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Magnetically Shielded Miniature Hall Thruster: Performance Assessment and Status Update

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The magnetically shielded miniature Hall thruster, originally tested at the University of California, Los Angeles, underwent performance validation experiments at the Jet Propulsion Laboratory. The thruster was operated over a range of discharge voltages, from 150 V – 300V, and currents, from 1 A – 2.3 A. It was discovered that the thruster operated in two distinct modes which were dependent on the thruster's temperature: a "jet" mode and a "diffuse" mode. At the nominal condition of 275 V and 1.2 A in the jet mode, a thrust of approximately 12 – 13 mN was measured by a thrust stand with an anode efficiency of approximately24%. At the same nominal conditions, the diffuse mode showed a thrust of 11 – 12 mN and an anode efficiency of approximately 21%. Characterization of the plume in both operating modes was accomplished using a shielded Faraday probe, a retarding potential analyzer, and an ExB probe. Discharge current oscillations on the order of 2.5 – 4 times the mean current were observed during jet mode operation, while the oscillations in the diffuse mode were on the order of 20% of the mean current. Results from the plume characterization, post-operation discharge channel inspection, and discharge oscillations, combined with the temperature-dependent mode shift, suggest that changes to the magnetic field strength and topology caused by saturation of the thruster's magnetic circuit may be occurring at elevated operating temperatures.

I. INTRODUCTION

A low-power Hall thruster demonstrating high efficiency and a long operational lifetime is an attractive prospect for NASA mission and spacecraft designers. A variety of 3 cm-scale Hall thrusters, such as the BHT-200 and the SPT-30, are commercially available. These thrusters deliver strong thrust and specific impulse performance (>10 mN and > 1100 s, respectively) at anode efficiencies of more than 30% [1–6]. However, they demonstrate a useful lifetime of less than approximately 1000 h, which is insufficient if these devices are to be used as the primary propulsion system for deep space missions [5,6]. In general, low-power Hall thrusters (<500 W and <7 cm dia.) suffer from rapid erosion and electron heating of the discharge channel walls caused by plasma-wall interactions enhanced by miniature thrusters' inherently larger surface-to-volume ratios. These effects yield poor life and low efficiency, ultimately limiting the utility of miniature Hall thrusters. In high-power Hall thrusters (>4 kW), life-limiting issues involving channel erosion, electron heating, and plasma-wall interactions are significantly reduced, if not eliminated, by the use of a magnetically shielded field topology. Magnetic shielding is achieved through a unique field topology that exploits two key features of Hall thrusters: magnetic field line isothermality and magnetic-force-line equipotentialization [7]. The field lines passing nearest to (but not intersecting) the channel walls confine cold electrons captured in the anode region (isothermality); holding these cold electrons near the

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channel surfaces reduces the plasma sheath potential drop near the walls and maintains a plasma potential close to the discharge voltage across the channel (equipotentialization). These effects combine to achieve significantly reduced ion-bombardment erosion of and electron power deposition to the channel walls, thereby increasing the thruster's useful life. The concept of magnetic shielding has been successfully applied to multiple Hall thrusters and is well understood [7–10]. In an effort to fill the technology gap between high- and low-power Hall thrusters with respect to both operational life and performance, the *Ma*gnetically *S*hielded *Mi*niature (MaSMi) Hall thruster was developed [11,12]. The MaSMi Hall thruster was designed to operate between 300 W and 400 W, employs a discharge channel with a 4.4 cm outer diameter and the capability of variable anode placement (10 – 16 mm channel length), and a magnetically shielded field topology. Further specifics on the design of the thruster can be found in the literature [11,12].

This investigation aims to further test the MaSMi Hall thruster in an effort to validate the thruster's previously calculated performance. A review of the published performance results calculated for the MaSMi thruster, including a brief description of the test facility and plasma diagnostics, is presented in Section II. The new experimental facility used for validation of MaSMi's performance is discussed in Section III. Results from this stage of the investigation are presented in Section IV, followed by a discussion and analysis of the results in Section V. Concluding remarks are made in Section VI with a brief Future Work discussion in Section VII.

II. PREVIOUS WORK

The results from the first stages of this investigation can be found in two previous papers [11,12]. Initial performance testing of the MaSMi Hall thruster was carried out at the Electric Propulsion Test Facility in the Plasma and Space Propulsion Laboratory at UCLA. The facility employs a cylindrical chamber measuring 2.8 m long and 1.8 m in diameter fitted with two CTI CryoTorr 10 pumps capable of a combined pumping speed of 1300 l/s. The nitrogen base pressure of the facility was approximately $5x10^{-7}$ torr; operation of the thruster at a total propellant flow rate of approximately 12 sccm yielded a background pressure of approximately $7x10^{-5}$ torr, corrected for xenon. A scanning planar probe and a retarding potential analyzer (RPA) were used to characterize the plasma discharge. A carbon-felt high-energy beam dump was mounted 80 cm downstream of the thruster. The thruster was coupled to a BaO-W cathode with its orifice mounted approximately 10 mm above the thruster centerline at a 22.5° angle relative to the thruster axis. A thermal radiator was mounted over the thruster to aid in power dissipation. During all initial testing, the thruster was operated at a discharge voltage of 275 V and a discharge power of 325 W.

Visual analysis of the plume near the discharge channel downstream edges showed a noticeable offset of the plasma from the channel walls, suggested that MaSMi achieved a magnetically shielded field topology [13]. After operation, the outer wall of the discharge channel was coated in a thick layer of carbon while the inner wall had a lighter dusting of carbon. The presence of carbon on the discharge channel walls post-operation offered further evidence of magnetic shielding (albeit weaker on the inner wall) [13]. Operational temperatures of approximately 450°C, measured at the upstream face of the discharge channel and the downstream face of the outer pole piece, were observed throughout the initial testing period. Scanning planar probe measurements recorded a beam current of 1.04 A and a plume divergence half-angle (capturing 95% of the beam current) of 30°; probe sheath expansion effects were assumed to be negligible for these measurements. A most probable ion potential of 252 V was measured by the RPA. Using an assumed beam species mix based on the H6MS Hall thruster and correcting for ingestion of background neutrals, the MaSMi Hall thruster produced a calculated thrust of 19 mN at a calculated specific impulse of 1870 s with a total efficiency of 43% [11–13]. It is important to note that these were *calculated* performance values based on limited plasma diagnostics and operation at relatively high background pressures.

III. EXPERIMENTAL CONFIGURATION

A. Vacuum Facility and Supporting Equipment

Validation experiments were conducted at the High-Bay vacuum facility at the NASA Jet Propulsion Laboratory. The High-Bay facility consists of a cylindrical vacuum chamber measuring 2.6 m in diameter and 5.2 m long. All internal surfaces of the chamber with line-of-sight to the thruster's discharge channel are covered with either graphite panels or carbon material. Three cryogenic pumps are operated in parallel for a combined xenon pumping speed of over 48,000 l/s. The chamber pressure is monitored by two ionization gauges, both calibrated for xenon. The first gauge is located on the thruster exit plane approximately 1 m from the thruster and is used as the primary indication of chamber pressure. The second gauge, used to confirm pressure readings from the first gauge, is mounted along the chamber wall just downstream of the thruster exit plane. For these experiments, the base pressure of the system was less than $7x10^{-8}$ torr. During operation with xenon flow of 10 – 15 sccm, the chamber pressure remains in the low-mid 10^{-6} torr range. A xenon flow bypass, regulated by a hand-operated needle valve, is incorporated into the flow system (flow outlet located approximately 2 m downstream of and oriented away from thruster face) to increase the facility background pressure if desired.

Commercially available power supplies and propellant flow controllers were used for all experiments. Thruster discharge, cathode heater, and cathode keeper power was supplied by Sorensen DLM-series power supplies while the coil magnets were powered by Power Ten supplies. Research grade xenon was supplied to the thruster and cathode by Apex 20 sccm and 5 sccm mass flow controllers, respectively, via stainless steel lines. Both controllers were calibrated prior to testing and were digitally controlled to an accuracy of ± 1% of the set point. A BaO-W cathode (used during the initial testing phase)based on the ISS plasma contactor cathode and NSTAR ion thruster cathode was utilized for this investigation. As before, the cathode was mounted at a 22.5° angle with respect to the thruster axis with the cathode orifice approximately 45 mm above the thruster centerline.

B. Diagnostics

The JPL High-Bay vacuum facility employs a variety of thruster and plasma diagnostics. No invasive probe measurements were taken due to the strong likelihood of significant plasma perturbation inside MaSMi's small discharge channel.

1) Thrust Measurements: A water-cooled inverted-pendulum thrust stand was used to directly measure the thrust of the MaSMi Hall thruster. Displacement of the thrust stand pendulum due to an applied thrust is converted to a digital signal via a linear variable differential transformer (LVDT). This signal is passed through a feedback-based damping control system which eliminates any AC component of the pendulum displacement caused by plasma oscillations, cryogenic pump operation vibrations, external facility vibrations, etc., maintaining that only the DC component of thrust is reported by the LVDT.A force-to-displacement calibration of the thrust stand was performed prior to each test and the thrust stand demonstrated a minimum thrust resolution of approximately 0.1 mN. Because the thrust stand is optimized for >1kW Hall thrusters, a large uncertainty is associated with the thrust stand measurements; efforts are currently underway to quantify this uncertainty.

2) Plasma Discharge Measurements: Several diagnostics were used to characterize MaSMi's plasma beam. Ion current measurements were taken using a 24 mm outer diameter cylindrical graphite Faraday probe with a collector diameter of 19 mm. The probe was biased to -28 V and swept ± 35 cm laterally across the plasma discharge at 8.8, 15, and 37 cm downstream of the thruster exit plane using LinTech probe stages driven by Vexta stepper motors. A five-grid RPA (plasma grid, electron suppressor, ion double-grid discriminator, and secondary electron suppressor) with a 19 mm orifice provided most probable ion potential measurements. The two electron suppression grids were biased to -28 V while the ion double-discriminator voltage was swept from 0 V to 400 V with a Kepco power supply. The RPA was mounted on a rotary stage 2 m downstream of the thruster. A custom-built **E**x**B** probe placed approximately 45 cm downstream of the thruster (only when beam composition measurements were recorded) was used to measure the ion species mix in MaSMi's plasma beam. A current probe on the thruster's anode power cable was fed to a Tektronix oscilloscope to provide information about discharge fluctuations.

IV. RESULTS

Experiments were conducted with the MaSMi Hall thruster at various operating conditions ranging from 150 – 300V at 1 – 2.3 A, focusing primarily on the nominal condition of 275 V and 1.2 A.A cathode coupling voltage of approximately -9 V ± 2 V was observed for all tests. A keeper current of 2 A was applied during most of this investigation's experiments to maintain the high cathode temperature; removal of the keeper current yielded slightly higher discharge currents but no notable change to the thruster's performance parameters. During testing, two distinct operating modes were observed that were directly related to the thruster's operating temperature. The shift from a low-temperature "jet" mode to a high-temperature "diffuse" mode occurred consistently at a thruster temperature of approximately 370 – 390°C. Once the thruster entered the diffuse mode, it was impossible to revert to the jet mode without a full shut-down and cool-down of the device. Temperature measurements were taken with K-type thermocouples located at 11 locations on and around the thruster and thrust stand, including the front pole piece, the thruster body, and the thrust stand pendulum. No temperature measurements were taken on the discharge channel. A custom thermal radiator fitted around the thruster was used for a portion of this investigation to ensure lower operating temperatures. With the radiator, MaSMi's stable operating temperature was approximately 275 – 300°C; without the radiator, temperatures increased to over400°C. The water-cooled thrust stand temperature remained stable at approximately 22°Cthroughout all testing.

It should be noted that the MaSMi Hall thruster was operated with both an elongated (16 mm) and shortened (10 mm) discharge channel during this investigation. This modification was made in an effort to reduce the unfavorable oscillations observed during operation in the low-temperature jet mode by reducing the transit distance of neutral particles from the anode to the ionization region (discussed in Section V.B.1). However, the performance of the thruster (thrust, efficiency, oscillations, etc.) in these two discharge channel configurations was nearly identical (less than 5% difference).

A. Jet Mode Performance

An image of the thruster plume operating in the low-temperature jet mode is shown in Figure 1. This operating mode is visually characterized by the presence of a plasma spike extending approximately 10 – 15 cm along the thruster centerline and a region of high luminosity just downstream of the thruster exit. As seen in the previous experiments conducted at UCLA, the plasma appeared to be offset from the outer channel wall, suggesting the presence of a magnetically shielded field topology [8,11–13].

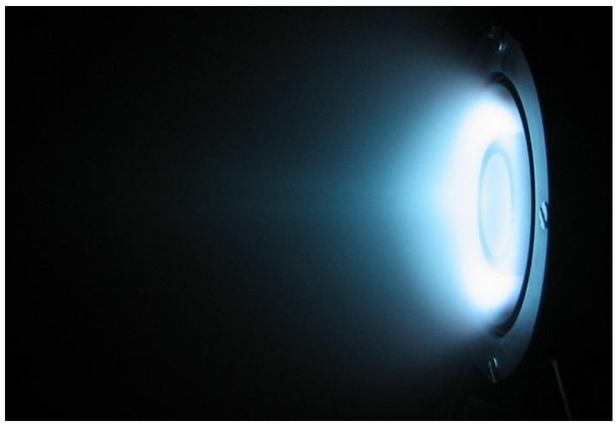

Figure 1. MaSMi's plasma discharge while operating at 275 V and 1.2 A in the low-temperature jet mode.

At the nominal operating condition of 1.2 A, a thrust of approximately 12 – 13 mN was recorded by the thrust stand. A maximum thrust of over 20 mN was observed at a discharge current of 2.3 A. At the nominal condition, the xenon flow to the anode was 12 sccm while the cathode flow was 1 sccm. The scanning Faraday probe measured an ion current of 0.82 A, corrected for charge exchange collisions using the theory presented in [14]. A beam divergence half angle of approximately 43°, containing approximately 95% of the momentum-weighted ion current, was observed [15]. Figure 2 shows the uncorrected and corrected traces of the Faraday probe scan. A most probable ion potential of approximately 250 V was reported by the RPA. MaSMi's plasma discharge was composed of approximately64.8% singly, 24.4% doubly, and 10.8% triply charged ions, as can be seen from the Gaussian fits to the **E**x**B** probe trace shown in Figure 4. The shape of the Gaussian fits are consistent with the wide thermal distribution of the ions in the plasma suggested by the derivative of the RPA traces, and are therefore valid fits for the **E**x**B** data. Using the theory presented in [11,12], these performance values correspond to a voltage utilization efficiency of 88.3%, a current utilization efficiency of 68.3%,a divergence efficiency of 53.5%, a charge utilization efficiency of 96.7%, and a mass utilization efficiency of 76.3%, multiplying to an anode efficiency of 23.8%. This agrees well with the 22% anode efficiency suggested by the thrust stand measurements.

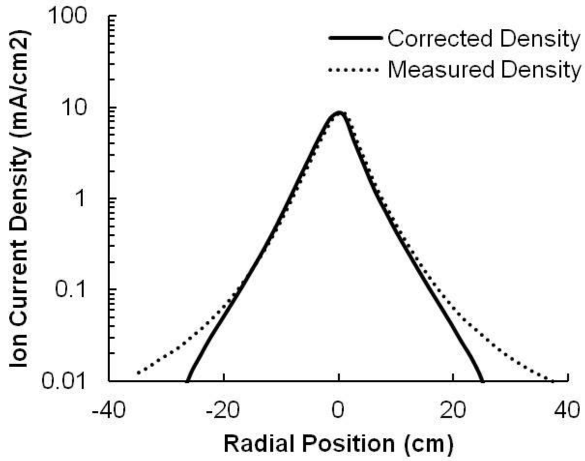

Figure 2. Ion current density as a function of Faraday probe lateral position from thruster centerline for MaSMi operating at nominal conditions in the low-temperature jet mode. Traces for the unaltered measurement data and the data corrected for background charge-exchange collisions are shown.

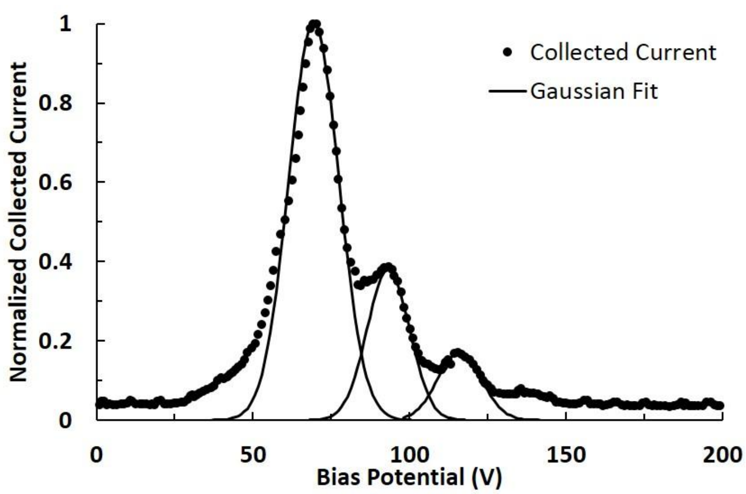

Figure 3. Normalized ExB probe current scan showing MaSMi's beam composition during operation at nominal conditions in the low-temperature jet mode. Gaussian fits are used to identify each ion species

B. Diffuse Mode Performance

A photograph of the thruster plume operating in the high-temperature diffuse mode is shown in Figure 4. This operating mode shows no plasma spike extending along the thruster centerline and significantly less luminosity of the plasma downstream of the thruster exit, instead having a more diffuse appearance. Like the jet mode, operation in the diffuse mode also showed a noticeable offset of the plasma from the outer discharge channel wall, suggesting the presence of magnetic shielding in this region [8,11–13]. Additionally, the anode was considerably brighter (increased visual radiation intensity) after thruster shutdown when compared to the jet mode, suggesting elevated anode temperatures.

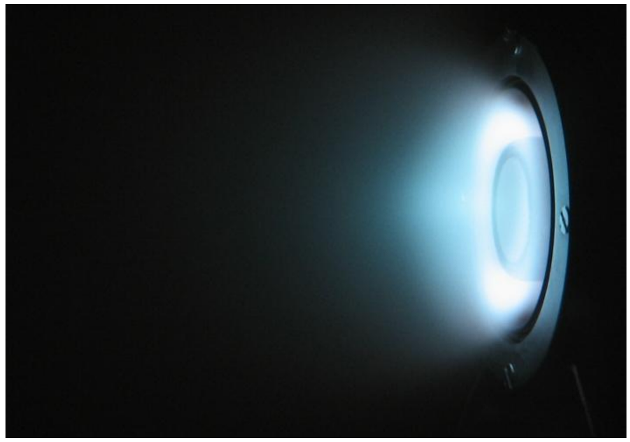

Figure 4. MaSMi's plasma discharge while operating at 275 V and 1.2 A in the high-temperature diffuse mode.

Thrust measurements taken at the nominal conditions were between 11 – 12 mN. Xenon mass flow rates were identical to operation in jet mode: 12 sccm to the anode and 1 sccm to the cathode. The ion current reported by the scanning Faraday probe was 0.80 A, corrected for charge exchange collisions, with a divergence half angle of approximately 48° containing approximately 95% of the momentum-weighted ion current; the uncorrected and corrected scans for this operating mode are shown in Figure 5 [14,15]. The RPA recorded a most probable ion potential of 261 V. As shown in Figure 6, a beam species mix of approximately73.6% singly, 19.0% doubly, and 7.4% triply charged ions was measured by the **E**x**B** probe, again using Gaussian fits to the data. Applying the theory presented in [11,12],the voltage utilization efficiency was 92.2%, the current utilization efficiency was 66.7%, the divergence efficiency was 44.8%, the charge utilization efficiency was 97.4%, and the mass utilization efficiency was 79.1%. This yields a calculated anode efficiency of 21.2% which matches the 19% anode efficiency suggested by the thrust stand measurements.

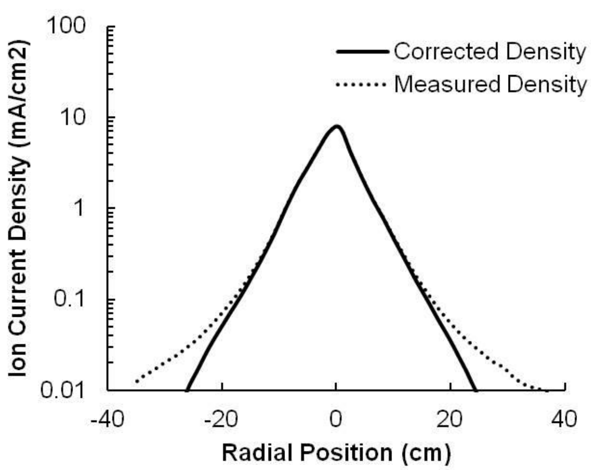

Figure 5. Ion current density as a function of Faraday probe lateral position from thruster centerline for MaSMi operating at nominal conditions in the high-temperature diffuse mode. Traces for the unaltered measurement data and the data corrected for background charge-exchange collisions are shown.

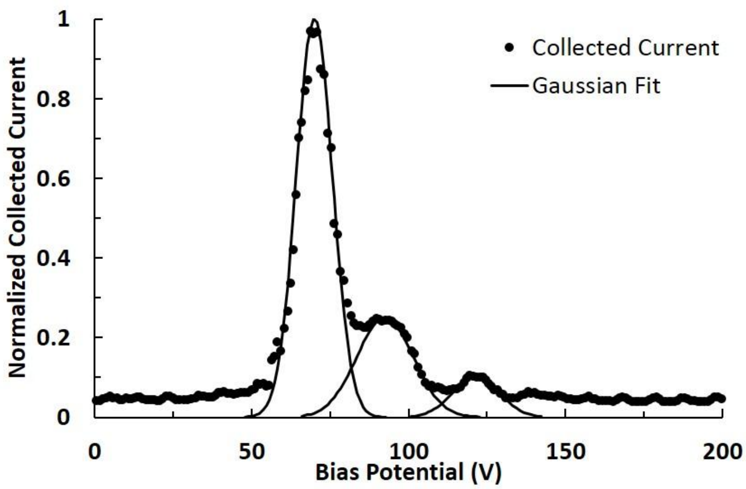

Figure 6. Normalized ExB probe current scan showing MaSMi's ion species mix during operation at nominal conditions in the high-temperature diffuse mode with Gaussian fits to each charge species.

V. DISCUSSION

A. Magnetic Shielding

The effectiveness of the magnetically shielded field topology was assessed based on visual observations of the near-exit plasma discharge during thruster operation and an inspection of the discharge channel after operation. During operation in both the jet and diffuse modes, a high-density plasma region in the shape of a torus formed just downstream of the discharge channel exit. This plasma was clearly offset from the outer discharge channel wall, which suggests strong magnetic shielding. It is worth noting that the gap between the plasma torus and outer channel wall appeared to be greater in the diffuse mode than in the jet mode. However, the plasma appeared to be coming close to, if not contacting, the inner wall. This can be seen from Figures 1 and 4.The buildup of carbon on the discharge channel walls of a Hall thruster suggests reduced erosion;"cleaning" of the channel surfaces is due to ion-bombardment, indicating the lack of a magnetically shielded field topology [8,11,12]. Inspection of MaSMi's discharge channel after operation in either mode showed a thick layer of carbon deposited along the full length of the outer wall. After operating MaSMi in the jet mode, a heavy coating of carbon was found on the majority of the inner channel wall with the exception of the downstream tip, which was noticeably cleaner (although still having a dusting of carbon). By contrast, the inner wall was significantly cleaner after operation in the diffuse mode, suggesting an increase in plasma-wall interactions (especially ion-bombardment erosion). A photograph comparing the discharge channel after operation in the two modes is shown in Figure 7.

Figure 7. Comparison of MaSMi's discharge channel after operation in the jet mode (left) and the diffuse mode (right), showing a significant reduction in carbon deposition along the inner channel wall.

These observations match those made during the UCLA experiments and are consistent with the previous conclusion: saturation of MaSMi's inner magnetic circuit (especially at elevated operating temperatures) reduces the circuit's ability to maintain the high magnetic flux required for full shielding of the inner channel wall. The magnetically shielded field topology appears to become partially compromised in this region, enabling greater plasma-wall interactions (erosion, electron heating, etc.) on the discharge channel's inner wall.

B. Plume Characterization

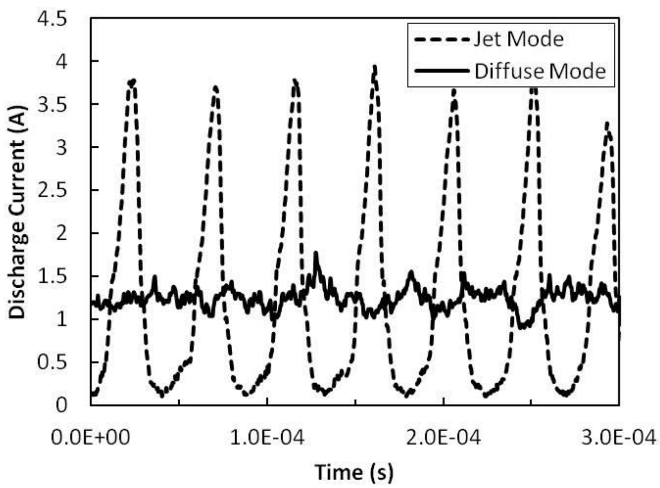

Figure 8. Comparison of the discharge current oscillations measured during operation of the MaSMi Hall thruster in the low-temperature jet mode and the high-temperature diffuse mode.

1) Discharge Current Oscillations: A comparison of MaSMi's performance metrics while operating in the two observed modes reveals that the thruster's overall thrust and efficiency is largely unchanged, slightly favoring the jet mode. In an effort to qualify the different plasma behaviors in each operating mode, discharge current oscillations were recorded. Figure 8 presents a comparison of the oscillations recorded for the jet and diffuse operating modes. The jet mode exhibited highly oscillatory behavior consistent with a deep breathing mode. For the nominal 1.2 A discharge with a 2 A applied keeper current, fluctuations in the current had a peak-to-peak value of approximately 3 – 4 A (2.5 – 3.5 times the mean current) with a frequency of 19 – 22 kHz. The trough of each cycle reached less than 10% of the mean current, suggesting that the thruster effectively enters a temporary "off" state; operation at under 33% of the mean discharge current persisted for more than 30% of the total oscillation cycle. When the keeper current was removed, the current oscillations increased (approximately 3 – 4 times the mean current), demonstrating that an applied keeper current had a minor stabilizing effect on the discharge. By contrast, the diffuse mode exhibited minor, randomized discharge current oscillations which remained within approximately 20% of the mean. As with the jet mode, the oscillations in the diffuse mode increased slightly (to approximately 25 – 30 % of the mean current) when the keeper current was removed.

The onset of the diffuse mode in the MaSMi Hall thruster was directly related to the thruster operating temperature. A similar trend was observed by Azziz when testing a BHT-1500 [16]. Before the BHT-1500 reached thermal equilibrium, only a "jet" mode was observed and was insensitive to changes in the applied magnetic field strength. This mode was visually characterized by a large plasma spike; deep breathing mode oscillations of approximately 100% of the mean discharge current at a frequency of 20 – 30 kHz were also observed. After thermal equilibrium was reached, however, the thruster could be operated in a "collimated" mode by reducing the magnetic field strength across the channel, yielding a wide, more diffuse plasma beam without a plasma spike. A reduction in thrust performance by approximately 5% and minimal discharge current oscillations of approximately 35% of the mean were reported. Analysis of the thruster's performance in these two modes suggested that changes in the magnetic field strength and topology (a result of reduced permeability of the thruster's magnetic circuit due to higher operating temperatures) may be forcing the ionization region upstream of its nominal position. This conclusion was further supported by discharge channel temperature measurements, where higher temperatures (suggesting increased plasma-wall interactions and plasma heating) were reported in the collimated mode.

Experiments with the BHT-1500 suggest that the strength and shape of a Hall thruster's applied magnetic field, which is affected (and sometimes limited) by the temperature of the thruster's magnetic circuit, has a the ability to change the operating mode of a Hall thruster. Similar to the BHT-1500, MaSMi entered a new operating mode (the diffuse mode) once a sufficient operating temperature was reached. This is consistent with the reduction in magnetic permeability (i.e. saturation) of MaSMi's inner magnetic circuit, where changes to the applied magnet coil currents cannot manifest proportional and consistent changes in magnetic flux due to material limitations. Additionally, MaSMi could not be reverted to the jet mode by changing the applied magnetic coil currents; a complete shut-down of the thruster followed by a 2- 3 h cool-down period was necessary to reestablish jet mode operation. This suggests that the level of saturation in MaSMi's magnetic circuit during nominal jet mode operation is greater than that of the BHT-1500, preventing a mode shift induced by changes to the magnetic field strength at high operating temperatures. Reducing the observed discharge current oscillations in MaSMi's jet mode and preventing the shift into the diffuse mode is a complex problem and is presently under further investigation.

2) Magnetic Field Induced Plasma Behaviors: Evidence of changes to MaSMi's magnetic field strength and topology at high operating temperatures can be seen from the Faraday probe data. For example, operation in diffuse mode yielded a10.4% increase in divergence half-angle and a10% reduction in centerline peak ion current. Assuming the cause of MaSMi's diffuse operating mode is similar to the BHT-1500's collimated mode (an upstream shift in the ionization region due to changes in magnetic field structure and strength), the most likely region for significant changes to MaSMi's field structure is near the inner wall where saturation is a known issue; the outer magnetic circuit appears to be free of saturation. Therefore, an upstream shift in the ionization region would likely be asymmetric across the channel, penetrating more deeply along the inner channel wall and skewing the field's lensing effect.

A notable change in beam composition was observed in MaSMi's two operating modes, as seen by the **E**x**B** data above. Operation in the jet mode yielded an ion species mix with high concentrations of doubly and triply charged ions relative to the singly charged ion population. These findings are consistent with published data on magnetically shielded Hall thrusters, suggesting that the thruster had achieved a magnetically shielded field configuration [13]. However, the species mix was significantly more biased towards singly charged particles when operating in the diffuse mode (approximately 9% more singly charged ion current). These data are more consistent with conventional miniature Hall thruster beam compositions, where the singly charged ion current is a larger portion of the total beam current compared to magnetically shielded thrusters [17]. These observations offer further evidence that saturation of MaSMi's inner magnetic core at high-temperatures causes the thruster's field topology to change: the ionization region appears to shift upstream and closer to the inner channel wall while the overall magnetic field structure in this region more closely resembles that of a conventional Hall thruster. The behaviors observed in the diffuse mode, which suggest increased plasma-wall interactions inherent to an unshielded magnetic field structure, indicate that MaSMi's shielded field topology may be compromised in this operating mode.

The proposed change from MaSMi's shielded jet mode field topology to the asymmetric, unshielded diffuse mode topology can be analyzed using Hall2De, a two-dimensional computational solver for the governing conservation equations of the partially ionized gases in Hall thrusters [7,18].Results for the electron temperature profiles (which follow the magnetic field topology) for the short discharge channel thruster configuration are shown in Figure 9; values are normalized to the same temperature for both plots. The jet mode simulation is based on magnetic field measurements taken before thruster operation. The diffuse mode simulation is an assumed field structure consistent with the above thruster behavior, plume observations, and carbon deposition patterns on the discharge channel walls: the plasma appeared to be contacting the inner channel wall while improved shielding was observed in the outer channel wall region. In the diffuse mode model, the magnetic lines of force near the outer wall penetrate deep into the channel towards the anode; however, instead of turning around and reconnecting to the inner pole piece as is expected in a magnetically shielded Hall thruster, many of these field lines terminate on the inner channel wall. This may enable facilitated electron transport across the discharge channel, which would lead to electron streaming to the anode. This offers a possible explanation for the increased anode temperatures seen after operation in the diffuse mode. Additionally, a lower concentration of high-temperature electrons appear to be confined to the ionization region in the diffuse mode, suggesting increased plasma-wall interactions likely resulting in electron heating (and loss) to the inner wall.

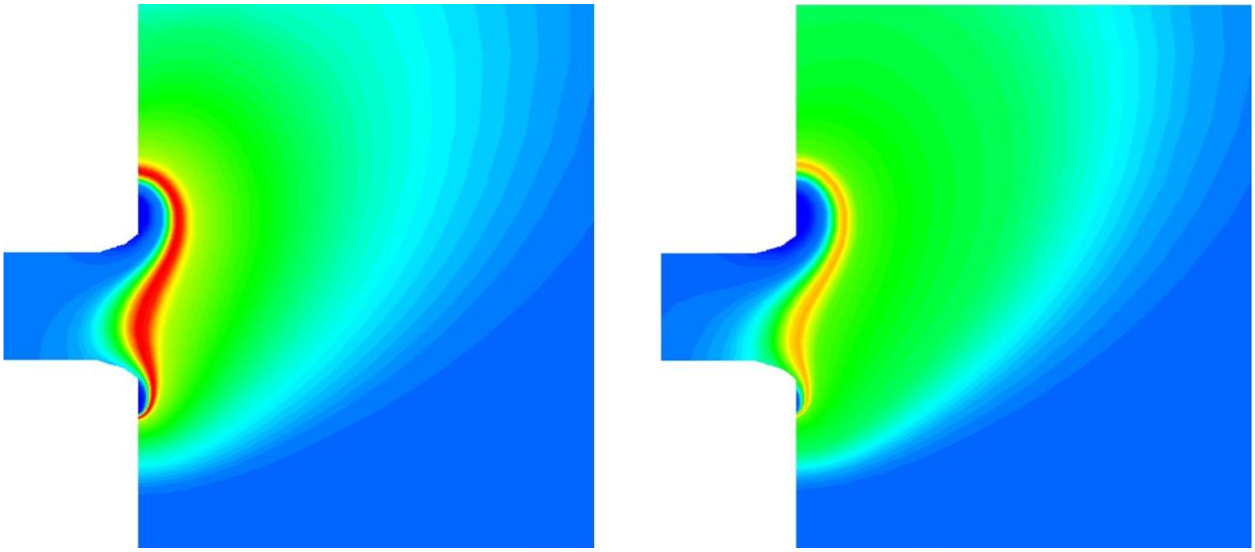

Figure 9. Normalized electron temperature profiles for MaSMi's measured jet mode field topology (left) and assumed diffuse mode field topology (right) created by saturation of the inner magnetic circuit at elevated operating temperatures.

VI. CONCLUSION

The magnetically shielded miniature Hall thruster underwent a series of experiments at the Jet Propulsion Laboratory to assess the thruster's performance. The thruster was found to operate in two distinct modes depending on the operating temperature. MaSMi's mode shift is likely caused by changes in the magnetic field strength and topology due to increased saturation of the magnetic circuit at elevated temperatures. Performance was similar between the two operating modes; a thrust of between 11 – 13 mN at an anode efficiency of between21 – 24%was recorded. These values are significantly lower than the performance calculated at UCLA, suggesting a significant change in the thruster's operation between the two facilities. Efforts to improve the magnetically shielded miniature Hall thruster's performance are ongoing.

VII. FUTURE WORK

The discovery of multiple operating modes and large oscillations in the plasma discharge of the MaSMi Hall thruster suggests the need to better understand the plasma's behavior in the ionization and acceleration regions. This is especially true when considering possible changes to the magnetic field strength and topology at elevated operating temperatures. This was explored briefly in this investigation using Hall2De simulations, but requires further efforts.

The immediate work to be completed is as follows. First, a commercially available thruster with established performance values will be used to validate the JPL experimental facility. Second, the MaSMi Hall thruster will be temporarily modified to produce an unshielded field topology. Operating the device as a conventional Hall thruster will enable identification of any design flaws that may be detracting from the thrusters overall performance and preventing nominal operation in a magnetically shielded configuration. Third, a thorough computational investigation using both Hall2De and thruster design tools (i.e. Infolytica's MagNet) will guide modifications to the MaSMi thruster's magnetic circuit. Changes to the thruster's materials and geometry will be considered to achieve the performance calculated in the previous effort in addition to improving the magnetic shielding of the inner channel wall.

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