Numerical Simulations of a Miniature Microwave Ion Thruster

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This study presents the numerical and experimental results of the second version of a miniature microwave ion thruster under development at The Pennsylvania State University. The thruster makes use of an electron cyclotron resonance discharge to create a plasma, obtained by coupling a permanent magnetic field created by two concentric magnets and a microwave antenna. The propellant used is argon or xenon, injected at a mass flow rate of 0.01 to 1 sccm inside the discharge chamber. Using argon, the thruster is expected to develop a thrust of 217 \( \mu \)N, with a propellant utilization efficiency of 46%, and a total electrical power of 8 W, of which 1 W is dedicated to propellant ionization. For argon, the ion extraction grids are set to a potential difference of 2,280 V. Numerical simulations of permanent magnetic field and oscillating electric field in the discharge chamber of the ion thruster were conducted using a commercially available software package. Using these two simulations, it was determined that the optimal location for the microwave antenna was 1.8 mm away from the magnets. The ion extraction grids were also simulated. The ion beam was shown to be focused, with an ion beam divergence of 23.8° and a transparency of 35.0% for the nominal parameters. The ion engine was tested in a vacuum environment. Power required to ionize argon gas was measured to be 3 to 4 W for mass flow rates between 0.01 and 0.1 sccm, while the power to sustain the argon plasma was as low as 0.4 W.

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Nomenclature

\( A \) = Generic area, \( m^2 \)
\( A_{ECR} \) = Area of the ECR layer, \( m^2 \)
\( a \) = Radius of a cylindrical tube, m
\( B \) = Magnetic flux density, T
\( \vec{B}_{MF} \) = Magnetic field obtained from a magnetic field simulation
\( \vec{b} \) = Unit vector in the local direction of the magnetic field
\( E_{\perp} \) = Electric field perpendicular to magnetic field lines, V \cdot m^-1
\( E_{\parallel} \) = Electric field parallel to magnetic field lines, V \cdot m^-1
\( E_{ECR} \) = Energy gained by an electron in one cyclotron gyration, J
\( \vec{E}_{EM} \) = Electric field obtained from a time-harmonic electromagnetic simulation
\( D \) = Diameter of a circular aperture, m
\( d \) = Diameter of a circular pipe, m
\( e \) = Elementary charge, \( 1.6 \times 10^{-19} \) C
\( f_c \) = Electron cyclotron frequency, Hz
\( I_B \) = Beam current, A
\( I_{ECR} \) = Index of ECR heating, V^2 \cdot T^{-1} \cdot m^{-1}
\( I_a \) = Accelerator grid current, A
\( I_b \) = Ion beamlet current, A
\( I_s \) = Screen grid current, A
\( I_{sp} \) = Specific impulse, s
\( J_B \) = Beam current density, A \cdot m^{-2}
\( L \) = Distance between two grids, m
\( l \) = Length of a tube, m
\( M \) = Atomic mass of the propellant, kg
\( m \) = Mass of an atom, kg
\( m_e \) = Mass of an electron, \( 9.1 \times 10^{-31} \) kg
\( \dot{m}_i \) = Ionized propellant mass flow rate, kg \cdot s^{-1}
\( \dot{m}_p \) = Non-ionized propellant mass flow rate, kg \cdot s^{-1}
\( N \) = Number of grid apertures
\( N_m \) = Flow rate, mol \cdot s^{-1}
\( \vec{n} \) = Unit vector perpendicular to the local magnetic field
\( P_1 \) = Pressure at the inlet of a tube, Pa
\( P_2 \) = Pressure at the outlet of a tube, Pa
\( P_c \) = Critical pressure of a gas, Pa
\( P_0 \) = Ionization power of an electric thruster, W
\( P_{in} \) = Input power for an electric thruster, W
\( P_{jet} \) = Kinetic thrust power of a beam, W
\( Q \) = Mass flow rate, sccm
\( Q_i \) = Mass flow rate of a single grid aperture, sccm
\( q \) = Total charge on a particle, C
\( R \) = Universal gas constant, J \cdot K^{-1} \cdot mol^{-1}
\( V_a \) = Change in electric potential between two grids, V
\( v_{\parallel} \) = Velocity of an electron parallel to magnetic field lines, m \cdot s^{-1}
\( T \) = Gas temperature, K
\( T \) = Thrust, N
\( T_c \) = Critical temperature of a gas, K
\( T_r \) = Ratio of the temperature of a gas and its critical temperature, 1
\( u_e \) = Exhaust velocity, (m \cdot s\(^{-1}\))
\( \varepsilon_0 \) = Permittivity of vacuum, \( 8.85 \times 10^{-12} \text{ F} \cdot \text{m}^{-1} \)
\( \zeta \) = Viscosity of a gas, Poise
\( \eta_M \) = Mass utilization efficiency of an ion thruster
\( \eta_T \) = Total efficiency of an ion thruster
\( \theta \) = Angle between magnetic field lines and electric field lines, °
\( \bar{\theta} \) = Average value of \( \theta \) on the exposed ECR zone, °
\( \xi \) = Viscosity parameter of a gas
\( \tau \) = Transparency of a grid, %
I. Introduction

Ion thrusters operate via the electrostatic acceleration of ions extracted from a plasma source. Multiple plasma sources have been investigated, such as radio-frequency discharges, microwave discharges, or direct current discharges. The ion exhaust velocity for ion engines is higher than for other types of propulsion, resulting in high specific impulse and efficient propellant usage. This leads to a larger vehicle ∆V, which makes this propulsion method suitable for station keeping, interplanetary, or asteroid rendezvous missions. In the past two decades, multiple missions have made successful use of ion engines, such as the European Space Agency’s large geostationary technology satellite ARTEMIS in 2001, the NASA NSTAR ion engine on the probe Deep Space 1, which operated for more than 30,000 hours, and the µ10 engine from JAXA, which operated on the Hayabusa probe for 31,400 hours over a time period of seven years.

More recently, miniature ion thrusters have attracted interest. The miniaturization of ion engines has been seen as a way to decrease the power requirements for the ion engine, which allows for a lower overall spacecraft mass. Miniature ion engines are well suited for low thrust (from 1 µN to 1 mN), low power (less than 10 W), low mass, and high specific impulse (5,000 s) missions such as station keeping, precise attitude control, or formation flight. CubeSat missions to the Moon using miniature ion thrusters have also been proposed. Previous work on the miniaturization of ion thrusters using microwave discharges as a plasma source has been conducted by Takao et al., with an ion engine able to create a 10-mA ion beam current with 8 W of input power, a mass flow rate of 0.2 sccm of xenon, and a propellant utilization efficiency of 72%. Koizumi and Kuninaka further miniaturized the µ10 engine and were able to obtain an ion beam current of 3.3 mA with 1 W of input power and 0.15 sccm of xenon, with a propellant efficiency of 37%. Both the work of Takao et al. and Koizumi and Kuninaka make use of the coupling between microwave radiation and permanent magnetic field to create a plasma through electron cyclotron resonance (ECR).

Work conducted at The Pennsylvania State University includes both a miniature radio-frequency and a miniature microwave engine. Trudel developed a 1-cm radio-frequency thruster operating at 16 W, 0.038 sccm of argon, and a propellant efficiency of 41.1%. Lubey developed a Miniature Microwave-Frequency Ion Thruster (MMIT, pictured in Fig. 1) operating at 1 W, 0.15 sccm of argon, and a propellant efficiency of 32.1% using ECR discharge as a plasma source.

This paper presents the current numerical and experimental developments of the MMIT. Section II presents the main ion thruster design and the performance expected, both with argon gas and xenon gas as propellant. Section III goes over the numerical experiments conducted to validate the design of the ion thruster. Finally, Section IV presents experimental results obtained in a vacuum environment with the assembled ion thruster, shown in Fig. 1.

Figure 1. (a) Original MMIT thruster. (b) Second version of the MMIT thruster.

II. Ion Thruster Design and Performance Predictions

The MMIT has been re-designed based on previous ion thrusters developed at the Japan Space Exploration Agency (JAXA) by Koizumi and Kuninaka and at The Pennsylvania State University by Trudel,
The new version of the thruster presents five main features:

- the back plate on which a microwave input and a gas feed are connected;
- the yoke plate, which serves as a support for permanent magnets;
- the discharge chamber in which the plasma is created;
- the front plate, which is used as a fastener for the ion extraction grids; and
- the permanent magnets and the microwave antenna, which create the plasma.

Figure 2 shows an overall CAD view and cross-section of the new version of the thruster.

The back and front plate and the discharge chamber are made of Macor, a carbide-machinable ceramic. Macor was chosen for its low outgassing at high vacuum, its electrical and thermal insulating properties, and its high temperature capability — Macor can be used for applications up to 1000°C. To reduce design costs, a low-carbon alloy of steel was used for the yoke plate instead of iron, the permanent magnets used are rare-earth neodymium magnets (NdFeB) instead of samarium–cobalt magnets (SmCo), and the extraction grids are stainless steel, instead of carbon or molybdenum grids. Following Refs. 8 and 9, the microwave antenna has a shape of a ring.

The design is modular and allows for the discharge chamber, the grid optics, or the microwave antenna to be changed at will.

A. Back plate

The back plate is used as a support for the microwave input and the gas line. The gas line is epoxied onto the back plate, while the microwave SMA candlestick is inserted through a hole in the back plate. The microwave candlestick is also shielded by a stainless steel tube in order to minimize the reflected power in the microwave line. The SMA candlestick is fastened to the back plate with 4 screws. The gas is injected inside an expansion chamber through a 1/16-in.-diameter stainless steel pipe, before being fed to the discharge chamber by 8 holes in the yoke plate. Figure 3 shows a CAD cross-section of the back plate.

B. Ion optics

1. Single hole grid

A single hole grid was designed to verify that the plasma could be created and sustained inside the discharge chamber. The grid is simply grounded and presents only a single hole of diameter 2.54 mm for the gas inside the discharge chamber to escape.
2. Extraction grids

The ion optics generate a large electric field able to accelerate the ionized propellant through the grid apertures, which in turn creates thrust. The MMIT has been designed with a two-grid system, and a target ion beam current of 5 mA, which is within the range of measured values for both the MRIT and the $\mu_1$ thruster.\textsuperscript{8–11} The two grids are electrically insulated from each other by a thin layer of PTFE.

The grids were designed based on the methodology outlined in Refs. 14 and 15:

- the transparency of the grids should be maximized to extract the maximum number of charged particles, while the neutral atoms are kept inside the discharge chamber, and
- the size of the apertures of the grid should be of the order of the size of a Child–Langmuir sheath for good focusing of the ion beam.

The first requirement is met by organizing the extraction apertures in an hexagonal pattern, as shown in Fig. 4. The second requirement is met by choosing a geometry and potential difference compatible with the Child–Langmuir law, given by:\textsuperscript{14,15}

$$J_B = \frac{4}{9} \varepsilon_0 \sqrt{\frac{2q V_a^{3/2}}{m L^2}},$$

where $q$ and $m$ are the charge and mass of the extracted particle, respectively, $V_a$ is the potential difference across the grids, $L$ is the distance between the grids, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, the permittivity of vacuum, and $J_B$ is the beam current density:

$$J_B = \frac{I_B}{\pi D^2},$$

with $I_B$ the beam current, and $D$ the diameter of a hole on the accelerator grid. Therefore, for a given beam current $I_B$, distance between two grids $L$, and voltage difference $V_a$, it is possible to calculate the aperture diameter using Eqs. (1) and (2). Conversely, it is possible to calculate the potential difference $V_a$ required for good focusing based on a given geometry. We chose the latter approach by specifying the distance between the two grids based on materials readily available to us, and based on a given aperture diameter, determined by machinability criteria.

Figure 4 shows a CAD picture of the accelerator grid. The 37 innermost apertures are for ion beam extraction, while the six outer ones are for fastening purposes. The last aperture on the side tab is for the grid to be connected to an electrical circuit. The aperture diameters were chosen to be 1.613 mm for the screen grid and 1.321 mm for the accelerator grid, based on machinability criteria. Table 1 details the size and material of each component of the ion optics.

The potential difference across the grid to extract the ions is given by Child’s law (Eq. (1)). For the geometry chosen, we obtained a target grid potential difference of 2,280 V for argon gas and of 3,350 V for xenon gas.
Table 1. Main dimensions of the screen and accelerator grids and of the insulating spacer

<table>
<thead>
<tr>
<th>Grid part</th>
<th>Material</th>
<th>Hole diameter (mm)</th>
<th>Number of apertures</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen grid</td>
<td>Stainless steel</td>
<td>1.613</td>
<td>37</td>
<td>0.635</td>
</tr>
<tr>
<td>Accelerator grid</td>
<td>Stainless steel</td>
<td>1.321</td>
<td>37</td>
<td>0.635</td>
</tr>
<tr>
<td>Spacer</td>
<td>PTFE</td>
<td>10.0</td>
<td>1</td>
<td>0.508</td>
</tr>
</tbody>
</table>

Figure 4. CAD front view of the accelerator grid.

C. Discharge chamber pressure

Poiseuille’s law is used to estimate the pressure inside the discharge chamber. For a cylindrical tube of radius $a$ and length $l$, Poiseuille’s law gives the rate $N_m$ at which the gas flows (in moles per second):\(^{14}\)

$$N_m = \frac{\pi}{16\zeta} \frac{a^4}{l} \frac{P_1^2 - P_2^2}{RT},$$

where $R$ is the universal gas constant, $P_1$ is the upstream pressure, $P_2$ the downstream pressure, $\zeta$ the gas viscosity in Poise, and $T$ the gas temperature in K. The upstream pressure, therefore, can be determined using the relation:\(^{14}\)

$$P_1^2 = P_2^2 + \frac{0.78Q\zeta T_r l}{d^4},$$

where the pressures are in Torr, $Q$ is the mass flow rate in sccm, $l$ is the length of the chamber in cm, $d$ is the diameter of the orifice in cm, and $T_r = T(K)/T_c$, where $T_c$ is the critical temperature of the gas. If $T_r \ll 1.5$, the viscosity $\zeta$ in Poise is given by:\(^{16}\)

$$\zeta = 0.34 \frac{\xi}{T_r^{0.94}},$$

where $\xi = T_c^{\frac{3}{2}} M^{\frac{1}{2}} P_c^{\frac{1}{2}}$ is the viscosity parameter, $P_c$ being the critical pressure. For the other cases, $\zeta$ (in Poise) is given by:\(^{16}\)

$$\zeta = \frac{0.1778}{\xi} (4.58T_r - 1.67)^{\frac{5}{2}} \times 10^{-7}.$$  

Table 2 summarizes the parameters $\xi$ and $T_c$ for xenon and argon.

Table 2. Compressible gas parameters for xenon and argon\(^{16}\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Xenon</th>
<th>Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi$</td>
<td>0.0151</td>
<td>0.0276</td>
</tr>
<tr>
<td>$T_c$ (K)</td>
<td>289.8</td>
<td>151.2</td>
</tr>
</tbody>
</table>
For a grid with multiple circular apertures such as the ion extraction grids, it is possible to apply Poiseuille’s law to each of these apertures. Considering $N$ apertures of the same diameter $d$ through a grid of length $l$, we have for each aperture

$$P_1^2 = P_2^2 + \frac{0.78Q\zeta T_l}{d^4},$$

(7)

where $Q_i$ is the mass flow rate going through each aperture. Since all these holes have the same diameter and width, $Q_i$ is the same for all the apertures. We denote it as $Q_a$. Since all these holes can be considered as pipes in parallel, we have the following relation for the mass flow rate

$$Q = \sum_{i=1}^{N} Q_i = NQ_a.$$  

(8)

Combining Eqs. (7) and (8), we obtain

$$P_1^2 = P_2^2 + \frac{0.78Q\zeta T_l}{Nd^4}.$$  

(9)

Figure 5 shows the estimation of the discharge chamber pressure for the two grid configurations detailed in Section II.B.1 and II.B.2.

![Figure 5. Discharge chamber pressure upstream of the grids, for the single-hole grid configuration (blue line, square markers) and the extraction grids configuration (red line, circle markers).](image)

### D. Performance prediction

The thrust created by an ion thruster in the space-charge limit is given by:

$$\frac{T}{A} = \frac{8}{9} \epsilon_0 \left( \frac{V_a}{L} \right)^2,$$

(10)

where $A$ is the area of a single-hole on the accelerator grid. We also define the total efficiency and mass efficiency as:

$$\eta_T = \frac{P_{\text{jet}}}{P_{\text{in}}} = \frac{T^2}{2m_p P_{\text{in}}},$$

(11)

$$\eta_M = \frac{\dot{m}_i}{\dot{m}_p} = \frac{T_B M}{e \dot{m}_p},$$

(12)
where $P_{\text{jet}}$ and $P_{\text{in}}$ correspond to the total extracted beam power and to the total input electrical power, respectively; $\dot{m}_{i}$ and $\dot{m}_{p}$ correspond to the ion mass flow rate and propellant mass flow rate, respectively; and $I_{B}$ and $M$ correspond to the beam current and atomic mass of the propellant. Equation 12 tells us how much propellant is being ionized in the discharge chamber. The total input power for the thruster is estimated to be equal to 8 W, with 1 W dedicated to ionization, and 7 W for ion extraction. Table 3 sums up the nominal values for estimation of the thrust and efficiencies, for both argon and xenon propellant. Using Refs. 8 and 9, the mass flow rate for xenon is estimated to be 0.25 sccm, which corresponds to a target ion beam current of 5 mA and an input microwave power of 1 W.

### Table 3. Nominal parameters for the new version of the MMIT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Argon</td>
</tr>
<tr>
<td>Beam current $I_{B}$ (mA)</td>
<td>5</td>
</tr>
<tr>
<td>Distance between grids $L$ (mm)</td>
<td>0.508</td>
</tr>
<tr>
<td>Potential difference (ions) $V_{a}$ (V)</td>
<td>2280</td>
</tr>
<tr>
<td>Single aperture diameter $D$ (mm)</td>
<td>1.3208</td>
</tr>
<tr>
<td>Ionization power $P_{0}$ (W)</td>
<td>1</td>
</tr>
<tr>
<td>Total input power $P_{\text{in}}$ (W)</td>
<td>8</td>
</tr>
<tr>
<td>Propellant mass flow rate $\dot{m}_{p}$ (sccm)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Table 4. Predicted efficiencies for the thruster mode for the given nominal parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Argon</td>
</tr>
<tr>
<td>Thrust $T$ ($\mu$N)</td>
<td>217</td>
</tr>
<tr>
<td>Total efficiency $\eta_{T}$ (%)</td>
<td>66.2</td>
</tr>
<tr>
<td>Mass utilization efficiency $\eta_{M}$ (%)</td>
<td>46</td>
</tr>
<tr>
<td>Exhaust velocity $u_{e}$ (m·s$^{-1}$)</td>
<td>105,000</td>
</tr>
<tr>
<td>Specific impulse $I_{sp}$ (s)</td>
<td>10,700</td>
</tr>
</tbody>
</table>

### III. Numerical Simulations

To validate the design and place the microwave antenna correctly, numerical simulations of the microwave radiation as well as the permanent magnetic field created by the two concentric ring magnets were conducted with COMSOL Multiphysics. Additionally, numerical simulations of the ion beam extracted from the ion optics were conducted with the FFX software.

A simplified model of the discharge chamber was created to model the magnetic and electric fields of the ion thruster. The discharge chamber contains the two magnets, the yoke plate, the SMA candlestick, its shield, and the surrounding Macor (front plate, back plate, discharge chamber). Fillets are added where necessary to avoid the corner effect inherent to finite element methods. The front grid is assumed to be completely sealed and grounded. Figure 6 shows the different parts of the simplified model.

#### A. Magnetic field simulation

The magnetic field simulation is used to determine the location of the ECR zone for a given frequency, the thickness of the yoke plate, and a range of positions for the antenna. The antenna is not included in this model. Simulations were run for various yoke plate thicknesses, ranging from 0.5 mm to 2.5 mm, with a step of 0.25 mm. Results for thicknesses of 0.5 mm, 1.5 mm, and 2.5 mm are shown in Fig. 7. It can be seen...
that the thickness of the yoke plate has little effect on the structure of the magnetic field in the discharge chamber. A flux density varying between 0.3 and 0.55 T is seen in the region in front of the two magnets. Given materials available to us, we chose a thickness of 1 mm for the yoke plate.

The electron cyclotron frequency can also be calculated through a magnetic field simulation, and gives us information about the regions of interest for the ECR discharge. The electron cyclotron frequency is given by:

$$f_c (\text{Hz}) = \frac{eB}{2\pi m_e}.$$  \hspace{1cm} (13)

A contour plot of electron cyclotron frequency in the region in front of the two magnets is shown on Fig. 8. Results were limited to a range of 4 to 8 GHz, which corresponds to attainable microwave frequencies with the equipment used.

The placement of the antenna is important for the ECR discharge, as a range of frequencies covering 4 GHz is produced along only 1.0 mm, as shown on Fig. 8. Given our original choice of 5 GHz for the microwave radiation frequency, the antenna has to be placed at most 2 mm in front of the magnets.

**B. Electromagnetic simulation**

Assuming that the velocity of the electrons parallel to the magnetic field lines, $$v_{\parallel}$$, is constant, the power delivered to the electrons passing inside the ECR zone by an oscillating electric field is given by:

$$E_{\text{ECR}} = \frac{\pi e E_{\perp}^2}{v_{\parallel} \left| \frac{\partial B}{\partial s} \right|}.$$  \hspace{1cm} (14)

where $$\left| \frac{\partial B}{\partial s} \right|$$ is the gradient of the flux of the magnetic field along a field line, and $$E_{\perp}$$ is the component of the electric field perpendicular to the magnetic field. Thus, the optimal power delivered by the microwave radiation is obtained when the electric field lines are strictly perpendicular the magnetic field lines. To quantify the energy transferred to the electrons, we use the *index of ECR heating* defined in Ref. 8:

$$I_{\text{ECR}} = \frac{E_{\perp}^2}{\left| \frac{\partial B}{\partial s} \right|}.$$  \hspace{1cm} (15)

The calculation of $$E_{\perp}^2$$ was obtained by decomposing the electric field vector in a local reference frame formed by the magnetic field and its normal, with unit vectors $$\vec{b} = \frac{\vec{B}}{\left| \vec{B} \right|}$$ and $$\vec{n}$$. The component of the electric field parallel to the magnetic field, $$E_{\parallel}$$, is given by:

$$E_{\parallel} = \vec{E} \cdot \vec{b} = \frac{\vec{E} \cdot \vec{B}}{\left| \vec{B} \right|}.$$  \hspace{1cm} (16)
We also have the magnitude of the electric field:

\[ |\vec{E}|^2 = E_{\perp}^2 + E_{\parallel}^2. \]  \hspace{1cm} (17)

Therefore, we obtain:

\[ E_{\perp}^2 = |\vec{E}|^2 - \left( \frac{\vec{E} \cdot \vec{B}}{|\vec{B}|} \right)^2. \]  \hspace{1cm} (18)

A time-harmonic electromagnetic simulation was conducted with COMSOL Multiphysics to find the optimal placement of the antenna, based on the electric field and magnetic field angle, and on the ECR index. It was assumed for the simulation that the electromagnetic field created by the antenna is not affected by the permanent magnetic field created by the magnets. The antenna has a thickness of 0.6 mm, and is connected to an SMA candlestick which has a diameter of 1.2 mm. The antenna has the shape of a ring. The frontal surface of the antenna is located between 0.8 and 2.0 mm away from the permanent magnets. A microwave signal with a 5-GHz frequency and 5 W of power is fed to the antenna.

The dot product between the electric field and magnetic field was calculated to obtain the local angle between the electric field and magnetic field:

\[ \vec{E}_{\text{EM}} \cdot \vec{B}_{\text{MF}} = |\vec{E}_{\text{EM}}| \cdot |\vec{B}_{\text{MF}}| \cos \theta, \]  \hspace{1cm} (19)

where \( \theta \) is the angle between the two fields, \( \vec{E}_{\text{EM}} \) is the electric field obtained from the time-harmonic electromagnetic simulation, and \( \vec{B}_{\text{MF}} \) is the magnetic field obtained from the magnetic field simulation. Equation (19) gives the angle:

\[ \theta = \arccos \left( \frac{\vec{E}_{\text{EM}} \cdot \vec{B}_{\text{MF}}}{|\vec{E}_{\text{EM}}| \cdot |\vec{B}_{\text{MF}}|} \right). \]  \hspace{1cm} (20)

The average value of \( \theta \) on the exposed ECR zone is obtained by performing the surface integral of Eq. (20):

\[ \bar{\theta} = \frac{1}{A_{\text{ECR}}} \int_{\text{ECR}} |\theta| \, dS, \]  \hspace{1cm} (21)
where we took the absolute value of the integrand since the direction of either field is not of importance.

The ECR zone was limited to the frequencies in the $5 \pm 0.05$ GHz range. An adaptive mesh refinement (AMR) was used to locate the ECR zone more precisely. The mesh for the numerical simulation is refined around the zone corresponding to an electron cyclotron frequency of 5 GHz. Figure 9 shows the mesh before and after the adaptive mesh refinement. The ECR zone has a high mesh density, thus leading to better accuracy for average angle calculations.

Table 5 shows the average angle between the two fields for various distances between the front of the antenna and the front of the magnets, as well as the average perpendicular electric field component $E_{\perp}$, and the average ECR index $I_{ECR}$. For distances between the magnets and the antenna of less than 1.4 mm, the average angle is found to be same, equal to 94.3°. With the exception of the distance of 1.8 mm, the index of ECR heating decreases as the distance decreases. The maximum index of ECR heating is obtained for an antenna position of 1.8 mm away from the magnets.

Figure 10 shows the values for the angle between the electric and permanent magnetic fields in the ECR zone for different distances between the antenna and the magnets. The configurations with a distance of 0.8 and 1.4 mm show the largest exposed ECR zone, as well as angles closer to 90°.

C. Grid optics simulation

The FFX software was used to validate the design of the grid optics. FFX is a three-dimensional simulation software that is able to model the electrostatic acceleration of an ion beamlet through a multi-grid setup, and to model the erosion of the grids. Details of the implementation of the FFX code, solvers used, and overall operation can be found in Refs. 18–20. The software was used only to perform the simulation of the...
Table 5. ECR exposed area, and average electric and magnetic field angle, average perpendicular electric field component, and average ECR index.

<table>
<thead>
<tr>
<th>Antenna distance (mm)</th>
<th>ECR exposed area (mm²)</th>
<th>Average angle value (°)</th>
<th>$E_{⊥}$ average (V m⁻¹)</th>
<th>$I_{ECR}$ average (V² m⁻¹ T⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.480</td>
<td>94.2</td>
<td>$2.04 \times 10^3$</td>
<td>$5.17 \times 10^5$</td>
</tr>
<tr>
<td>1.0</td>
<td>0.480</td>
<td>94.3</td>
<td>$2.63 \times 10^3$</td>
<td>$9.18 \times 10^5$</td>
</tr>
<tr>
<td>1.2</td>
<td>0.480</td>
<td>94.3</td>
<td>$3.17 \times 10^3$</td>
<td>$1.30 \times 10^6$</td>
</tr>
<tr>
<td>1.4</td>
<td>0.480</td>
<td>94.3</td>
<td>$3.63 \times 10^3$</td>
<td>$1.59 \times 10^6$</td>
</tr>
<tr>
<td>1.6</td>
<td>0.468</td>
<td>94.7</td>
<td>$4.21 \times 10^3$</td>
<td>$2.51 \times 10^6$</td>
</tr>
<tr>
<td>1.8</td>
<td>0.447</td>
<td>95.4</td>
<td>$4.87 \times 10^3$</td>
<td>$3.02 \times 10^6$</td>
</tr>
<tr>
<td>2.0</td>
<td>0.441</td>
<td>95.7</td>
<td>$5.21 \times 10^3$</td>
<td>$2.67 \times 10^6$</td>
</tr>
</tbody>
</table>

Figure 10. Contour plot of the absolute value of the electric field and magnetic field angle $|\theta|$ (in °) in the ECR zone, for an antenna to magnets distance of (a) 0.8 mm, (b) 1.4 mm, and (c) 2.0 mm. Results are limited to the range 90±10°.

The ion beam and to ensure that the ion impingement on the grids was minimal. The software was also used to determine the transparency of the ion optics, and the divergence angle of the ion beam. The transparency for ion optics is defined as:  

$$\tau = \frac{I_b}{I_b + I_s + I_a}, \quad (22)$$

where $I_b$, $I_s$, and $I_a$ are the ion beamlet current, screen grid current, and accelerator grid current, respectively. The ion beamlet current $I_b$ is obtained by dividing the total ion beam current by the number of
apertures in the grids. Given our initial ion beam current, we obtained an ion beamlet current of 0.135 mA.

Argon gas at a 300 K temperature was considered, with a plasma potential in the discharge chamber equal to 10.0 V. The screen grid was set to a potential of 0 V, while the accelerator grid was set to a potential of $-2,280$ V, thus ensuring a potential difference equal to the one calculated with Child’s law (Eq. (1)) in Section II.B.2. A mass propellant efficiency of 46.0% was considered, as calculated in Section II.D with Eq. (12). Table 6 details all the input parameters of the simulation for the nominal parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Grid type</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Propellant mass (amu)</td>
<td>39.948</td>
</tr>
<tr>
<td>Propellant temperature (K)</td>
<td>300</td>
</tr>
<tr>
<td>Propellant utilization efficiency (%)</td>
<td>46.0</td>
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<tr>
<td>Beamlet current (mA)</td>
<td>0.135</td>
</tr>
<tr>
<td>Upstream plasma potential (V)</td>
<td>10</td>
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<tr>
<td>Upstream electron temperature (eV)</td>
<td>6.0</td>
</tr>
<tr>
<td>Upstream ion temperature (eV)</td>
<td>0.043</td>
</tr>
<tr>
<td>Downstream plasma potential (V)</td>
<td>$-1,710$</td>
</tr>
<tr>
<td>Downstream electron temperature (eV)</td>
<td>1.0</td>
</tr>
<tr>
<td>Downstream ion temperature (eV)</td>
<td>0.043</td>
</tr>
<tr>
<td>Screen grid potential (V)</td>
<td>0</td>
</tr>
<tr>
<td>Accelerator grid potential (V)</td>
<td>$-2,280$</td>
</tr>
<tr>
<td>Accelerator grid current (mA)</td>
<td>0</td>
</tr>
</tbody>
</table>

Results from the FFX simulation are shown in Figs. 11, and 12. Both Figs. 11 and 12 show that the ion beam is focused and show the existence of a plasma sheath upstream of the screen grid. Figure 11 shows that the electrons are confined within the discharge chamber.

Additional results from the simulation include the divergence angle of the ion beam, equal to 23.6°, and the screen grid current, equal to 0.25 mA, which is below the maximum current acceptable by our voltage sources. Using Eq. (22), the transparency is found to be 35.0%.

It is worth noting that the grids are not optimized. Indeed, the transparency should be in the 70–80% range, and the ion beam divergence angle should be in the 10–20° range. However, the ion beam is focused and the screen grid current is within an acceptable range, which is enough for our testing purposes. Further iterations of the thruster will improve on these preliminary grid results and increase the grid transparency, reduce the ion beam divergence, and decrease the screen grid current.

IV. Experimental Setup and Results

The new version of the MMIT was able to create a plasma for both the single-grid and extraction-grid configurations (Fig. 13).

A. Vacuum chamber

The vacuum chamber used for testing has a diameter of 0.7 m and a length of 1 m. Two pumps ensure evacuation to pressures down to $1 \times 10^{-5}$ Torr. A BOC Edwards IPUP dry pump gets the chamber down to approximately $5 \times 10^{-3}$ Torr. A CTI-Cryogenics Cryo-Torr cryopump then evacuates the chamber to high-vacuum pressures of $1 \times 10^{-5}$ Torr. Pressure inside the chamber is monitored with a MKS Series 999 Quatro Multi-sensor pressure transducer, connected to a MKS Series 999 Controller pressure reader. Pressure reading accuracy is $0.01 \times 10^n$ Torr, where $n$ is the order of the pressure measurement. The temperature of the head of the cryopump is monitored with a Lakeshore Cryotronics 818 Cryopump Monitor.

A Hewlett-Packard 8683D Signal Generator provides the microwave signal, which is amplified by a Hughes
Figure 11. Results of FFX for the normal input parameters. (a) Ion density (1/m$^3$). (b) Neutral density (1/m$^3$). (c) Electron density (1/m$^3$).

Figure 12. (a) Ion pathlines. (b) Plasma sheath location.

8010H Traveling Wave Tube Amplifier. Power transmitted to and reflected from the microwave antenna was measured with a Narda bi-directional 20-dB coupler and two Mini circuits PWR-SEN-6G+ which operate in the range of 1 to 6 GHz. A Harris Type 306A double stub tuner is used to match the microwave line and the antenna to 50 Ω.

The direct current voltage required to electrostatically accelerate the ions from the plasma is provided by a Stanford Research Systems, Inc. Model PS310 high voltage power supply that has maximum DC voltage rating of 1250 V and a Stanford Research Systems, Inc. Model PS350 high voltage power supply that has maximum DC voltage rating of 5000 V.
A 1/8-in.-diameter stainless steel pipe with a CF gas feed-through allow the argon propellant (purity 99.999%) to be fed to the thruster. Argon has been chosen as the first propellant for the thruster to reduce cost of operation. Xenon will eventually replace argon. The thruster is interfaced to the vacuum chamber piping with a 1/16-in-diameter inlet pipe through a Swagelok fitting. A Horiba-Stec SEC-7320 Mass Flow Controller allowing mass flow rates up to 1 sccm and a MKS Vacuum Gauge Measurement and Control System Type 146 provide control over the mass flow rate.

B. Plasma power requirements

The ECR discharge was tested and characterized in terms of power requirements for both sustaining and creating the plasma. The single-hole grid was used for that experiment. Argon mass flow rate was within the range of 0.01 to 0.1 sccm. The power required to create the plasma was obtained by slowly increasing the input power by increments of 0.2 W, while the power required to sustain the plasma was obtained by decreasing the input power by decrements of 0.1 W until plasma extinction. Power requirements to create and sustain the plasma are shown in Fig. 14.

Figure 14. Microwave power for the thruster to create the plasma (red squares) and to sustain the plasma (green circles)
V. Conclusion

A new version of the Miniature Microwave Ion Thruster was designed. The thruster makes use of both microwave radiation and permanent magnetic fields to create a plasma through ECR discharge. Using 0.15 sccm of argon, the ion engine is expected to have a mass utilization efficiency of 46%, develop a thrust of 217 $\mu$N, and use 8 W of total electric power, of which 1 W is used for ionization.

Numerical simulations of the permanent magnetic field structure and microwave radiation inside the discharge chamber guided the placement of the microwave antenna 1.8 mm away from the permanent magnets, while simulations of the ion optics showed a screen grid current of 0.25 mA, an ion beam divergence angle of 23.6°, and a transparency of 35.0%. Further iterations of the ion thruster will optimize the ion optics.

The thruster was tested in a vacuum environment at The Pennsylvania State University. The power required to create a plasma was found to be in the 3 to 4 W range, while the power to sustain the plasma was 0.5 W, for mass flow rates between 0.01 sccm and 0.1 sccm of argon.

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References