Design of the Miniature Microwave-Frequency Ion Thruster

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Miniature ion thrusters offer low-thrust, high specific impulse capabilities to small spacecraft for use in attitude and orbit control systems. This paper presents the design of a miniature ion thruster called the Miniature Microwave-frequency Ion Thruster (MMIT). This thruster uses coaxially input 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 ion optics uses 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 maximum thrust of approximately 250 µN with a total efficiency of 32%, mass utilization efficiency of 32%, and an electrical efficiency of approximately 50%. This configuration should 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 constant electric field across the grids. These predictions will be tested with experiments in a vacuum chamber at 10^{-5} Torr with a Langmuir probe and Faraday cup used to provide measurements of exiting beam properties.

I. Introduction

MINIATURE ion thrusters offer low-thrust, high specific impulse capabilities to small spacecraft with applications ranging from precise attitude and orbit control systems to spacecraft station-keeping. The Miniature Microwave-Frequency Ion Thruster (MMIT, shown in Figure 1) currently under development at The Pennsylvania State University is designed to provide such functionality with a tunable thrust level approximately between 1–250 µN and a theoretically predicted specific impulse of ~5500 s. The MMIT achieves this operation through the ionization of an inert propellant (such as argon or xenon) with 4.2-GHz microwave-frequency radiation, and propellant extraction via a two-grid optics assembly with a 2000-V (nominal) potential difference.

The MMIT is the latest in a series of miniature electric propulsion systems developed at The Pennsylvania State University. Whereas previous systems, primarily the Miniature Radio-frequency Ion Thruster (MRIT),[1,2] utilized radio-frequency propellant ionization techniques, the MMIT utilizes microwave-frequency ionization via a coaxial antenna. This paper presents the design of the MMIT (Section II) and experimental setup and methods used to evaluate the thruster performance (Section III). Conclusions relating to thruster performance are also provided as well as suggestions for future development of the MMIT (Section IV).

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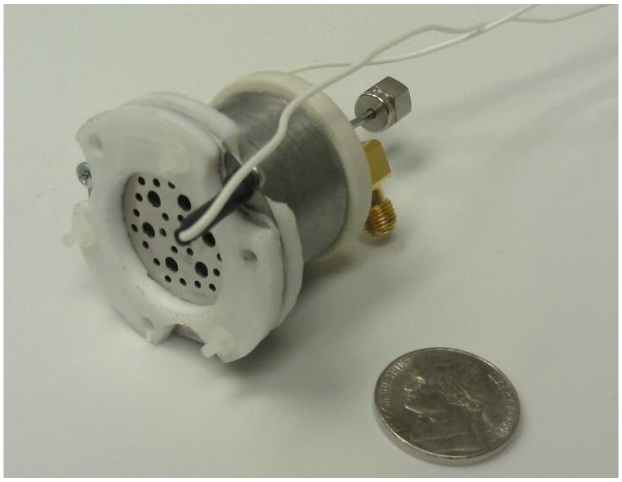

Figure 1. Size comparison for the MMIT.

II. MMIT Design

The MMIT was developed, in part, using design history from the MRIT family of thrusters and information from other thrusters with similar requirements, specifically the µ1 thruster developed by JAXA.[3] The specifics of the MMIT's design are presented in the following three subsections and are further explored in Ref. 4.

A. Propellant Inlet and Discharge Chamber

The main body of the MMIT is composed of two primary sections: the propellant inlet and the discharge chamber. The propellant inlet (shown as a CAD representation in Figure 2) introduces the propellant (typically xenon or argon) into the thruster at a nominal flow rate of 0.15 sccm. It directs the propellant through 1/16-in.-diameter (0.159 cm) stainless steel tubing to a gas plenum with six 0.01-in.-diameter (0.0254 cm) apertures located in a circular pattern between two permanent ring magnets. A coaxial "candlestick" antenna modified to act as a ring antenna is offset from the primary axis. This antenna introduces 1 W (nominal) of microwave radiation at 4.2 GHz into the discharge chamber for the purposes of propellant ionization. Upon ionization, the permanent ring magnets initiate electron cyclotron motion leading to their absorption into the chamber walls. This leaves the positively charged ions to be electrostatically accelerated through the ion optics.

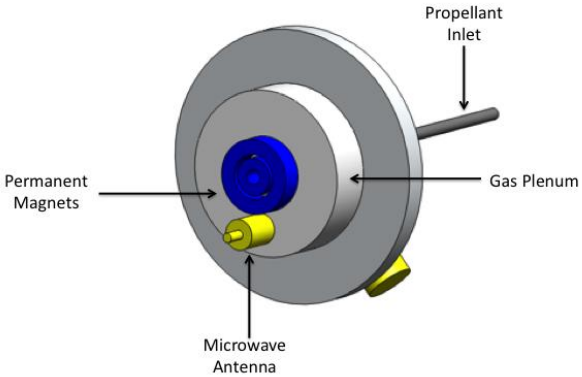

Figure 2. CAD representation of the MMIT's propellant inlet subassembly.

The propellant inlet is primarily composed of Macor™. Macor is a carbide-machinable ceramic with good thermal and electrical insulating properties, and it is stable up to working temperatures of 1000 °C. All iterations of the MRIT used this material successfully throughout fabrication and testing, so it was ultimately chosen to be the primary material for the MMIT. The permanent magnets are composed of alnico, a ferromagnetic iron alloy combined with aluminum, nickel, cobalt, and trace elements. Alnico retains its strong magnetic properties up to 520 °C, which makes it a viable alternative to samarium cobalt (SmCo) magnets, which are traditionally used in similar electric propulsion systems. Finally, the candlestick antenna is a standard antenna composed of gold plated brass with a PTFE dielectric. It is modified with a brass attachment to form a ring antenna for more efficient broadcasting.

The microwave antenna is inserted in the Electron Cyclotron Resonance (ECR) layer created by the two magnets. The magnetic bottle serves as a trap for electrons, which gain energy from the microwave to ionize the neutral atoms that are flowing through the plenum.[6,7] The shape of the antenna is based on the JAXA's μ1 design, but given our low flow rate and incident microwave power, a disc antenna will also be tried. It has a wider surface contact with the ECR layer, which leads to a better microwave–plasma coupling in order to overcome the losses by recombination with the antenna at low plasma density.[7]

The discharge chamber (shown as a CAD representation in Figure 3) has several purposes including: containing the plasma created by the microwave radiation, shielding the plasma from external fields, and providing a mounting interface for the ion optics. The plasma is contained within a cylindrical Macor chamber measuring 20 mm in diameter and 15 mm in length. A stainless steel pipe around the discharge chamber serves as a Faraday cage around the plasma. A PTFE mounting spacer is located at the end of the discharge to provide a fastening interface for the ion optics. Like the other materials chosen for the MMIT, PTFE was chosen for its electrical and thermal insulating properties and its low outgassing at Ultra High Vacuum (UHV) compared to similar materials.

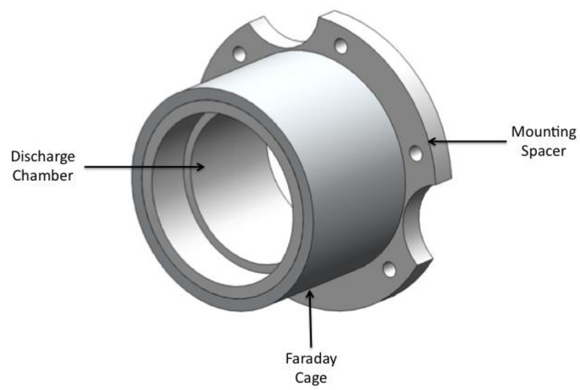

Figure 3. CAD representation of the MMIT's discharge chamber subassembly.

The components within the propellant inlet and discharge chamber (except the microwave antenna) are epoxied together with 3M® Scotch Weld™ DP-8005 Structural Plastic and Loctite® Epoxi-Patch® Adhesive. The microwave antenna is soldered with the brass ring attachment to the protruding candlestick, which is held in place by fasteners on the yoke plate. This makes the antenna replaceable should it burn out during testing. Kapton® tape is also used at certain interfaces to reduce propellant leakage.

B. Ion Optics

The ion optics assembly provides a large voltage difference for the ionized propellant to accelerate across, resulting in forward thrust. The MMIT uses a two-grid scheme with a screen grid kept at +1500 V and the accelerator grid kept at −500 V (nominal values). Typically grids for such a thruster would be composed of an erosion-resistant material like molybdenum, but in order to reduce fabrication and testing costs, stainless steel was chosen as a suitable replacement. A 0.02-in.-thick (0.051 cm) PTFE spacer in between the two grids physically separates and electrically isolates them. Another PTFE spacer in front of the accelerator grid mates with the spacer on the discharge chamber via six nylon fasteners. This type of interface enables the grids to be replaceable, which allows for the testing of different grid geometries and the replacement of grids as they erode.

The primary grid geometries are detailed in Table 1 and Figure 4. Aperture sizes were designed to accommodate available machining methods and to operate primarily with xenon propellant. Each grid contains 30 apertures with two different diameters. The smaller apertures are designed to extract positively charged ions when the MMIT is operating in thruster mode. Similarly, the larger apertures are designed to extract electrons when operating in a neutralizer mode.

Table 1. Extraction Grid Geometry.

Grid	**Thickness** inches (cm)	**Ion Aperture Diameter** inches (cm)	**Electron Aperture Diameter** inches (cm)
Screen	0.016 (0.041)	0.063 (0.16)	0.125 (0.318)
Accel	0.016 (0.041)	0.050 (0.16)	0.100 (0.254)

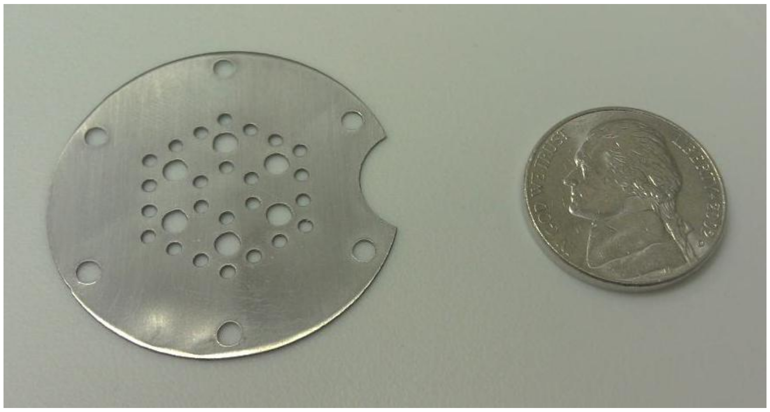

Figure 4. The MMIT's accelerator grid.

The ion-extraction aperture size was chosen to ensure that a Child–Langmuir sheath would be established on the screen grid when the MMIT is operating in thruster mode in order to promote efficient extraction of ions, narrow exhaust plumes, and reflection of electrons in thruster mode.[5] In order to determine the diameter range needed to accomplish this, the maximum beam current density through the ion optics ($J_{B,\max}$) was determined as follows:[5]

$$J_{B,\max} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{M}}\frac{V_T^{3/2}}{l_e^2} \tag{1}$$

with

$$l_e = \sqrt{(l_g + t_s)^2 + \frac{d_s^2}{4}}\ , \tag{2}$$

where V_T is the total voltage across the ion optics (2000 V), l_e is the sheath thickness, l_g is the grid separation distance (0.01 in.), t_s is the screen grid thickness (0.016 in.), and d_s is the screen grid aperture diameter (solved for iteratively). When evaluated for singly ionized ($q = e$) xenon propellant (M = 2.18×10^{-25} kg) with a screen grid aperture diameter of 0.625 in., the maximum beam current density is 41 mA/cm^2. Given a beam current density, J_B, and the previously calculated parameters, one can calculate the Child-Langmuir sheath thickness as

$$d = \sqrt{\frac{J_{B,\max} l_e^2}{J_B}}\ . \tag{3}$$

A Child–Langmuir sheath exists when the aperture size is on the same order as the sheath thickness, and based on these calculations for a 0.0625in.-diameter screen grid aperture that occurs between 5 mA/cm^2 and the maximum beam current density (41 mA/cm^2). Converting this to a beam current yields values between 1.5–9.0 mA, values similar to beam currents measured for the MRIT and μ1 thrusters.[1–3]

C. Performance Predictions

With the beam current estimated to be between 1.5–9.0 mA, a corresponding thrust, T, value can be obtained via

$$T = \sqrt{\frac{2M}{e}} I_b \sqrt{V_b}\ . \tag{4}$$

For this beam current range the corresponding thrust using nominal operating parameters for the MMIT is 111–667 μN. Realistically, the beam current will likely be similar to the 3.5 mA current measured with the μ1 thruster due to the similarities in the ionization and extraction schemes. At this beam current a thrust of 258 μN would be expected using Equation 4.

Efficiencies for the thruster can be similarly estimated. Expressions for the overall efficiency, mass utilization efficiency, and electrical efficiency, respectively, are[5]

$$\eta_T = \frac{P_{\text{jet}}}{P_{\text{in}}} = \frac{T^2}{2\dot{m}_p P_{\text{in}}}\ , \tag{5}$$

$$\eta_m = \frac{\dot{m}_i}{\dot{m}_p} = \frac{I_b}{e}\frac{M}{\dot{m}_p}\text{, and} \tag{6}$$

$$\eta_e = \frac{P_b}{P_T} = \frac{I_b V_b}{I_b V_b + P_0}\ . \tag{7}$$

The values here are P_{jet} for extracted beam power, P_{in}, 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 5–7 yields MMIT efficiencies of η_T = 32.2%, η_m = 32.1%, and η_e = 50.0%. These efficiencies will be slightly reduced as a result of using argon in testing, but they should remain close in magnitude.

Another metric used to measure the efficiency of the thruster as a whole is specific impulse (I_{sp}). For an ion thruster this metric can easily be calculated using[5]

$$I_{\text{sp}} = \frac{v_{\text{ex}}}{g} \tag{8}$$

with axial exhaust velocity

$$v_{\text{ex}} = \sqrt{\frac{2qV_b}{M}}\ , \tag{9}$$

where g is gravitational acceleration at sea level on Earth (9.81 m/s^2). Using nominal operating values for the MMIT reveals that the specific impulse will be approximately 5540 s. As with the efficiency calculations, certain assumptions used to calculate this value will lead to experimental measurements being slightly lower. These assumptions include complete single ionization of the propellant and no exhaust plume angle. Langmuir probe and Faraday cup measurements of the exiting beam will show how accurate these assumptions are.

III. Experimental Setup

The facilities at Penn State used in the testing of the MMIT were previously used to test other electric propulsion devices such as the MRIT[1,2] series of ion thrusters. The vacuum chamber (shown in Figure 5) measures approximately 0.6 m in diameter and 1.0 m deep. The dual pump system uses a BOC Edwards IPUP scroll pump as a roughing pump that is capable of evacuating the chamber to a pressure of approximately 4×10^{-3} Torr. The roughing pump is succeeded by a CTI-Cryogenics Cryo-Torr 10 series cryopump, which further evacuates the chamber to an ultimate pressure of approximately 1×10^{-5} Torr. Pressure measurements are provided by an MKS Instruments Series 999 Quattro Multi-Sensor Vacuum Transducer, which is capable of measuring pressures between atmospheric and 10^{-10} Torr with accuracies of 0.01×10^{n} Torr, where n is the order of the pressure measurement.

The vacuum chamber contains several electrical and gas flow ports for the purposes of connecting the MMIT’s antenna to a microwave source, connecting the grids to DC voltage sources, introducing argon propellant into the thruster, and establishing a data link between the Langmuir probe and Faraday cup used to measure the thruster’s exiting beam properties. The microwave generation equipment (shown in Figure 6) includes a Hewlett-Packard 8683D Signal Generator that operates in the range of 2.3–13.0 GHz, a Hughes 8010H Traveling Wave Tube Amplifier that operates in the range of 4.0–8.0 GHz, a Narda bi-directional coaxial coupler, two Mini-Circuits

PWR-SEN-6G+ power sensors that operate in the range of 1–6000 MHz, and a Harris Type 306A double stub tuner used to match the line to 50 Ω for maximum power transfer. These components are connected in series outside of the vacuum chamber via N-connector cabling. A dual female SMA-type KF-40 feed-through rated to 8 GHz is mounted on the side of the vacuum chamber to complete the interface between the microwave generation equipment outside the vacuum chamber and the MMIT's antenna within the chamber.

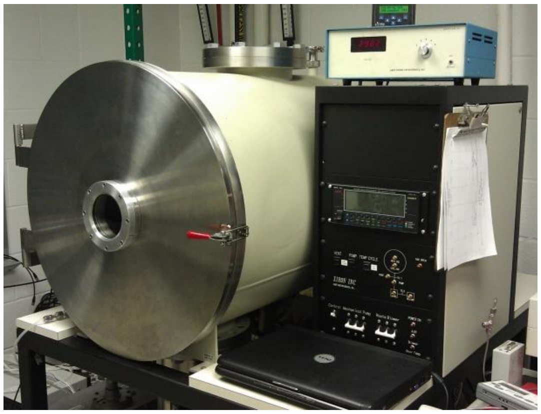

Figure 5. Vacuum chamber used for testing the MMIT.

Figure 6. MMIT microwave generation and measurement equipment.

The voltage on the extraction grids is supplied 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. The former is connected via BNC-connector cabling and a feed-through to the accelerator grid to establish a nominal operating voltage of −500 V, and the latter is similarly connected to the screen grid to establish a nominal operating voltage of 1500 V.

Ultra-high purity (99.999%) argon propellant is supplied to the MMIT via 1/8-in.-diameter stainless steel piping and a Swagelok® interface with the thruster's 1/16-in.-diameter propellant inlet pipe. A CF gas feed-through and additional 1/8-in.-diameter stainless steel piping lead to a Horiba-Stec SEC-7320 Mass Flow Controller (MFC) that is calibrated for xenon gas at a max flow rate of 1 sccm. This MFC is connected to a MKS Type 146 Vacuum Gauge Measurement and Control System, which allows the user to select flow set-points and engage or disengage flow. A valve placed in between the MFC and the vacuum chamber feed-through ensures that propellant flow is completely stopped when the thruster is not in operation. During operation, a nominal argon propellant flow rate of 0.15 sccm creates a working pressure in the discharge chamber on the order of 10^{-3} Torr.

In order to characterize thruster performance, a Langmuir probe (shown in Figure 7) and Faraday cup (shown in Figure 8) are used to observe exiting beam properties. Both probes provide accurate measurements of the beam current, which is related to various performance parameters (directly and indirectly) including: thrust, thermal efficiency, mass utilization efficiency, and overall efficiency. These relations are detailed in the following section. Additionally, the Faraday cup provides a method of investigating of beam divergence when measurements are taken at different angles off the thrust axis. These measurements will help to characterize the non-ideal nature of the MMIT, as most efficiency equations neglect effects like exhaust plume angles.

Figure 7. Langmuir probe used in testing the MMIT.

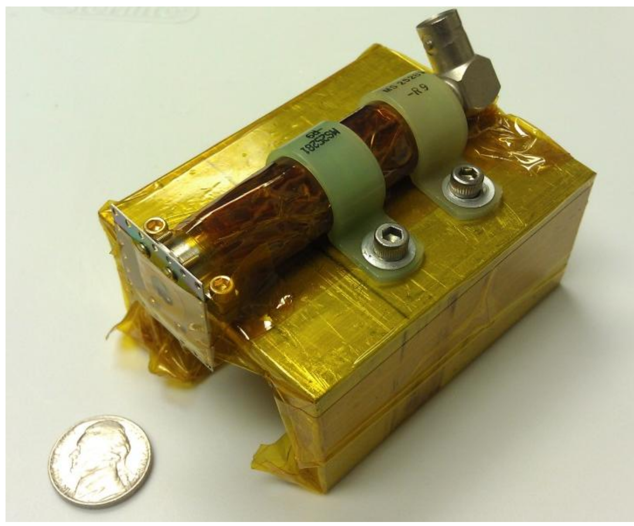

Figure 8. Faraday cup used in testing the MMIT.

IV. Conclusions and Future Work

The design presented in this paper is based on Penn State's MRIT ion thruster and JAXA's µ1 electrostatic thruster. The MMIT uses microwave power radiated via an antenna to ionize the propellant while a two-grid system made of stainless steel accelerates the ions through a 2000 V potential difference. The MMIT is designed to operate with a 0.15-sccm xenon flow rate, 4.2-GHz microwave frequency with 1 W of power, +1500 V on the screen grid, −500 V on the accelerator grid, and a total of 6 W delivered to the grids. It is predicted to give a total thrust of ~250 µN, a total efficiency and a mass utilization efficiency of 32%, an electrical efficiency of 50%, and a specific impulse of ~5500s. These predictions are based on assumptions such as no plume angle, single ionization of the propellant, and a beam current equal to the JAXA's µ1 electrostatic thruster. Therefore, the MMIT will be less efficient than these predictions show.

Testing is currently being conducted in a 10^{-5} Torr vacuum chamber at Penn State (Figure 9). A Langmuir probe and a Faraday cup will be used to provide measurements of the exit beam properties. The nominal operating conditions will be adjusted to increase the thruster performance.

Future work will include improvement of the general design as well as the microwave input design and the development of a second prototype thruster. The goal of this research is to produce an electric propulsion system with low enough mass and power requirements to be installed on 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.

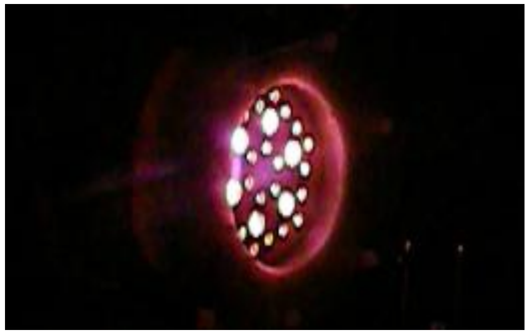

Figure 9. MMIT firing into the vacuum chamber.

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