DEVELOPMENT OF A MINIATURE MICROWAVE-FREQUENCY ION THRUSTER

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ABSTRACT

Miniature ion thrusters offer low-thrust, high specific impulse capabilities to small spacecraft for use in attitude and orbit control systems. This thesis presents the design of a miniature ion thruster called the Miniature Microwave-frequency Ion Thruster (MMIT). This thruster uses coaxially inputted microwave power at 4.2 GHz with argon or xenon propellant injected via a gas plenum at 0.15 sccm during nominal operating conditions. The optics use a two-grid system with the screen grid kept at a nominal voltage of 1500 V and the accelerator grid kept at −500 V. In this operational mode, the MMIT is predicted to produce a thrust of approximately 258 μN with a total efficiency of 32%, mass utilization efficiency of 32%, and an electrical efficiency of approximately 50%. This configuration will also produce exit velocities of approximately 54 km/s, which translates into a specific impulse of approximately 5500 s, assuming complete single ionization of the propellant, no exiting plume angle, and a constant electric field across the grids. These predictions will be tested with experiments in a vacuum chamber at 10^{-6} Torr with a Langmuir probe and Faraday cup used to provide measurements of exiting beam properties.
# Table of Contents

LIST OF FIGURES .......................................................................................................................... III

LIST OF TABLES ............................................................................................................................... IV

NOMENCLATURE ............................................................................................................................... V

ABBREVIATIONS ............................................................................................................................... VI

ACKNOWLEDGMENTS ....................................................................................................................... VII

1. INTRODUCTION ............................................................................................................................ 1

   1.1 OVERVIEW OF ION PROPULSION ......................................................................................... 1
   1.2 OVERVIEW OF MMIT PROJECT ......................................................................................... 5

2. THRUSTER DESIGN ....................................................................................................................... 9

   2.1 YOKE PLATE ASSEMBLY ..................................................................................................... 10
   2.2 CHAMBER ASSEMBLY ......................................................................................................... 12
   2.3 OPTICS ASSEMBLY ............................................................................................................. 14
   2.4 ASSEMBLY AND INTEGRATION ........................................................................................ 19

3. THEORETICAL PREDICTIONS ..................................................................................................... 20

4. EXPERIMENTAL SETUP ............................................................................................................... 24

5. SUMMARY AND FUTURE WORK ............................................................................................... 28

REFERENCES ..................................................................................................................................... 30
List of Figures

Figure 1. Schematic of Cylindrical Ion Thruster ........................................................................3
Figure 2. Schematic of Grid Apertures for a Typical Optics Arrangement .......................... 5
Figure 3. Miniature Microwave-frequency Ion Thruster (MMIT) ....................................... 6
Figure 4. Potential Thruster Arrangements for Switching Scheme ...................................... 7
Figure 5. Grid Design for JAXA Switching Scheme ................................................................. 8
Figure 6. Three-Dimensional Representation of MMIT ......................................................... 9
Figure 7. Exploded View of MMIT Showing the Main Assemblies ...................................... 10
Figure 8. MMIT's Yoke Plate Assembly .................................................................................. 11
Figure 9. MMIT Propellant Injection Scheme ....................................................................... 12
Figure 10. MMIT Chamber Assembly ..................................................................................... 13
Figure 11. MMIT Optics Assembly ......................................................................................... 15
Figure 12. Redesigned MMIT Screen Grid ............................................................................ 17
Figure 13. Child-Langmuir Length vs. Ion Mass and Beam Current .................................... 18
Figure 14. Relation Between Beam Current and Microwave Power for JAXA's µ1 .......... 21
Figure 15. Vacuum Chamber Used for Testing MMIT ......................................................... 25
List of Tables

Table 1. Components Within the Yoke Plate Assembly................................................................. 11
Table 2. Components Within the Chamber Assembly................................................................. 14
Table 3. Components Within the Optics Assembly........................................................................ 15
Table 4. MMIT Grid Geometries.................................................................................................. 17
Table 5. MMIT Component Masses ............................................................................................. 19
Nomenclature

$d_s$ Screen grid aperture diameter, m
$e$ Elementary charge, $1.609 \times 10^{-19}$ C
$g$ Gravitational constant, 9.81 m/s$^2$
$I_b$ Ion beam current, A
$I_{sp}$ Specific impulse, s
$l_e$ Sheath thickness, m
$l_g$ Distance between grids, m
$M$ Particle mass, kg
$m_i$ Ion mass, kg
$P_b$ Ion beam power, W
$P_{in}$ Power input to thruster, W
$P_{jet}$ Power extracted from thruster, W
$P_o$ Power required for ionization, W
$P_T$ Total power, W
$q$ Mean ion charge, $1.609 \times 10^{-19}$ C
$T$ Thrust, N
$t_s$ Grid thickness, m
$V_b$ Ion beam potential, V
$V_{ex}$ Exhaust velocity, m/s
$V_T$ Total voltage, V
$\varepsilon_0$ Permittivity of free space, $8.85 \times 10^{-12}$ F/m
$\eta_e$ Electrical efficiency
$\eta_m$ Mass utilization efficiency
$\eta_T$ Total efficiency
## Abbreviations

<table>
<thead>
<tr>
<th>ID</th>
<th>Inner Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
</tr>
<tr>
<td>MFC</td>
<td>Mass Flow Controller</td>
</tr>
<tr>
<td>MMIT</td>
<td>Miniature Microwave-frequency Ion Thruster</td>
</tr>
<tr>
<td>MRIT</td>
<td>Miniaturized Radio-Frequency Ion Thruster</td>
</tr>
<tr>
<td>OD</td>
<td>Outer Diameter</td>
</tr>
<tr>
<td>sccm</td>
<td>standard cubic centimeters per minute</td>
</tr>
</tbody>
</table>
Acknowledgments

I would like to thank my thesis advisers Dr. Sven G. Bilén and Dr. Michael M. Micci for the chance to conduct this research and for their help and guidance throughout this project. Specifically, I would to thank Dr. Bilén for his guidance throughout my education at Penn State as both a professor and the adviser of the Student Space Programs Laboratory (SSPL). I would also like to thank Tom Trudel, the designer of the MRIT, for his help throughout this project. I would also like to thank several students who helped make this work possible. First, I would like to thank Pierre-Yves Taunay for his help as a research partner and for continuing to develop MMIT in the future. Second, I would like to thank Erica Capalungan, Jeff Hopkins, and Allen Kummer for their help setting up and calibrating the equipment used to test MMIT. Finally, I would like to thank the other members of Penn State’s Plasmas Group for their assistance each and every week.
1. Introduction

1.1 Overview of Ion Propulsion

Ion propulsion systems provide low thrust, high specific impulse, and incredibly long burn times with a small amount of propellant. With thrusts generally ranging between 1 µN–10 N, these systems are not viable for use as launch systems or quasi-impulsive maneuvers, but they offer a whole range of applications that chemical systems cannot. Historically, these systems have been used aboard spacecraft for several different applications including low-thrust trajectories, station keeping, and deep space navigation.

Originally theorized by Robert Goddard in 1906 and Konstantin Tsiolkovskiy in 1911, ion propulsion was first practically realized in the 1960s aboard U.S. and Russian spacecraft [3]. These early systems typically used cesium or mercury for propellants, as opposed to the noble gas propellants that are used in more modern systems. Initially used as a means of station-keeping, applications of electric propulsion systems were expanded in the following decades. Beginning in the 1990s they were successfully employed on deep space missions such as NASA’s Deep Space 1 and Dawn, ESA’s SMART-1, and JAXA’s Hayabusa. In the near future, these systems will likely be used more prominently in attitude control systems and in orbit control systems about asteroids and other non-spherical bodies. A more complete history of the development of this field can be found in Jahn and Choueiri [6] along with other references on the subject.
Ion propulsion, or more generically Electric Propulsion, encompasses many different types of propulsion mechanisms including, but not limited to, ion thrusters, Hall thrusters, pulsed plasma thrusters, and magnetoplasmadynamic thrusters. Each of these propulsion systems relies upon different mechanisms for producing thrust, but on the simplest level, each system operates by producing ions from a neutral fuel source (typically xenon), accelerating the ions through a large voltage difference and/or magnetic field, extracting the ions at a large exit velocity, and neutralizing the exiting beam to prevent back-streaming and charge accumulation. The methods these propulsion systems use to create and extract ions vary radically. This paper will focus specifically on miniature (approximately 200 μN of thrust) ion thrusters that use microwave-frequency (approximately 4.2 GHz) radiation to ionize the propellant.

A schematic of a typical ion thruster is shown in Figure 1. For ion thrusters with a cylindrical discharge chamber, the inert gas propellant is pumped into the center of the discharge chamber through a yoke plate, i.e., the plate that forms the backing to the discharge chamber. Upon entering the discharge chamber, the gas is excited by some means in order to create a plasma. There are a number of means for creating this plasma, but the principal techniques include electron bombardment and photoexcitation. This paper will focus on microwave-frequency plasma generation techniques. This technique involves placing a ring antenna with a coaxial input in the discharge chamber that operates at around 4.2 GHz. The radiation excites and partially ionizes the gas, thus creating a plasma within the chamber. The permanent ring magnets in and around the discharge chamber create a field that inhibits electron loss by initiating cyclotron motion. This motion eventually causes the free electrons to be absorbed into the walls of the discharge chamber or an anode meant for this purpose depending on the system’s design.
Being much slower-moving particles, the ions are not as affected by the $qv \times B$ magnetic force as are the electrons. These positively charged particles continue moving along the length of the chamber until they reach the grid system. Typically, the grid system comprises two grids: the screen grid and the accelerator grid. The former is kept at high positive voltage relative to the system (around $+1500$ V), and the latter is kept at a negative voltage (around $-500$ V). This substantial voltage difference accelerates the particles to large exit velocities on the order of $10–100$ km/s [5]. Upon exiting, the beam of positively charged particles is neutralized with an electron-emitting source. This action prevents the positively charged particles from back streaming and attaching to the spacecraft, an action that would negate the thrust that was achieved through expelling the particles.

![Figure 1. Schematic of Cylindrical Ion Thruster [10]](image)

Each grid contains a configuration of apertures. The diameter and arrangement of these apertures depends on a number of factors, including propellant type, particle energies, and
mission characteristics like required operational lifetime. The screen and accelerator grids, together known as the ion optics, mirror one another in terms of aperture position, but aperture diameter usually varies between the two. In this configuration, the optics that produces a beamlet (an ion beam from a single pairing of an accelerator and screen aperture) has five degrees of freedom: screen grid thickness, accelerator grid thickness, screen grid aperture diameter, accelerator grid aperture diameter, and distance between the screen and accelerator grids. A schematic of this arrangement is shown in Figure 2. The value of each of these parameters independently impacts the trajectory of individual ions, and inevitably the efficiency of the entire propulsion system. An overview of how these parameters were chosen for the Miniature Microwave-Frequency Ion Thruster’s (MMIT) optics is provided in Chapter 2. Predictions relating to performance of these optics are subsequently provided in Chapter 3.

The design of ion thrusters can differ significantly based on a specific mission’s requirements. The above outline summarizes basic operating principles for an ion thruster like the MMIT, but other ion thrusters may operate differently with different components. Several texts are available that provide an in-depth treatment of electric propulsion and the physics behind it including Jahn’s *Physics of Electric Propulsion* [5] and Goebel and Katz’ *Fundamentals of Electric Propulsion* [3]. The information garnered from these and other texts along with lessons learned from ion thrusters previously engineered at Penn State [9] were used to guide the design of MMIT. Reasons for design decisions are provided as appropriate.
1.2 Overview of MMIT Project

This paper focuses on the development of a specific ion thruster. The MMIT (pictured in Figure 3) is the latest ion thruster developed at Penn State, with heritage from the Miniaturized Radio-frequency Ion Thruster (MRIT; a radio-frequency ion thruster previously developed at Penn State) used to help guide its design [9]. MMIT is in the miniature range (~200 µN thrust). It uses microwave-frequency (4.2 GHz) radiation supplied via a ring antenna and coaxial cable to ionize the propellant. The thruster is designed to operate with xenon propellant, but it will be tested with argon propellant to reduce test and development costs. It has a cylindrical discharge chamber that uses a gas plenum to inject the neutral propellant from six circularly symmetric ports. Specific details relating to the design of MMIT are provided in Chapter 2.
Unlike most ion thrusters, the MMIT is designed to operate in two modes: thruster and neutralizer. Thruster mode is typical for most ion thruster systems, but the neutralizer mode will allow the MMIT to extract electrons rather than ions. With multiple MMITs, an external cathode to neutralize the exiting ion beamlets is not required. Instead, two MMITs could be paired together (one as a thruster and one as a neutralizer) in order to produce a neutralized exit plume with net thrust.

This project seeks to verify and expand upon recent developments in the field of electric propulsion. Experiments conducted by the Japan Aerospace Exploration Agency (JAXA) have demonstrated that certain grid geometries give electric propulsion systems the ability to operate in thruster or neutralizer mode [1]. When operated in tandem this means that one thruster is
responsible for expelling ions while the other expels electrons. Several configurations for this switching scheme are depicted in Figure 4.

The optics that allows this switching scheme is depicted in Figure 5. As is usual, the apertures form a hexagonal pattern for good ion transparency [3], but six larger apertures interrupt this pattern. These larger apertures are meant for electron extraction when the system is operating in neutralizer mode; the larger size is based on physical characteristics of electrons relative to the xenon ions.
In general, this thesis presents the design of new ion thruster developed at Penn State. Chapter 2 details the overall design of MMIT. Chapter 3 provides theoretical predictions regarding the performance of MMIT in operation. Chapter 4 provides information relating to planned experiments performed with MMIT. Chapter 5 concludes the paper with lessons learned and suggestions for future work.
2. Thruster Design

The MMIT’s design was largely inspired by the Penn State’s MRIT system [9] and JAXA’s μl thruster [1]. This design allows the MMIT to operate in a mode-switching scheme similar to JAXA’s design. A three-dimensional representation of MMIT is shown in Figure 6. The MMIT has a cylindrical discharge chamber, an axial propellant injection system, and two circular grids for ion extraction. The yellow item behind the thruster’s yolk plate is a right-angled, SMA candlestick antenna used to inject microwave radiation at 4.2 GHz. The optics is also designed to be replaceable between tests.

![Three-Dimensional Representation of MMIT](image)

Figure 6. Three-Dimensional Representation of MMIT

The MMIT can be broken down logically into three main sections: the yoke plate assembly, the chamber assembly, and the optics assembly. An exploded view of MMIT with these three assemblies separated can be seen in Figure 7. The following three subsections detail the design of each of these assemblies.
2.1 Yoke Plate Assembly

The yoke plate assembly includes several components: the inlet pipe, the ring antenna, the inlet plate, the gas plenum, and the permanent ring magnets. The major structural components are made of a carbide-machinable ceramic known as Macor™. This material is meant for high temperature applications (up to 1000 °C) [7]. Macor is also a great electrical and thermal insulator so it can sustain high temperature plasma without shielding the fields that allow the plasma to remain. The magnets are composed of alnico, which is a material that retains its magnetic properties at operating temperatures up to 975 °F [8]. In this arrangement, these concentric ring magnets establish a 0.3-T field near the propellant inlet. The inlet pipe is 1/16-in.-diameter stainless steel. The ring antenna is composed of a standard right-angled SMA
“candlestick” adaptor soldered to silver-coated stainless steel wire to form the ring. Table 1 summarizes all of the components in this assembly.

![Figure 8. MMIT's Yoke Plate Assembly](image)

**Table 1. Components within the Yoke Plate Assembly**

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Material</th>
<th>Principal Dimensions (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Pipe</td>
<td>Stainless Steel</td>
<td>OD: 0.0625 ID: 0.0313</td>
</tr>
<tr>
<td>Ring Antenna</td>
<td>Silver Coated Copper</td>
<td>N/A</td>
</tr>
<tr>
<td>Inlet Plate</td>
<td>Macor</td>
<td>OD: 1.5 t: 0.25</td>
</tr>
<tr>
<td>Gas Plenum</td>
<td>Macor</td>
<td>OD: 0.75 t: 0.375</td>
</tr>
<tr>
<td>Inner Ring Magnet</td>
<td>Samarium Cobalt</td>
<td>OD: 0.125 ID: 0.0625</td>
</tr>
<tr>
<td>Outer Ring Magnet</td>
<td>Samarium Cobalt</td>
<td>OD: 0.375 ID: 0.25</td>
</tr>
</tbody>
</table>
This assembly supports the injection of propellant, the introduction of ionizing radiation, and the containment of electrons via an axisymmetric magnetic field. Propellant is injected via the inlet tube at a flow rate of 0.15 sccm. This tube is epoxied to the inlet plate, which, in turn, is secured to the gas plenum. Inside the plenum, the flow is directed to one of six 0.01-in.-diameter apertures in a circular pattern. This aperture pattern is concentric and lies in between the two ring magnets, so the flow enters the discharge chamber between the two magnets (depicted in Figure 9). At this point, the microwave radiation partially ionizes the propellant. The electrons begin cyclotron motion in the permanent magnetic field, and they are either absorbed in the discharge chamber walls or extracted through the optics depending on in which mode the thruster is set.

![Figure 9. MMIT Propellant Injection Scheme](image)

### 2.2 Chamber Assembly

The chamber and yoke plate assemblies are permanently affixed to one another to prevent leaking during operation. The gas plenum on the yoke plate is designed to fit within the 20-mm-
diameter-by-15-mm-long Macor discharge chamber. The discharge chamber is, in turn, sheathed by a stainless-steel Faraday cage. The neck cut into the discharge chamber is where the front end of the gas plenum rests. This interface offers a better seal and is, therefore, more conducive to creating a plasma in a quasi-vacuum environment relative to a constant diameter interface. The circular piece at the front end of the chamber is composed of Teflon™. It provides a fastener interface for the optics assembly with six 2-mm-diameter holes around its perimeter. The fasteners used are made of Nylon 6/6 to prevent short circuits between the screen and accelerator grids. The semicircular holes cut along the perimeter of this component offer access to the screen grid so that it can be wired to establish a grid voltage. This arrangement is depicted in Figure 10 and the components within this assembly are detailed in Table 2.

![Figure 10. MMIT Chamber Assembly](image-url)
Within this chamber assembly, the initially neutral propellant is ionized by the coaxial microwave signal. The permanent magnets then contain the electrons while the ions are extracted through the optics (in thruster mode). Essentially, this assembly’s purpose is related to plasma containment and transport.

### 2.3 Optics Assembly

The optics assembly (depicted in Figure 11) encompasses the screen grid, accelerator grid, grid spacer, and an external mounting spacer. As described above, these components are fastened together with Nylon fasteners, and the gaps in the external mounting spacers are used to wire the grids. Each of the spacers is composed of Teflon™, a non-reactive polymer that is malleable yet well suited to the high-temperatures expected at the propellant outlet. The external spacer serves as a fastening surface and it allows the optics to be handled without damaging the accelerator grid. The grid spacer is made out of 0.01-in.-thick Teflon™, and its purpose is to put a small gap between the grids so that particles can accelerate while retaining the electrical independence of each grid relative to one another.
The optics is what makes this thruster unique. They are responsible for the thruster’s ability to operate in either thruster or neutralizer mode. Ordinarily, these grids would be constructed out of molybdenum since this material resists the plasma’s erosion, but because of cost and availability issues, the MMIT’s optics grids were fabricated out of stainless steel. This will require the grids to be replaced throughout its testing cycle, but as the thruster’s optics were designed to be removable, this is not a problem.
Similar to JAXA’s μ1 thruster, the grids contain small apertures in a hexagonal pattern for ion extraction and larger apertures for electron extraction. Ions and electrons will incidentally exit through the other’s apertures at times, which can reduce the efficiency of the system as a whole. This efficiency will also be reduced due to the fact that testing will utilize argon propellant as opposed to xenon, on which the thruster was designed to operate. Testing will verify whether or not adjusting voltages on either grid can effectively mitigate these issues.

The grid shown in Figure 11 is the ideal grid for MMIT. The aperture sizes and positions are similar to the ones used on JAXA’s μ1 [1] with some modifications that will allow MMIT to operate in additional modes.

While Figure 11 shows the ideal optics for MMIT, the design had to be adapted to accommodate available equipment and machining methods. Figure 12 shows the redesigned screen grid. The apertures are noticeably larger, but the arrangement is roughly the same as the ideal case. The ion apertures form a hexagonal pattern for good ion transparency, and the larger electron apertures are located in the same relative location. Table 4 provides information on key dimensions for each grid. This overall design will reduce the overall efficiency of the system by requiring lower current densities to achieve plasma extraction, but tuning the optics’ voltages can at least mitigate these issues.
The aperture sizes were chosen such that a Child–Langmuir sheath would be established on the screen grid when operating in thruster mode. This sheath promotes efficient extraction of ions and narrow exhaust plumes. Using Equations 2.1 and 2.2 one can determine the max beam current density \( J_{B,\text{max}} \) that can be extracted from a single aperture:

\[
J_{B,\text{max}} = \frac{4 \varepsilon_0}{9} \sqrt{\frac{2q}{M \bar{l}_e^2}} V_{\text{f}}^{3/2}
\]  

(Eqn. 2.1)

![Redesigned MMIT Screen Grid](image)
\[ l_e = \sqrt{(l_g + t_s)^2 + \frac{d_s^2}{4}} \]  
(Eqn. 2.2)

\( V_T \) is the total voltage the ions are accelerated through (2000 V), \( l_e \) is the sheath thickness, \( l_g \) is the grid separation distance, \( t_s \) is the screen grid thickness, and \( d_s \) is the screen grid aperture diameter. Assuming single ionization \((q = e)\) with xenon propellant, the max beam current density is approximately 40 mA/cm\(^2\).

Figure 13 shows that, for this max beam current, the chosen aperture diameters will establish a Child–Langmuir sheath. The larger apertures will produce beamlets that are over-focused, but design iteration following preliminary testing will help to mitigate these issues.
2.4 Assembly and Integration

Unless otherwise mentioned, all components in this thruster are epoxied together with 3M® Scotch Weld™ DP-8005 Structural Plastic Adhesive to promote strength and prevent leaking. Additionally, Loctite® Epoxi-Patch® Adhesive is used to seal sections prone to leaking, such as the inlet. Kapton™ tape is also used to prevent lateral leaking from the optics. Once completely assembled, the thruster has a mass of approximately 57.4 g. Table 5 outlines the mass of each of the major components.

Table 5. MMIT Component Masses

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Plate</td>
<td>8.1</td>
</tr>
<tr>
<td>Faraday Cage</td>
<td>17.3</td>
</tr>
<tr>
<td>Antenna</td>
<td>5.4</td>
</tr>
<tr>
<td>Plenum</td>
<td>4.6</td>
</tr>
<tr>
<td>Chamber</td>
<td>6.6</td>
</tr>
<tr>
<td>Outer spacer</td>
<td>4.4</td>
</tr>
<tr>
<td>Inner spacer</td>
<td>3.8</td>
</tr>
<tr>
<td>Plastic Fasteners</td>
<td>0.3</td>
</tr>
<tr>
<td>Antenna Fasteners</td>
<td>0.4</td>
</tr>
<tr>
<td>Grids</td>
<td>6.0</td>
</tr>
<tr>
<td>Magnets</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>57.4</strong></td>
</tr>
</tbody>
</table>
3. Theoretical Predictions

As mentioned, MMIT will operate in two modes: thruster and neutralizer. Both modes will utilize the same grid geometry. Predictions regarding MMIT’s capabilities and efficiencies in these modes are provided in this chapter.

As the neutralization technique between MMIT and JAXA’s µ1 is similar (coaxially input microwave radiation at 4.2 GHz), it can safely be assumed that the resulting beam currents will be similar in magnitude. Figure 14 depicts experimental results obtained from operating JAXA’s µ1 in thruster and neutralizer mode, respectively [1]. These graphs represent changing ion and electron beam currents as the input microwave power and flow rate are varied. Nominal operation occurs at 1 W of microwave power and a flow rate of 0.15 sccm (assumed to be xenon for now), which resulted in an ion beam current ($I_b$) of approximately 3.5 mA and an electron emission current of approximately 3.6 mA. Assuming complete single ionization of each xenon particle, the thrust delivered by the engine in thruster mode can be written as,

$$T = \frac{2M}{e} I_b \sqrt{V_b}$$  
(Eqn. 3.1)

where $T$ is the delivered thrust, $M$ is the propellant particle mass, is the value of the elementary charge ($1.609 \times 10^{-19}$ C), and $V_b$ is the voltage across which the particles are accelerated. The MMIT’s grids will nominally operate with 1500 V and −500 V on the screen and accelerator grids, respectively. Considering this information, combining it with the beam current provided
above and the mass of a xenon particle yields a net calculated thrust of approximately \(258 \, \mu N\). This value will be higher than the empirical results because the above approach neglects effects like plume angles, incomplete ionization, and the presence of multiply charged ions.

**Figure 14. Relation between Beam Current and Microwave Power for JAXA's µ1 [1]**

Efficiencies for ion thrusters are generally quoted in terms of its overall efficiency, mass utilization efficiency, and electrical efficiency. These values can be obtained using the following equations:

\[
\eta_r = \frac{P_{\text{jet}}}{P_{\text{in}}} = \frac{T^2}{2 \dot{m}_p P_{\text{in}}} 
\]  
(Eqn. 3.2)

\[
\eta_m = \frac{\dot{m}_i}{\dot{m}_p} = \frac{I_b}{e} \frac{M}{\dot{m}_p} 
\]  
(Eqn. 3.3)
\[ \eta_e = \frac{P_b}{P_T} = \frac{I_b V_b}{I_b V_b + P_0} \]  
(Eqn. 3.4)

The values here are \( P_{jet} \) for extracted beam power, \( P_m \) for total power put into the thruster (approximately 7 W), \( \dot{m}_p \) for propellant mass flow rate, \( \dot{m}_i \) for ion mass flow rate, \( P_b \) for ion beam power, \( P_T \) for total power, and \( P_0 \) for microwave ionization power (1 W). Substituting all of these values into Equations 3.2-4 yields MMIT efficiencies of \( \eta_T = 32.2\% \), \( \eta_m = 32.1\% \), and \( \eta_e = 50.0\% \). These efficiencies will be slightly reduced as a result of using argon in testing, but they should remain close in magnitude.

The final metric relating to the efficiency of the thruster is its specific impulse (\( I_{sp} \)). Electric propulsion systems have incredibly high \( I_{sp} \) values relative to chemical rockets. Effectively, this means that they use their propellant more efficiently. Specific impulse can be calculated as such:

\[ v_{ex} = \sqrt{\frac{2qV_b}{M}} \]  
(Eqn. 3.5)

\[ I_{sp} = \frac{v_{ex}}{g} \]  
(Eqn. 3.6)

The values here are \( v_{ex} \) for axial exhaust velocity and \( g \) for gravitational acceleration at sea-level on Earth (9.81 m/s\(^2\)). Substituting in these values into Equations 3.5 and 3.6 yields exhaust velocity of 54.3 km/s and a specific impulse of 5540 s. These calculations make certain ideal assumptions, such as no plume angles, completely ionized propellant, a vacuum environment,
and no significant gravity. Some of these assumptions are not entirely accurate, so these values will not be as high when measured empirically. A more realistic value for specific impulse is likely around 3000-4000 s.
4. Experimental Setup

The MMIT will undergo a battery of tests to verify the thruster’s performance in each of its modes in the near future. These experiments will be conducted in a vacuum chamber measuring approximately 0.75 m in diameter and 1.2 m long at pressures on the order of $10^{-5}$ Torr. This chamber (pictured in Figure 15), located in Penn State’s Electrical Engineering East Building, has played host to testing of several ion thrusters in the past (including the MRIT) with great success.

Aside from measuring devices, the thruster requires electronics to control the microwave power input, the propellant flow, and the voltage on the grids. To generate, measure, and control the microwave input power the following components will be used: a Hewlett Packard 8683D 2.3–13.0 GHz Signal Generator, a Hughes 8010H Traveling Wave Tube Amplifier, and a Hewlett Packard EPM-441A Power Meter. Input microwave power will be on the order of 1 W, though this value will be adjusted based on thruster performance and to identify its relation to ion beam and electron emission currents.
To control the flow of propellant into the chamber, a UNIT 8100 Mass Flow Controller used with a MKS147B Control Box will be connected to a pressurized argon tank. Some calibration is needed to modify this system (generally intended for nitrogen) to work with argon. This same setup was used with the MRIT (also run on argon), so there are calibration procedures available.

The controlled flow will be injected into the chamber via 1/8 in. Swagelok® tubing and fittings. This flow will eventually reach the 1/16-in. thruster tubing with a nominal flow rate of 0.15 sccm. This value likely will be adjusted to determine correlations between flow rate, input power, and other performance metrics.
Establishing the voltages on each of the grids and having the ability to tune these voltages is vital for successful testing. As these grids were redesigned to accommodate available machining methods, the estimated voltages for the screen and accelerator grids will likely need to be tuned to optimize thruster performance. To accomplish this, two Bertran 205B Series High Voltage Sources will be used to establish the screen and accelerator grid voltages. This test setup will require three grounds – one for the chamber and one for each voltage source. The latter two will be tied together to ensure that grids share the same reference potential, but the chamber itself will be grounded at a higher voltage relative to the grids’ ground to aid in the extraction of the ionized particles.

In solely thruster mode, MMIT will require a neutralizer, too. A thermionic emitter operating just outside of the thruster will provide the neutralizing electrons needed to cancel out the charged exhaust and prevent back-streaming – a phenomenon that negates the thrust.

The thruster’s performance in each mode will be characterized by measurements from a Faraday cup and a Langmuir probe. By varying the voltage on the Langmuir probe, one obtains a plasma current curve that can be used to obtain data relating to ion beam current and thrust, among other metrics. The Faraday cup will directly measure ion current density, which with some calculations can also reveal the system’s total thrust. Measurements taken at various angles relative to the optics will allow for the direct observation of beam dispersion and exhaust plume angles. These metrics will help to determine how optimally the grids were designed.
Currently, testing is in the set up phase. Most of the electronics have been secured, so the current work is in sensor calibration for the Langmuir probe, Faraday cup, mass flow controller, and other sensors related to vacuum chamber operation. As soon as these tasks are completed the preliminary testing of MMIT can commence, and the feasibility of self-neutralizing grid geometries can be identified.
5. Summary and Future Work

The design presented in this paper is currently being realized with preliminary testing set to begin soon. The design uses heritage from two previous thrusters: Penn State’s MRIT and JAXA’s μ1. The MMIT design present here uses microwave radiation to ionize its propellant, and a two-grid system to extract the ions through a 2000-V potential difference. Additionally, the MMIT can be set to neutralizer mode. This will cause it to extract electrons rather than ions, so when two thrusters are paired together they will produce a neutralized beam with a net thrust without needing external neutralizer systems.

Though many of these parameters are variable, the MMIT will nominally operate with a 0.15-sccm propellant flow rate, 0.3-T surface magnetic field strength, 4.2-GHz microwave frequency with 1 W of power, 1500 V fixed on the screen grid, −500 V on the accelerator grid, and a total of 6 W delivered to the grids. Design iteration will seek to limit the amount of power consumed by the thruster.

Theoretical predictions for MMIT were provided based on its design. It is assumed that, because of the similarity of μ1’s ionization method and flow rate with MMIT’s, the extracted beam currents will be approximately equal. This assumption allows one to approximate the thrust as 258 μN, the total efficiency as 32.2%, the mass utilization efficiency as 32.1%, and the electrical efficiency as 50%. Additionally, specific impulse is predicted to be approximately 5500 seconds. All of these predictions include certain limiting assumptions such as only single ionization of the propellant and neglecting plume angles. In general, these effects will lead to the MMIT being slightly less efficient than these predictions show.
Experimental methods will be used to verify and improve upon these initial calculations. Testing in a $10^{-6}$ Torr vacuum chamber with a Langmuir probe and Faraday cup providing direct measurements of exit beam properties. This allows for the incorporation of effects like plume angles in the performance calculations. It will also verify whether the beam current assumption is accurate. Adjustment of nominal operating conditions will also help to optimize thruster performance.

Aside from experimentally verifying thruster performance, other suggestions for future work include developing models of the thruster to help in the design iteration process, and developing a second thruster for testing a combination system. In the former case, models in a program like COMSOL Multiphysics will give more accurate theoretical predictions, which will help to limit the costs associated with design iteration and testing. In the latter case, Figure 4 illustrates that a multi-thruster configuration allows for full attitude and orbit control of a spacecraft without needed external neutralizer systems for each MMIT.

The inevitable goal of this research is to produce an electric propulsion system with low enough mass and power requirements to be feasible for introduction into small spacecraft orbit and attitude determination systems. The MMIT design presented in this paper is the starting point for this goal. This long-term goal will help to guide research, design, and testing of MMIT in the future.
References


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