Design of Miniature Ring-Cusp Ion Thrusters via Analysis of Discharge EEDF and Plasma Parameter Mapping

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An experimental effort was undertaken to understand and improve the discharge efficiency of the Miniature Xenon Ion (MiXI) thruster. Analyses were performed on the 3 cm discharge with a 3-ring and 5-ring cusp configurations, which lead to a new axial ring cusp design that shows considerable promise. For each configuration, a Langmuir probe was used to make 2D maps of the electron energy distribution function (EEDF) and other important plasma parameters throughout the discharge chamber. For the standard ring-cusp configurations, the results show that the plasma structure is dominated by the cusp fields at the miniature scale and suggest that primary electron loss to the walls likely dominates discharge losses at this scale. The insight derived from the testing of the ring-cusp configurations led to the development of a new design approach: the Miniature Axial Ring Cusp Ion (MARCI) prototype thruster. Discharge mapping and performance testing of the MARCI discharge demonstrate favorable plasma conditions within the discharge and near the extraction plane, and that the device can potentially achieve discharge losses and mass utilization efficiencies near 245 W/A and 0.89, respectively. As such, the new MARCI design approach may allow miniature ion thrusters to achieve the performance and efficiency levels of highly efficient conventional ion thrusters.

I. Introduction

MINIATURIZED ion thrusters, capable of efficiently producing 1–2 mN of continuous thrust, are a mission enabling technology.1-3 They offer an attractive option as a primary propulsion system for small spacecraft and as part of an attitude control system for larger spacecraft. Conventional scale ion thrusters have already been demonstrated to achieve high total efficiencies of >80%. Miniature ion thrusters have yet to approach the same performance due to their inherently higher surface area-to-volume ratio leading to increased discharge loss. Direct-current (DC) ion thrusters that rely on primary electron bombardment for ion production suffer from a non-linear decrease in the effective primary electron path length. The 3 cm Miniature Xenon Ion (MiXI) thruster, developed by Wirz, was the first to demonstrate stable operation with noteworthy total efficiency for its size.4 This was achieve by reducing the strength of the ring-cusp magnets to prevent discharge instabilities.5,6 In addition, significant improvements to the grid system allowed for higher neutral densities within the discharge chamber without large penalties to the mass utilization efficiency. However, the weaker cusp fields led to high discharge loss of ~450 eV/ion at maximum efficiency due to the poor primary electron confinement.

The design of conventional scale ring-cusp ion thrusters have relied on non-dimensional analytical models7-9 and semi-empirical treatment of cusp confinement physics10,11. Samarium cobalt permanent magnets produce strong and relatively short-ranged magnetic fields that are ideal for larger discharge chambers. Placed in alternating polarity, the arrangement generates strong cusp boundaries near the walls to confine the plasma while the bulk plasma remains effectively unmagnetized, ideal for uniform plasma generation and beam flatness. Therefore, the cusp magnetic fields are treated as boundary-only effects. Plasma losses to the cusp are estimated using the semi-empirical hybrid leak width and concepts such as the “highest closed
magnetic field contour" are used as a design figure-of-merit and for discharge models.\textsuperscript{8,12} At the miniature scale (<5 cm), these design principles become difficult to implement as the cusp fields can no longer be estimated as a boundary effect. The multiple ring cusps produce complex and strong B-field structures that dominate most of the chamber volume.

Since conventional DC ring-cusp ion thrusters have already achieved desirable efficiencies, there have been little motivation to map the internal plasma. To date, only a handful of authors have attempted to acquire a partial or full map of the plasma structure within an ion thruster discharge chamber. Many researchers have used various probes to measure the plasma properties at sparse locations to characterize the overall performance. Herman and Gallimore partially mapped the plasma parameters as well as generated EEDF curves inside the 30 cm NSTAR ion thruster in the region near the hollow cathode and the grid system.\textsuperscript{13} Tsukizaki used both Langmuir and optical probes through the grid system to measure a coarse plasma parameter map of the $\mu$-10 ECR ion thruster.\textsuperscript{14} Mao has thus far, been the only researcher to have fully mapped a miniature (3 cm) ring cusp discharge\textsuperscript{15} and the results showed a highly structured and non-uniform plasma density contours. However, the discharge was not designed as an ion thruster and his results did not include an EEDF map. Previous authors have yet to obtain a full plasma parameter or EEDF map to resolve the primary electron population within an ion thruster’s discharge chamber. Computational results from DC-ION have suggested that the MiXI thruster is primary dominated, where the primary electron is responsible for 95% of the ionization and accounts for 10% of the total electron density.\textsuperscript{16}

The objective of this research is to obtain a full plasma structure map of a miniature ion thruster discharge chamber in order to better understand the plasma behavior in relation to the magnetic field configurations and discharge conditions. This methodology will provide ion thruster designers with direct measurements and rapid observation of the discharge rather than relying on macroscopic performance data and beam profile measurements. Section II will present the approach and various magnetic field configurations that have been tested. The results are discussed in section III, where the discharge mapping data from the MiXI thruster led to crucial insight to miniature ion thruster design. The knowledge and tools acquired directly led to the development of a new prototype ion thruster.

### II. Experimental Approach & Apparatus

The miniature ion thruster experiments were conducted inside a 20" diameter by 36" height bell-jar vacuum chamber at the UCLA Plasma and Space Propulsion Lab. A 7" cryopump allows for a base and operating pressure of $2 \times 10^{-6}$ Torr and less than $5 \times 10^{-5}$ Torr, respectively. All thruster experiments are performed without ion beam extraction which allows the discharge cathode to be grounded with the

![Figure 1. Electrical diagram of the test apparatus including power supplies and the Langmuir probe circuit. Since an ion beam is not produced, the beam power supply is not connected and the negative terminal of the discharge supply is grounded.](image-url)
chamber. Figure 1 shows a simple wiring diagram of the MiXI thruster and power supplies required for plasma generation and measurement the simulated beam current. For some configurations, a secondary discharge power supply is wired to the rear plate to segment the chamber surfaces. All voltage and current sources shown in the diagram are Sorensen DLM series power supplies. Xenon gas is injected into the chamber using an Apex Vacuum 1.0 sccm flow controller through an electrically isolated gas feed line. Probes are mounted onto a set of Velmex XSlide linear stages configured to raster along an azimuthal slice of the chamber.

A. Miniature Xenon Ion (MiXI) Thruster

The original MiXI thruster is used as a modifiable platform to test various magnetic field configurations. The thruster includes an aluminum 3 cm diameter discharge chamber and an annular porous-metal gas injector located upstream of the rear pole piece. The MiXI grid system was designed based on the Small Hole Accelerator Grid (SHAG) optics. The smaller grid diameter permitted closer grid spacing that improved neutral confinement while maintaining high ion transparency. The side pole piece interacts with the downstream ring cusp by pulling the field lines closer to the wall and towards the grids. It also aided in mounting the grid system and securing the ring magnets. The miniature discharge hollow cathode was replaced with a 5 mil tungsten filament cathode until a final design is iterated upon. This was required for the discharge mapping as well as to reduce noise in the probe measurements. The filament is \( \sim 2.5" \) in total length is typically heated with 18 to 20 W of power. A set of trim coils is added to fine tune the magnetic fields within the center region of the chamber where the fields are weakest. A thermocouple is attached to the outer walls of the side pole piece.

The magnetic field contour in fig. 2 shows the MiXI thruster configured with the original 3-rings (3R) and a new 5-rings (5R) cusp configuration. The ring cusp elements consists of an axially magnetized continuous ring magnet upstream of the chamber and radially magnetized discrete block magnets surrounding the cylindrical wall. Samarium cobalt permanent magnets are used for their high field strength and operating temperatures. The B-field contours are generated using Ansoft Maxwell 2D program and verified using a Lakeshore 460 Gaussmeter with a 3-axis probe. Although the original MiXI (3R) thruster used large NSTAR magnets, they have been subjected to slight thermal demagnetization and only generates \( \sim 70\% \) of their original field strength at the face. The intention of the 5R design was to maximize the low field region in the chamber to expand the effective plasma volume and improve the beam flatness. The smaller magnets still produced strong fields but are also more short ranged. Initial simulations using a particle pusher indicated better overall primary electron confinement despite the greater total cusp leak area. The added trim coils are able to manipulate the fields structure within the bulk region where the permanent magnetic fields are weaker. However, they are inefficient in this configuration because the large coil radius and the magnetic side pole piece that partially shields out external fields.

Figure 2. Diagram of the MiXI thruster test platform with the default 3-ring (left) and 5-ring (right) configurations. The computed values of the normalized magnetic field are in logarithmic scale and verified using a 3-axis Gaussmeter. A Helmholtz coil is placed around the thruster to superimpose an axial field inside discharge chamber.
B. Miniature Axial Ring Cusp Ion (MARCI) Prototype Thruster

The MARCI thruster shown in fig. 3 was designed as a test platform for a new cusp confinement approach based on results from the MiXI thruster to be discussed in section III. The design allows for easy adjustments of key features: the discharge chamber height, the placement of the ring magnets, and the location and type of cathode used. The discharge chamber is kept at 3 cm in diameter as a performance comparison constant and in order to use the MiXI grid mount. The neutral gas is injected into the lower chamber through a ring plenum and enters the discharge chamber through the cathode opening and holes underneath the cylindrical walls. The cathode is the same 5 mil tungsten filament from the original MiXI thruster and operates at similar heater power. High temperature trim coils are wrapped directly around the discharge chamber and operate more efficiently due to their proximity. Thermocouples are attached to the external sides of the back plate and cylindrical wall.

C. Simulated Ion Thruster Performance

The ion optics for the original MiXI grids were designed for a plasma densities typical of the original thruster (~ 2 × 10^{17} m^{-3}). In order to focus on discharge design and reduce the design variability of the grids, the discharge was operated without beam extraction. The predicted performance is determined base off a simple model described by Brophy. The model accounts for an equivalent neutral flow rate since beam ions that would normally leave the thruster instead contributes to an additional flow rate. The predicted beam current (\(I_b\)) is calculated by multiplying the measured total ion current incident to the grid system (\(I_g\)) with the reported ion transparency of the MiXI grid system, \(I_b = I_g \Phi_i\). The effective neutral flow rate can then be calculated using:

\[
\dot{m}_p^* = \dot{m}_p + \frac{I_b}{\alpha_m} \left( \frac{M}{e} \right)
\]

where \(\dot{m}_p\) is the flow rate as measured by the flow controller, \(\alpha_m\) is the doubly charged ion correction factor, and \(M\) and \(e\) are the electron mass and charge, respectively. This expression assumes that all ions collected at the accelerator grid returns to the discharge as a neutral atoms. Although Brophy determined that only ~ 45% of the accelerator grid current reenters the discharge chamber in the J-Series thruster, the value is expected to be much greater for the MiXI thruster due to the geometry of the SHAG optics. The mass utilization efficiency (\(\eta_{ud}\)), discharge loss (\(\epsilon_d\)), electrical efficiency (\(\eta_e\)), and total efficiency (\(\eta_T\)) are calculated using standardized expressions:

\[
\eta_{ud} = \alpha_m \frac{I_b M}{e \dot{m}_p^*}
\]

\[
\epsilon_b = \frac{(I_d - I_b)V_d}{I_b}
\]
\[ \eta_e = \frac{I_b V_b}{I_b V_b + P_0} \]  

(4)

\[ \eta_T = \alpha^2 \eta_e \eta_{ud} \]  

(5)

where \( \alpha \) is the thrust efficiency, \( V_b \) is the beam voltage, \( V_d \) and \( I_d \) are the discharge voltage and current, respectively, and \( P_0 \) includes any other sources of power aside from the beam supply. The discharge performance data were measured by keeping the discharge voltage constant and slowly increasing the discharge current by adjusting the cathode filament heater power. Performance data were acquired at discrete flow rate and trim coils settings. The performance results were calculated with assumptions based on operational data of the original MiXI thruster with beam extraction. This includes: 1100 V beam voltage, grids with 75% ion transparency, no beam divergence, and negligible doubly charge ion population. In addition, the performance figures shown in section III will not include possible additional power usage and/or gas flow for the discharge and neutralizer cathode. All power supply voltage and current values are measured using the NI PXIe 4300 DAQ module. Lastly, the beam flatness parameter is calculated using:

\[ F_B = \frac{\int_0^R 2\pi r j_B(r)dr}{\pi R^2 j_{B_{max}}} \]  

(6)

where \( j_B \) is the local beam density and \( R \) is the radius of the grids. Since an ion beam isn’t extracted, a theoretical flatness parameter is instead calculated from the projected beam profile using the discharge mapping data of the plasma density and electron temperature at the screen grid plane. In reality, local plasma density affects the ion transparency of each beamlet which would alter beam profile.

D. Discharge Mapping

In order to access the entire discharge chamber, a set of stainless steel probing grids were fabricated and installed in lieu of the original MiXI grids. The probing grids feature a thin slit across the chamber diameter which allows for probe access. To account for the increase neutral transparency, the gas flow rate was increased by a factor of 2.5 times to match the discharge loss per propellant utilization curve when operated using the MiXI grids. The probes are able to access an entire azimuthal slice of the discharge chamber sans the region very near the cathode filament. Each scan generally includes upwards of 500 data points and is automated through a custom LabVIEW program. The raster pattern is programmed for smaller step sizes near the cusp to obtain higher resolution at the most structured location.

A schematic of the probing apparatus is shown in fig. 1. Plasma properties were measured using a cylindrical Langmuir probe, constructed with a 1.2 mm length by 0.2 mm diameter tungsten wire protruding from a 1.1 mm diameter alumina tube. The probe is biased relative to ground with a Kepco BOP-200...
bipolar amplifier, controlled through the analog output from a NI PXIe-4322 module. The probe current is measured across a 32 Ω shunt resistor by the NI PXIe-4300 DAQ module with a 16 bits analog input resolution. The output DAQ generates a triangle wave voltage sweep at 200 Hz and acquires 1 second of data at each spatial location. A total of 400 I-V curves are binned and averaged in order to reduce the noise from the plasma and electronics. An adaptive smoothing cubic spline is used to fit the raw data and calculate the first and second derivative. The small Langmuir probe does not noticeably disturb the discharge plasma during operation. There is at most a 2% effect on the discharge current and estimated beam current when the probe is scanning near the center-line upstream region inside the discharge chamber.

The Langmuir probe measurements are analyzed using probe theories to account for the small probe size and strong magnetic fields. The electron retarding region of the standard current-voltage (I-V), particularly near the plasma potential, is strongly affected by local magnetic field. Initially, a kinetic theory was used to extract the EEDF and more precisely determine the plasma potential and density. The method requires accurate magnetic field data to determine the local diffusion constant. Although the method provided consistent results between probes at different orientation, it was time consuming to implement for multiple design iterations. The standard EEDF Langmuir probe theory provided results that was adequate for qualitative comparison between different configurations. The plasma potential is found at the maximum first derivative of the I-V data. The second derivative data is used to calculate the electron temperature using a Maxwellian fit in the region near the floating point potential. This method avoids fitting near the plasma potential as the low energy electrons are more affected by the magnetic fields. The plasma density is calculated through integration of the electron distribution function. The plasma density is also calculated from ion saturation curve that are less affected by the magnetic fields. The Bernstein-Rabinowitz-Laframboise (BRL) theory was employed for the ion fit, which accounts for effects of sheath expansion and ion orbital motion.\textsuperscript{18} The primary electron energy distribution is found by subtracting the fitted Maxwellian curve for the plasma electron population from the second derivative data. The approximate primary electron density can then be calculated by integrating remaining energy distribution.

III. Results & Discussion

The screen and accelerator grids were biased to 5 and 20 volts below the cathode potential, respectively. An additional collector plate downstream of the thruster confirmed that there was negligible ion current leaving the thruster. The discharge voltage is kept at 25 V for all tested conditions despite certain field configurations showing better performance at lower or higher voltages. The discharge current is controlled through adjusting the filament cathode heater power. Measurements were acquired once the discharge performance stabilizes when thermal equilibrium is reached.
A. MiXI Thruster Results

1. Performance Data

The performance curves at different actual flow rate settings are shown in fig. 5 for the default MiXI 3-ring configuration. Although this device was operated without beam extraction, estimates of the thruster efficiency and discharge characteristics using the simulated ion thruster operation were similar to those previously obtained by Wirz with beam extraction. Although it appears as if the discharge performs universally better at higher flow rates, the estimated beam current is not constant along each curve unlike standard discharge loss plots. The right figure shows that the thruster is more efficient with lower flow rates when it would be extracting lower beam currents. At lower discharge currents, the 0.080 sccm condition is more propellant efficient while the beam current scales similarly to the higher flow conditions. However, the beam current quickly asymptotes to a lower value at lower flow rates, leading to higher discharge loss with increasing discharge currents. With higher flow rates, the device operates more efficiently when extracting higher beam currents. At 0.65 A discharge current, the device was already operating at $>260^\circ$C measured on the side pole piece. Therefore, the data points were limited to those shown.

Figure 6 is a performance comparison between the 3-rings and 5-rings magnetic field configurations. The performance curve chosen for each configuration represents a flow rate that showed the highest total efficiency near 0.50 A of discharge current. The results show that the default 3-rings outperforms the non-trimmed 5-ring configuration. The 5R performance was much closer to the 3R configuration near the start of testing and gradually decreased as thermal equilibrium was reached. This reduction was caused by demagnetization of the permanent magnets (up to 40% reduction at the magnet face) was due to excessive temperatures and was confirmed with the Gaussmeter. The performance of the partially demagnetized 5R configuration increased gradually with increasing trim coils currents, reaching a maximum with an additional $\sim 60$ Gauss of trim B-field. The trim coils allow the 5R simulated performance to exceed the 3R configuration by notable margin, achieving higher propellant utilization and lower discharge loss at a given beam current. However, these performance values do not factor in important parameters such as beam flatness. In addition, measurements of the internal plasma structure are required to understand the mechanism for the drastic performance increase with the trim coils.

2. Discharge Map

The four plots shown in fig. 7 are sample Langmuir probe data and analysis at an arbitrary location inside the 3-ring discharge. The top right plot shows the standard $I - V$ trace in a semi-log plot along with the calculated first and second derivative. From visual inspection, the standard $I - V$ sweep would yield
Figure 7. Example Langmuir probe data and analysis. (a) The binned, then averaged I-V sweep. (b) The probe sweep and its derivative plotted in a semi-log scale. (c) Extraction of the primary electron density through subtraction of a Maxwellian plasma electron population. (d) The ion saturation curve fitted using the BRL method.

a slightly higher electron temperature than that from the derivative curves. In addition, a higher energy electron population can be detected in the second derivative data by the kink in the curve at the higher energies. The bottom left figure shows the process in calculating the primary electron density. The primary electron population is the difference between the full population and Maxwellian estimate for the plasma electrons. Although the Maxwellian fit may not match the data well at lower energies, the higher energy electrons are less affected by the magnetic fields. The bottom right plot shows the ion saturation fit using the BRL theory which iterates to a plasma density based on the sheath size. Generally, integrating the EEDF with the standard Druyvesteyn formula will result in underestimation of the plasma density in a magnetic field. In addition, previous authors have found that the BRL theory has the tendency to overestimate the plasma density for many conditions. The reported plasma density contours herein are found using the BRL theory. Although the values may be exaggerated, they are sufficient for qualitative comparisons and interpretation of the plasma structure.

The results shown in fig. 8 are interpolated contour plots of the plasma parameters for the default 3R configuration of the MiXI thruster measured at 0.35 A discharge current and 0.140 sccm flow. The plasma density structure shows strong correlation with the magnetic fields structure shown in fig. 2, an attribute resembling the results found by Mao. The primary electron contour coincides within the plasma density structure and possibly accounts for more than ~10% of the total electron density within the bulk plasma. The electron temperature ranges between 2.5 to 3.0 eV and exhibits a more gradual delineation compare to the density contours. The plasma potential is by and large uniform at ~28 V relative to the cathode potential within the entire discharge chamber. The overall low electron temperature is an indication of poor primary electron confinement as most of the discharge energy is lost directly to the chamber walls rather than to ionization or thermalization to the plasma electron population. The majority of the ionization is directly from primary electron bombardment rather than the high energy tail of the plasma electron
Figure 8. Discharge mapping results for the 3R configuration showing the: a) plasma density (m$^{-3}$), b) primary electron density (m$^{-3}$), c) electron temperature (eV), and d) plasma potential (V). The cathode filament is located in the empty rectangular space at the center.

population. Therefore, the primary electron density is higher than conventional sized discharges and its structure resembles a “skeleton” of the plasma density contour. In addition, the plasma potential values indicate a strong positive sheath of about one electron temperature which suggests excessive loss of primary and plasma electrons to the walls.\footnote{5}

The contour plots in fig. 9 is a comparison of the plasma parameters for the 5R configuration, measured at the same discharge and flow conditions, with and without the trim B-field. The discharge plasma without trim coils exhibits characteristics similar to the 3-ring configuration but with poorer confinement. The plasma density, primary density, and electron temperature are lower throughout the discharge plasma. The bulk plasma extends almost entirely to the chamber walls due to larger low B-field region. With the addition of the trim coil fields, there is a drastic increase in plasma density, primary density, and electron temperature. The trim coils generate a predominately axial magnetic field in the bulk plasma which obscures any direct path of the primaries to the anode wall. Therefore, the primary electrons are confined to the center-line of the discharge where the primary density is over 4 times greater than without any trim fields. Subsequently, the electron temperature is almost twice as high within the center-line region and higher throughout the discharge chamber. The more pronounced gradient along the radial direction is expected as electrons must now diffuse across an axial magnetic fields to reach the anode. The higher center-line primary density and electron temperature leads to a local increase of the ionization rate and plasma density values that are up to 2.5 times greater than the non-trimmed condition. The plasma potential, although lower than the non-trimmed results, is still almost an electron temperature above the discharge voltage and indicates that there is still excessive plasma electron losses to the chamber wall.

The mapping results show that the substantial simulated performance leap in the 5R trimmed configu-
ration is almost entirely attributed to improved confinement of the primary electrons. Figure 10 shows the projected normalized beam profile for each configuration, calculated from the plasma density and electron temperature values along the extraction plane. Although the 5R trimmed theoretical operated more efficiently, as measured by the greater total ion current collected at the grids, the beam profiles show that it also has the poorest beam flatness. With the MiXI grids, the 5R trimmed performance is appreciably overstated as the beamlet current surpasses the perveance limit of the grid design. In addition, the highly non-uniform beam would lead to faster and uneven erosion of the extraction grids as well as design difficulties to account for the steep density gradient. In addition, the high center-line primary density and higher electron temperature may cause high local generation of doubly-charged ions. The strong center-line densities are traits similar to earlier Kaufman ion thruster designs, which also has a predominately axial magnetic field. Oscillations were detected with in the Langmuir probe measurements for the 5R trimmed condition. The oscillation frequency ranged from 1 kHz to 20 kHz and was strongly correlated to the trim coil settings. No detectable oscillations in the discharge current suggests that the probe oscillation are azimuthal in nature. This is also similar to Kaufmann thrusters where $E \times B$ driven instabilities increased the radial transport of electrons. However, the 5R trimmed configuration is not impaired by high discharge voltage operation because the relatively weak magnetic fields and short diffusion path length to the anode.

Results from fig. 9 suggested that there was ample possibility to obtain better performance by improving the beam flatness and plasma electron confinement while maintaining the improved primary electron confinement. From fig. 10, the original 3R configuration shows a remarkably flat projected beam profile.

![Figure 9. Discharge mapping results of the modified 5R configuration with the same units as fig. 8. The left and right side of each contour map shows the plasma structure with and without the trim coil magnetic fields, respectively.](image)
similar to the extracted beam measurements previously reported by Wirz. Figure 2 as well as fig. 8 show that the MiXI discharge field topology allows the plasma to spread across the screen grid. This topology is produced by the two closely spaced ring-cusps which pushes the null region of the downstream ring-cusp past the extraction plane. As a result, the cusp and plasma structure is relatively aligned with the extraction plane. The screen grid is at cathode potential which behaves as an electrostatic confinement boundary for the primary electrons. This is important in the MiXI thruster due to design of the grid mounting fixture which limits the proximity of the downstream ring-cusp to the extraction plane. However, the two ring cusp also produces a relatively strong point cusp in between the two null regions. The plasma and primary electron density are shown to peak at the upstream ring-cusp null region. The primary electrons and ions within this region are impeded by the point cusp in between the ring magnets and are thus confined against freely diffusing to the screen grid region.

B. MARCI Thruster Results

Traditional ring-cusp design principles have inherent design limitations at the miniature scale because their field structure dominates the bulk discharge. A radially magnetized ring magnet around the chamber walls generates strong magnetic fields and density gradients along the radial direction, which generally leads to poor beam flatness. Therefore, the overall magnetic fields must be limited to configurations that would precisely align the cusp structure along the extraction plane. In addition, primary and plasma electrons are loss to the same leak area. The total cusp leak area must be adequate to extract a stable discharge current which leads to excessive loss of primary electrons.

The discharge mapping of several magnetic field configurations led to an improve understanding of miniature discharge design and to the development of the MARCI prototype thruster. The thruster addresses the key obstacles with traditional ring cusp design: primary electron confinement and beam uniformity. Although the field topology and discharge map are not shown in the preceding, the same test methodology indicates significant improvements in efficiency and operation compared to traditional miniature ion thruster designs.

1. Performance Data

The thruster was tested at the same discharge conditions as the MiXI thruster with the discharge voltage, screen grid, and accelerator grid biased to 25 V, -10 V, and -20 V, respectively. Figure 11 shows that the MARCI thruster achieves significant improvements in all performance metric compared to the previous configuration. The thruster still performs better with the trim coils but now requires less than 1.5 W of coil power to reach max efficiency. It is able to a attain a discharge loss of under 250 eV/ion at 0.90 ideal propellant utilization, values that were previously limited to efficient conventional scale ion thrusters.
Figure 11. Performance comparison of the MARCI thruster and various MiXI thruster configurations. The results show that the MARCI thruster is able to produce much greater ion flux to the extraction plane for a given discharge power.

thruster is able to produce 60 mA of simulated beam current at 15 W of discharge power without excessive temperature at the permanent magnets. The maximum thrust is only currently limited by the original MiXI grids, which are designed to efficiently extract up to 54 mA of beam current.

2. Discharge Map

Although the discharge map results are not shown here, they indicate better overall confinement and confirms the MARCI thruster’s performance data. The plasma density map reveals that the improved performance is not impaired by poor beam uniformity such as with the 5R trimmed configuration. The plasma is well distributed across in the radial direction and towards the extraction plane. The electron temperature ranges between 4 to 5 eV and is not localized to just the center-line region. Along with the primary electron density map, they illustrate that the primary electrons are well confined and spatially distributed for efficient ion generation along the grids. This is reflected in the appreciably flat simulated beam profile shown in fig. 12. The MARCI thruster exhibits a slight dip in the beam profile near the center-line that allows for an off-centered and larger area of maximum beam current. With the trim coils, beam profile is squeezed slight

Figure 12. Comparison of the estimated beam current for the MARCI and default MiXI discharge geometries. The MARCI discharge exhibits a slightly hollow beam. Note: the beam current estimates are based on an ion transparency of 75% was assumed across the grid plane and grid perveance considerations are not included.
more inwards, reducing the beam flatness. Similar to the 5R trimmed configuration, the trim coils increase the plasma density through enhanced confinement but at the expense of the beam flatness.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$I_b$ (mA)</th>
<th>$\epsilon_b$</th>
<th>$\eta_{ud}$</th>
<th>$\eta_T$</th>
<th>$F_B$</th>
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<tr>
<td>MiXI 3R Default</td>
<td>30</td>
<td>480</td>
<td>0.75</td>
<td>0.53</td>
<td>0.73</td>
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<tr>
<td>MiXI 5R w/ Coils</td>
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<td>300</td>
<td>0.76</td>
<td>0.60</td>
<td>0.33</td>
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<tr>
<td>MARCI w/o Coils</td>
<td>48</td>
<td>305</td>
<td>0.85</td>
<td>0.68</td>
<td>0.72</td>
</tr>
<tr>
<td>MARCI w/ Coils</td>
<td>60</td>
<td>245</td>
<td>0.89</td>
<td>0.74</td>
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Table 1. Theoretical performance comparison at 15 W discharge power. These values assume an ion and neutral transparency of 75% and 6%, respectively. Efficiency values does not include trim coil and filament heater power.

Table 1 shows the theoretical performance at 15 W discharge power for the various configurations previously discussed. These values are idealistic as they assume a grid system that is capable of 75% average ion transparency for each configuration while maintaining the same neutral transparency as the MiXI grids. The MiXI grids were designed to operate at a maximum of 54 mA total beam current, where it encounters the perveance limit for the given beam profile. Although the MARCI thruster performance data presented in table 1 shows at a beam current of 60 mA, fig. 11 shows that the thruster still operates with similar efficiencies at lower beam currents. The performance value also does not include the doubly–charged ion correction. Although MiXI thruster was shown to have negligible doubly-charged ion, certain configurations tested herein operated at noticeably higher electron temperature and primary electron confinement, and therefore double ions contributions may not be negligible.

IV. Conclusion

This experimental effort successfully demonstrated a new approach to miniature ion thruster discharge design that circumvents the scaling limitations of traditional ring-cusp discharges. The development of the MARCI thruster required a better understanding of plasma behavior in miniature cusp-confined ion thrusters. This was accomplished via a detailed EEDF and plasma parameter map of the MiXI thruster discharge in its default and modified configurations. This newly implemented technique allows researchers to resolve and understand the plasma structure of miniature cusp devices at an unprecedented speed and accuracy. The results show that the entire plasma structure is governed by the cusp field topology and the placement of cusp elements is severely limited to topologies that would allow for uniform beam extraction. In addition, the primary electrons are easily lost at the cusp and was found to be leading the contribution to the discharge loss. The knowledge and experience gained from testing several discharge configurations, along with insight into the plasma behavior of each design, led to the MARCI thruster concept. Preliminary performance testing and discharge mapping shows a potential improvement of up to 20% total efficiency compared to the current state-of-the-art MiXI thruster. At the very least, it can be seen that the MARCI thruster is able to achieve twice the ion current flux to the extraction plane for a given discharge power and internal neutral density compared to the original MiXI thruster.

V. Future Work

The next step will be to verify the MARCI thruster’s performance by extracting an ion beam and acquiring thrust stand measurements. Plume measurements will measure the beam divergence and an $E \times B$ probe will be used to measure the doubly-charged ion content. The filament cathode will then be replaced with a miniature hollow cathode that has been successfully tested on the MiXI thruster. The hollow cathode operation may affect the beam uniformity due to point source injection of the primary electrons and modifications to the fields may be required. In addition, there is ample room to optimize the MARCI thruster design. The results presented in this preceding was a first take on a new design approach and has not been iterated upon since acquiring the first discharge map. The magnetic field design can be optimized for a flatter beam profile and to operate at maximum efficiency without using the trim coils. Lastly, the MiXI grids will be redesigned to cater to the operating conditions of the MARCI discharge.
Acknowledgments

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References