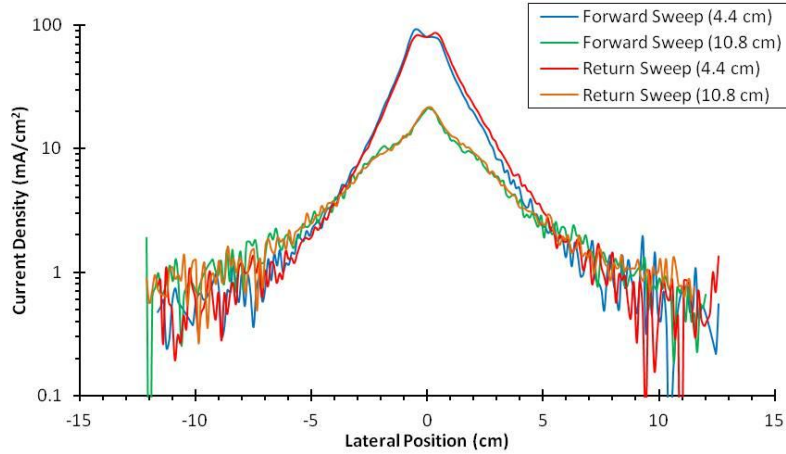


Figure 12. Current density as a function of the planar probe's lateral position from the thruster centerline, uncorrected for background charge exchange ion effects and measured for nominal MaSMi operating conditions at 4.4 cm and 10.8 cm downstream of the thruster face.

The ion current was determined from the 4.4 cm downstream planar probe trace because charge exchange effects are reduced near the thruster face (in this case, one discharge channel diameter downstream). However, a correction is still necessary to account for facility background charge exchange ion effects, which exist both in the wings of the probe trace as well as near the thruster centerline [10]. This was accomplished by first determining the average value of the ion current density from ± 7 cm to ± 12 cm laterally away from the thruster centerline (encompassing the wings of the trace), which was approximately 0.68 mA/cm^2 . This value was then subtracted from each ion current density measurement to account for effects of background charge exchange ions across the entire probe trace. The calculated ion current using this charge exchange correction was slightly more conservative than using an exponential curve generated for the data collected near the thruster axis and extended to the limits of the data collection range, which is an alternative method suggested in the literature [37]. The corrected ion current density as a function of the probe's lateral position for the thruster centerline is shown in Figure 13. Again, both the forward and return sweeps are presented to show measurement repeatability.

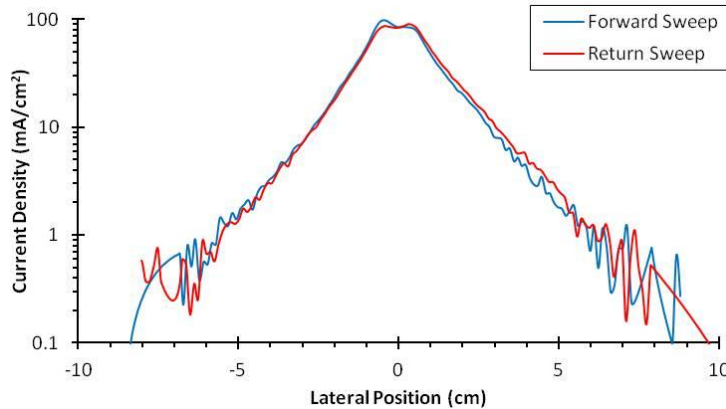


Figure 13. Current density as a function of the planar probe's lateral position from the thruster centerline, corrected for background charge exchange ion effects and measured for nominal MaSMi operating conditions at 4.4 cm downstream of the thruster face.

The ion current, calculated from Equation 8 and based on the current density measurement corrected for background charge exchange ion effects, was 1.04 A. Several methods were employed to determine the approximate uncertainty of this measurement. Sheath expansion effects were considered based on the studies of probe-plasma interactions by Sheridan; however, the results presented are applicable to a double-sided flat probe in a stationary plasma [38]. Because the ions in a Hall thruster discharge comprise a flowing plasma (on the order of 10^3 's of km/s) and the planar probe utilized was single-sided, it was assumed that sheath expansion effects were negligible. Additionally, the probe was observed to be cooler than the temperature required for significant electron current emission. The beam current utilization efficiency, calculated using Equation 17, was therefore found to be 88% with an uncertainty of approximately $\pm 2\%$ related to the planar probe measurement.

The plume divergence angle was approximated by determining the portion of the beam that contained 95% of the total current (corrected for charge exchange). A beam divergence half-angle of approximately 30° was observed, yielding a plume divergence efficiency of 75% (Equation 17) with an uncertainty of approximately +2%/-8% based on the planar probe measurement.

III. Retarding Potential Analyzer Results

The ion current collected from the RPA traces are presented in Figure 14; both the normalized ion current and its normalized derivative with respect to voltage are presented as functions of the ion discriminator grid bias for the nominal operation point of the MaSMi Hall thruster.

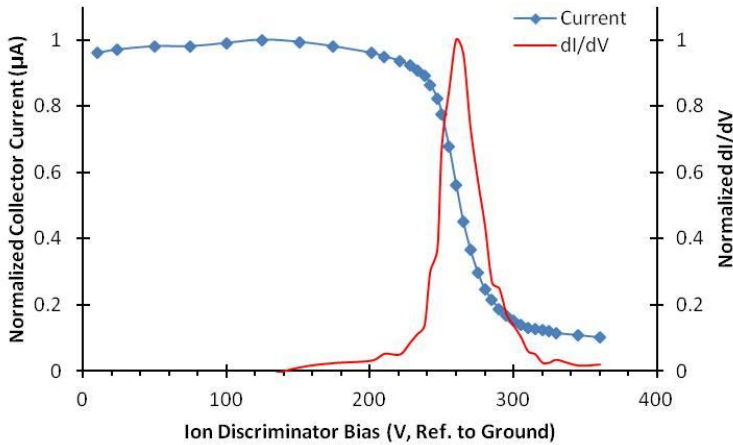


Figure 14. RPA scans of normalized ion current and its normalized derivative as functions of the ion discriminator grid potential for MaSMi's nominal operating condition.

The most probable ion potential measured directly from the RPA was approximately 261 V; however, this value must be corrected to account for the plasma potential at the RPA location (the RPA body was grounded during this test). The floating potential was measured from the RPA's plasma grid during each thruster test and values were approximately 1 V. Because an emissive probe was unavailable to directly measure the plasma potential at the RPA location, a series of assumptions were made to determine this value. First, a local electron temperature of 3 eV was assumed at the RPA location; this relatively high value was selected to maintain a conservative estimate of the plasma potential. Second, the plasma potential was approximated by equating the electron current with the fast (beam) and slow (charge exchange) ion currents local to the RPA, taking the form of

$$\frac{1}{4} n_e e A_{RPA} \sqrt{\frac{8kT_e}{\pi m}} e^{-\frac{e\Phi}{kT_e}} = e A_{RPA} \left(\frac{1}{2} n_{i,slow} \sqrt{\frac{kT_e}{M}} + n_{i,fast} \sqrt{\frac{2e\eta_v V_d}{M}} \right) \quad (25)$$

where A_{RPA} is the area of the RPA orifice, $n_{i,slow}$ is the slow ion density, and $n_{i,fast}$ is the fast ion density. The fast ion density near the RPA was approximated based on the plasma density calculated from the planar probe measurements taken at 4.4 cm and 10.8 cm downstream of the thruster and then extrapolated for a 30° plume expansion based on the ratio of the beam area at the two downstream locations. The centerline values of the plasma density were used for this calculation as the RPA was located axially downstream of the thruster. This resulted in a plasma density reduction factor of approximately $1.6 \times 10^{15} \text{ m}^{-3}$ divided by the beam area at a given downstream location, yielding a fast ion density of $2.4 \times 10^{15} \text{ m}^{-3}$ near the RPA. The slow ion density was calculated based on equating the rate of charge exchange ion production in the beam and the rate of ions lost from the beam traveling at the Bohm velocity. The resulting slow ion density was several orders of magnitude smaller than the fast ion density and was neglected, which allowed for the assumption of quasineutrality ($n_e \approx n_{i,fast}$). The voltage utilization efficiency was initially guessed and then iterated on simultaneously with the plasma potential, Φ (note that Equation 25 is a function of both the plasma potential and the voltage utilization efficiency). The result was a calculated plasma potential of 8 V, or roughly $3T_e$, above the local floating potential. Subtracting the calculated plasma potential from the RPA-measured ion energy results in a most probable ion potential of 252 V; an approximate uncertainty of the plasma potential of $2T_e$ (6 V) was assumed. Applying these values to Equation 17, a voltage utilization efficiency of 92% is achieved with an uncertainty of approximately +/-3%.

IV. Efficiency, Thrust, and Specific Impulse

To calculate MaSMi's total efficiency, the ion beam composition must be assumed (recall that **ExB** probe measurements were unavailable at the time of testing). Conventionally unshielded miniature Hall thrusters of the same scale as MaSMi generate favorable ion species mixes. The BHT-200-X3, for example, produces approximately 95.5% singly charged, 3.7% doubly charged, and 0.8% triply charged ions [39]. By contrast, the H6MS Hall thruster generates a species mix of 57.5% singly, 25.9% doubly, and 16.6% triply and quadruply charged ions [10]. In an effort to maintain conservative results, MaSMi's beam was assumed to be composed of three ion charge states and that the species mix was equal to that produced by the H6MS.

Using the H6MS species mix, the mass utilization efficiency was calculated using Equation 17. This resulted in a mass utilization efficiency of 102% with an assumed uncertainty of +0/-10%. The mass utilization efficiency was calculated to be greater than 100% due to uncertainty in the ion current probe measurement and the ion species fractions. The cathode efficiency, calculated as a ratio of the corrected anode flow rate and total propellant flow rate, was approximately 91% with an uncertainty of less than +/-1% as reported by the flow controller manufacturer.

MaSMi's electrical utilization efficiency was calculated based on the power supply readings during stable operation. Nominal operation of the thruster occurred at 275 V with a discharge power of 325 W. The hollow cathode keeper, which was left on during all testing to avoid having to restart the cathode heater if the anode discharge went out, was current controlled at 2 A with a power of 40 W. The inner and outer magnet coils operated at 5.2 A and 1.5 A, respectively, for a combined power of 29 W. Summing these values, MaSMi's total power was 394 W with an electrical efficiency of 83%. This value has an uncertainty of less than +/-1% as reported by the power supply manufacturers.

A summary of MaSMi's total efficiency, including each contributing term from Equation 16, is presented in Table 1. The MaSMi Hall thruster demonstrated a calculated total efficiency of approximately 44% with an uncertainty of +5%/-15%. This corresponds to a thrust of approximately 20 mN at a specific impulse of approximately 1940 s. MaSMi's anode efficiency was approximately 59% with an uncertainty of +6%/-19% while the thruster efficiency (thruster and cathode contributions) was approximately 54% with an uncertainty of +6%/-18%. A summary of the three measures of MaSMi's calculated efficiency is presented in Table 2. It should be noted that while the calculated thrust matches very well with the pre-fabrication scaling model's prediction (Section III.A), a significant difference was observed in the predicted and measured specific impulse likely due to the high multiply charged ion content of the beam not considered in the scaling model.

Table 1. Summary of the MaSMi Hall thruster's efficiency and associated uncertainty.

	Efficiency	Uncertainty
η_b	88%	+2%/-8%
η_v	92%	+/- 3%
η_m	102%	+0%/-10%
η_d	75%	+2%/-8%
η_q	96%	+2%/-8%
η_c	91%	+/- 1%
η_o	83%	+/- 1%
η_T	44%	+5% / -15%

Table 2. Summary of the MaSMi Hall thruster's anode, thruster (thruster and cathode contributions), and total efficiency with associated uncertainty.

	Efficiency	Uncertainty
η_a	59%	+6%/-19%
η_{tc}	54%	+6%/-18%
η_T	44%	+5%/-15%

The above values represent the performance of the thruster without considering the presence of entrained background neutrals and must therefore be corrected. An entrained mass flow of approximately 8.2×10^{-8} kg/s was calculated using Equation 19, yielding an entrained current of approximately 60 mA (Equation 20), or 5% of the discharge current. The thrust correction (Equation 22) applied to the calculated thrust yields a true thrust of approximately 19 mN, corresponding to a specific impulse of approximately 1870 s. Applying these values to Equation 23 give a true (or vacuum) total efficiency of 43%. If the total efficiency is calculated using a common beam composition for miniature Hall thrusters (the BHT-200, for example) instead of the more conservative H6MS species mix, the true total efficiency increases significantly.

The total efficiency changed by approximately 1% with the application of the background neutral correction due to the calculated entrained mass flow, which is two orders of magnitude smaller than the measured anode mass flow. Additionally, assuming a +/-20% uncertainty in the facility pressure (used to calculate the entrained mass flow) resulted in a change of significantly less than +/-1% uncertainty in the thruster's true total efficiency. A summary of the thrust, and specific impulse, and efficiency of the MaSMi Hall thruster both with and without the background neutral correction is presented in Table 3.

Table 3. Estimates of the MaSMi Hall thruster's thrust, specific impulse, and total efficiency before and after accounting for facility background neutrals.

	Uncorrected	True	Δ
T (mN)	20	19	5%
I_{sp} (s)	1940	1870	4%
η_T (%)	44	43	2%

VI. Future Work

Further investigations of MaSMi's performance will be conducted at the UCLA Microthruster Test Facility. A key addition to the facility will be an ExB analyzer to measure the ion species mix; this diagnostic is currently under construction. Other diagnostics to be installed are a Faraday probe, a Langmuir probe, and an emissive probe to gather more accurate plume data. The MaSMi Hall thruster's magnetic circuit design will be examined and modified in an effort to improve the weaker magnetic shielding of the inner discharge channel wall and achieve a completely shielded magnetic field topography. The results from the UCLA Microthruster Test Facility will be validated by operating the thruster on a thrust stand at JPL. Sputter-erosion measurements made using diagnostics available at JPL to assess the life and thermal stability of the thruster design are also under consideration.

VII. Conclusion

A 4 cm Hall thruster was developed and tested to demonstrate that the application of magnetic shielding is possible on a miniature scale. The results showed that MaSMi achieved improved performance values and efficiencies compared to conventionally unshielded Hall thruster of the same scale while also dramatically improving the projected operational lifetime. The miniature magnetically shielded Hall thruster showed strong

shielding of the outer discharge channel wall while the inner channel wall appeared to be weakly shielded. The erosion rate of the shielded discharge channel walls based on carbon redeposition calculations was estimated to be three orders of magnitude less than the measured erosion rates of unshielded Hall thrusters, suggesting a dramatic reduction in ion bombardment erosion and a significant increase in operational lifetime. The total efficiency of the device, accounting for the presence of background neutrals and charge exchange ions, was 43%, corresponding to a thrust of 19 mN and a specific impulse of 1870 s. While testing on a thrust stand is necessary to validate these performance figures, the concept of magnetic shielding was successfully demonstrated on a miniature scale.

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