Prototyping and Optimization of a Miniature Microwave-Frequency Ion Thruster

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Mohammed Asif[1], Michael M. Micci[2], and Sven G. Bilén[3]
The Pennsylvania State University, University Park, 16802, USA

We present progress on the development of the Miniature Microwave-Frequency Ion Thruster (MMIT), currently being developed at Penn State as a microthruster with high specific impulse that can be used on small satellites for station keeping, attitude adjustments, and modest delta-V maneuvers. The MMIT works by generating a microwave electron cyclotron resonance (ECR) discharge plasma, then accelerating ions through a series of electrostatic grids. Using argon as the propellant, the MMIT can start with as low as 2.6 W of total absorbed power from a 4.9-GHz coaxial input power source. For the current MMIT iteration, our research thrusts have been threefold: demonstrating plasma generation; sustaining and containing the plasma; and extracting the ion beam. We have largely focused on optimizing the geometry of the magnets and antenna used for ECR plasma generation; defining the geometry of the chamber for containment of the plasma; and developing grid geometries for efficient beam extraction. Progress to date toward a functional prototype has leveraged numerical simulations and experimental measurements on the proof-of-concept design, which we are currently further optimizing. A Langmuir probe is used to measure ion density and temperature in the plume as well as beam current, and a Faraday cup is used to measure the current density of the beam. The measurements obtained from these probes are used as the basis for determining a calculated thrust for the MMIT.

Nomenclature

A = effective area, m^2
g_e = acceleration due to gravity at Earth's surface, 9.81 m/s^2
I_b = ion beam current, A
I_sp = specific impulse, s
j = current density, A/m^2
L = distance between grids, m
m = atomic mass of argon, 6.6335×10^{-26} kg
$\dot{m}_\mathrm{p}$ = propellant mass flow rate, kg/s
P_in = total input electrical power, W
P_jet = jet power, W
q = elementary charge, 1.602×10^{-19} C
u_e = exhaust velocity, m/s
V = potential difference between grids, V
ε_0 = permittivity in vacuum, 8.854×10^{-12} C
η_M = mass utilization efficiency

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[1] Graduate Student, Aerospace Engineering, asif.aero@psu.edu
[2] Professor, Aerospace Engineering, micci@psu.edu
[3] Professor, Engineering Design, Electrical Engineering, and Aerospace Engineering, sbilen@psu.edu

η_T = total efficiency
τ = thrust, N

I. Introduction

ION thrusters are increasingly being used as in-space propulsion, and continued miniaturization of these devices would allow them also to be considered for microspacecraft missions, which require high efficiency and generally have significant power, mass, volume, and cost constraints. Miniature ion thrusters are typically designed to operate at a lower power settings (less than 10 W) while providing higher specific impulses (5000 s to 9000 s). In recent years, development of this technology at the small end has been directed toward potential CubeSat missions. This research and development includes the Miniature Microwave Ion Thruster (MMIT) at The Pennsylvania State University, which is being designed for station keeping, attitude adjustments, and modest delta-V maneuvers on small satellites.

Previous research on a small microwave discharge ion thruster by Koizumi and Kuinaka resulted in the development of the µ1 engine, which obtained an ion beam current of 3.3 mA using 1 W of input power and 0.15 sccm of xenon as propellant with 37% propellant utilization efficiency.[1] Their research was based on progress made by Takao al.,[2–4] who described an ion engine with 72% propellant utilization efficiency but using 8 W of input power at mass flow rates of 0.2 sccm of xenon.

Research on and development of miniature ion thrusters at Penn State began with Trudel's design of the 1-cm radio-frequency (RF) thruster with propellant efficiency of 41% using 16 W of input power and 0.038 sccm of argon.[5] Lubey refocused efforts from RF to microwave discharges, which resulted in the Miniature Microwave-Frequency Ion Thruster (MMIT).[6,7] His design, based on JAXA's µ1 design, had theoretical estimated values of power propellant utilization efficiency of 32% operating at 1 W power with a frequency of 4.2 GHz. Taunay redesigned the MMIT but used the same principle as the µ1, which resulted in a thruster with predictions of 217 µN thrust with 8 W total input power.[8,9] Both versions of the MMIT demonstrated plasma generation but were unable to demonstrate proper extraction of the ion beam; however, theoretical estimates of thrust, specific impulse, and efficiencies were made through numerical simulations of the thruster design. Their progress serves as the platform for the research presented in this paper.

Our research presents progress on the development of the MMIT. Section II covers background information and equations for thrust. Section III covers the design changes and considerations employed for optimization. Section IV describes the experimental facility and setup used in the experiments. Section V provides the experimental results from the current thruster iteration and issues faced. Section VI summarizes the progress made on the current MMIT iteration and possible future development paths for the thruster.

II. Background

There are three main types of electric propulsion (EP) thrusters: electrostatic, electrothermal, and electromagnetic. The ion thruster is a type of electrostatic thruster that uses the acceleration of ions from a plasma source to produce thrust. This is done by generating a potential difference between a set of extraction grids. A neutralizing device is used to recombine the ions and the electrons in the plume, which neutralizes the beam and avoids beam stalling. Miniaturization of ion thrusters is challenging due to the conditions required for plasma generation and extraction at the reduced scale. The MMIT works by generating an electron cyclotron resonance (ECR) discharge plasma using microwave power transmitted through an antenna and a strong magnetic field generated to confine the electrons. The electrons acquire energy through the ECR process and start to collide, and as a result create additional ions and electrons. This process depends on the electromagnetic interaction between the microwave antenna and the strong magnetic field based on the dimensions and positions of the components to generate more plasma and, in turn, provide the ions needed for extraction through electrostatic grids, thereby generating thrust in the system.

A. Thruster Parameter Calculations

In this section we provide the equations used to calculate thruster parameters using experimental data, which include thrust, specific impulse, and efficiencies.

Exhaust velocity (u_e) depends on the charge-to-mass ratio across a given potential difference, and can be written[10]

$$u_\mathrm{e} = \sqrt{\frac{2q\mathrm{V}}{m}}, \tag{1}$$

where m is atomic mass of the propellant, which here is argon. Specific impulse (I_sp) can be calculated from[11]

$$I_{\mathrm{sp}} = \frac{1}{g_{\mathrm{e}}} \sqrt{\frac{2qV}{m}} \tag{2}$$

or

$$I_{\mathrm{sp}} = \frac{1}{g_{\mathrm{e}}} \frac{\tau}{\dot{m}_{\mathrm{p}}} \,. \tag{3}$$

Ideally, if the beam can completely pass through the acceleration grids, the thrust per unit area is given by[11]

$$\frac{\tau}{A} = \frac{8}{9} \varepsilon_0 \left(\frac{V}{L}\right)^2 . \tag{4}$$

Thus, maximum thrust is based on the potential difference between the two acceleration grids, i.e., the acceleration electric field, which must be below the voltage-breakdown limit between the two grids.

In electric propulsion, the thruster has highly efficient utilization of propellant mass, which can be defined as mass utilization efficiency, η_M, which accounts for ionized versus un-ionized propellant and is defined for singly-charged ions as[12]

$$\eta_{\mathrm{M}} = \frac{I_{\mathrm{b}}}{q} \frac{m}{\dot{m}_{\mathrm{p}}} \,. \tag{5}$$

The total efficiency, η_T, is defined as the jet power divided by the total electrical power into the thruster, i.e.,

$$\eta_{\mathrm{T}} = \frac{P_{\mathrm{jet}}}{P_{\mathrm{in}}} \,. \tag{6}$$

The jet power of any electric propulsion thruster can be written as

$$P_{\mathrm{jet}} = \frac{\tau^2}{2\dot{m}_{\mathrm{p}}} \,. \tag{7}$$

Thus, the total efficiency can be expressed as

$$\eta_{\mathrm{T}} = \frac{P_{\mathrm{jet}}}{P_{\mathrm{in}}} = \frac{\tau^2}{2\dot{m}_{\mathrm{p}} P_{\mathrm{in}}} \,. \tag{8}$$

III.MMIT Design

The original MMIT design has undergone multiple revisions to reach the current version (Figure 1). Here, we outline the design considerations and revisions made to previous designs. The original version[5] was designed to operate at 4.2 GHz, but was later shown that this was not the resonant frequency of the thruster, which explained its performance issues. Taunay's[8] redesigned version of the MMIT (inspired by JAXA's μ1 thruster design[1]) incorporated elements of the original thruster design while changing its resonant properties and is best operated at 4.9 GHz. However, there remained some mismatches, which limited microwave power absorption, along with arcing problems between the grids and between the grids and the microwave antenna.[8] These problems were mitigated by minor changes in the system that are presented below.

B. Design Considerations

The prototype described here is fabricated with materials that are different from those of a flight thruster to facilitate an iterative design process and to reduce costs. These materials are the same as the previous version. With reference to Figure 2, the back plate is made of Macor®, as it is a carbide-machinable ceramic. The yoke plate is made of a low-carbon steel alloy (Steel 1018) with a high relative magnetic permeability, required to complete the magnetic circuit. The magnets are made of neodymium (Nd-Fe-B) and placed as two concentric circular magnets with the ring antenna located at the center of the magnets. The microwave input power is provided by an SMA candlestick that is shielded by a stainless-steel tube to reduce the power reflections in the microwave line. This line is attached to the antenna, which is made of copper. The gas enters the discharge chamber through 8 holes placed on the yoke plate such

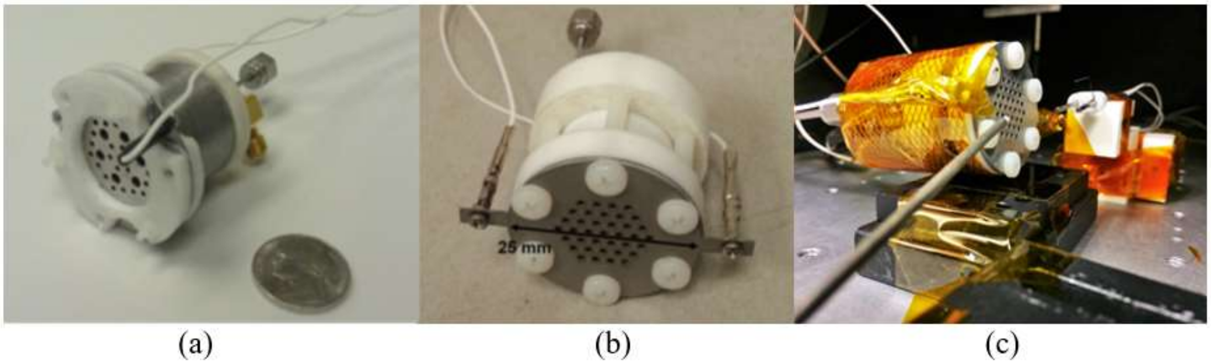

Figure 1. (a) Lubey's MMIT,[6] (b) Taunay's MMIT,[8] and (c) latest MMIT version.

that the gas flows in between the two concentric magnets. The discharge chamber is 22.33 mm in diameter and leads towards the Macor front plate.[8,9] The extraction grids are made of stainless steel, with a polytetrafluorethylene (PTFE) spacer between them. There are 37 holes in a hexagonal grid with an aperture diameter of 1.613 mm for the screen grid, 1.321 mm for the acceleration grid. The thickness of the screen and acceleration grids is 0.635 mm, and the spacer in between the grids is 0.508 mm. The faraday cage around the thruster is made of a copper mesh with a layer of Kapton® film to prevent it from arcing.

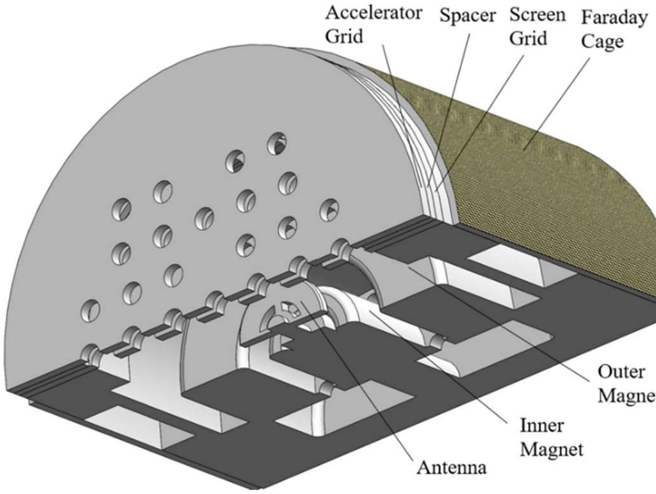

Figure 2. Cross-section view of current MMIT version

A flight version of the MMIT would use xenon as propellant, which is easier to ionize and has a higher atomic mass than argon. The yoke plate would be made of iron and the permanent magnets would be made of samarium cobalt (Sm-Co), which has a higher Curie temperature of 800 °C, necessary as the MMIT heats up during operation. The Faraday cage is being redesigned to fit around the discharge chamber using an aluminum mesh. The glass quartz[8] discharge chamber has the benefit of being able to observe the plasma formation in the thruster during testing, but would not be used for a flight version; rather, ceramic would be used. The extraction grids would be made of molybdenum for its low sputter erosion rate, good thermal and structural properties, and its ability to be chemically etched to form the aperture array. Hence, the grids would be manufactured with a chemical etching process that would provide tighter tolerances and eliminate sharp edges where arcing could occur.

IV.Experimental Setup

Testing of the current MMIT prototype and its predecessor designs was conducted within a vacuum chamber at Penn State that has a diameter of approximately 0.6 m and depth of and 1.0 m. The vacuum flanges accommodate the necessary feed-through connections and other connectors. The vacuum chamber has a dual-pump setup that uses a BOC Edwards IPUP dry pump to pump the chamber down a pressure of approximately 4×10^{-3} Torr. High vacuum conditions are reached by using a CTI-Cryogenics Cryo-Torr 10 series cryopump, which brings the chamber down to a base pressure of approximately 1 × 10^{-5} Torr. The pressure inside the vacuum chamber is monitored by a Pfeiffer Vacuum Inc. PKR 251 Compact Full Range Gauge.

With reference to Figure 3, the microwave signal required to create the plasma in the MMIT is generated by a Hewlett-Packard 8683D Signal Generator, which has a frequency range of 2.3–13.0 GHz. This signal is amplified using a Hughes 8010H Traveling Wave Tube Amplifier, which has a frequency range of 4.0 GHz to 8.0 GHz with 30-dB power gain. A Narda 3024 bi-directional coaxial coupler is used to measure the forward and reflected power of the system with two Agilent power sensors connected to a Hewlett-Packard E4419A power meter. Impedance matching between the microwave coaxial feed line and the thruster's input antenna is achieved using a Harris 306A double-stub tuner. These components are connected in series with coaxial cables and the final output is sent inside the chamber through an SMA feed-through.

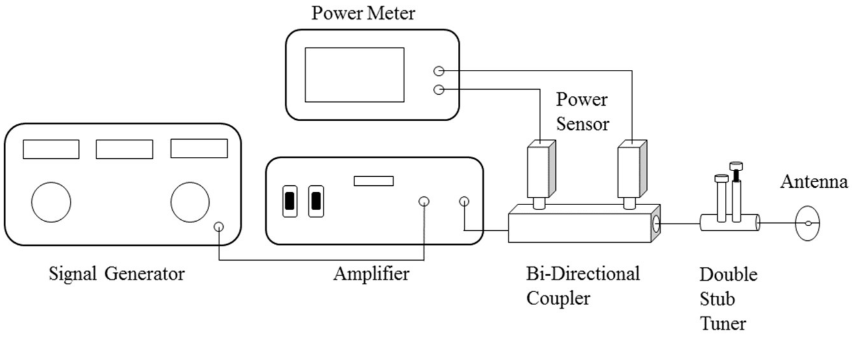

Figure 3. Schematic for microwave power injection into MMIT.

The extraction grid voltages are set using a Stanford Research Systems, Inc. Model PS310 high-voltage power supply with a maximum DC voltage of 1250 V and a Stanford Research Systems, Inc. Model PS350 with a maximum voltage of 5000 V. The high-voltage power supplies are connected using BNC coaxial cables.

A Keithley 2410 source meter is used with the Langmuir probe and Faraday cup for measuring ion beam currents (Figure 4). The Langmuir probe is used to measure the ion density, ion temperature, and the ion beam current. The Faraday cup is used to measure the current density of the beam. Data from both these devices are used to calculate thrust.

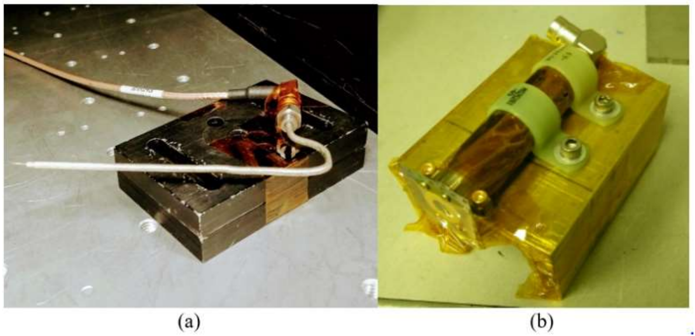
(a) (b)

Figure 4. (a) Langmuir probe and (b) Faraday cup.[8]

V.Results

Our research thrusts for the current MMIT iteration have been the following: demonstrating plasma generation; sustaining and containing the plasma; and extracting the ion beam. The work done on the MMIT has been iterative between experimental and numerical simulations. Each iteration brings us closer to the desired end goal of the MMIT project, which is to have a fully functioning flight thruster suitable for applications on micro-spacecraft, such as CubeSats.

The previous MMIT iteration could create plasma only at higher power levels than what numerical simulations had predicted and was unsuccessful in extracting the ion beam. Specific goals for this iteration were to lower the overall power requirements, reduce microwave power reflected by the thruster head, and demonstrate extraction of ion beam. Achieving these goals allows us to calculate thrust, specific impulse, and efficiency based on experimental data rather than numerical simulations.

The changes made to the thruster design overviewed in Section III have reduced the input power requirements for the thruster operation, decreased the reflected power, and demonstrated beam extraction. These changes were made considering the previous numerical simulation data and the current experimental research, which has indicated a need for orientation changes to the antenna and magnets. The log-mag plots of the reflected power (S_{11}) over the operating frequency range for the current and previous version of the MMIT are shown in Figure 5. The new design shows better

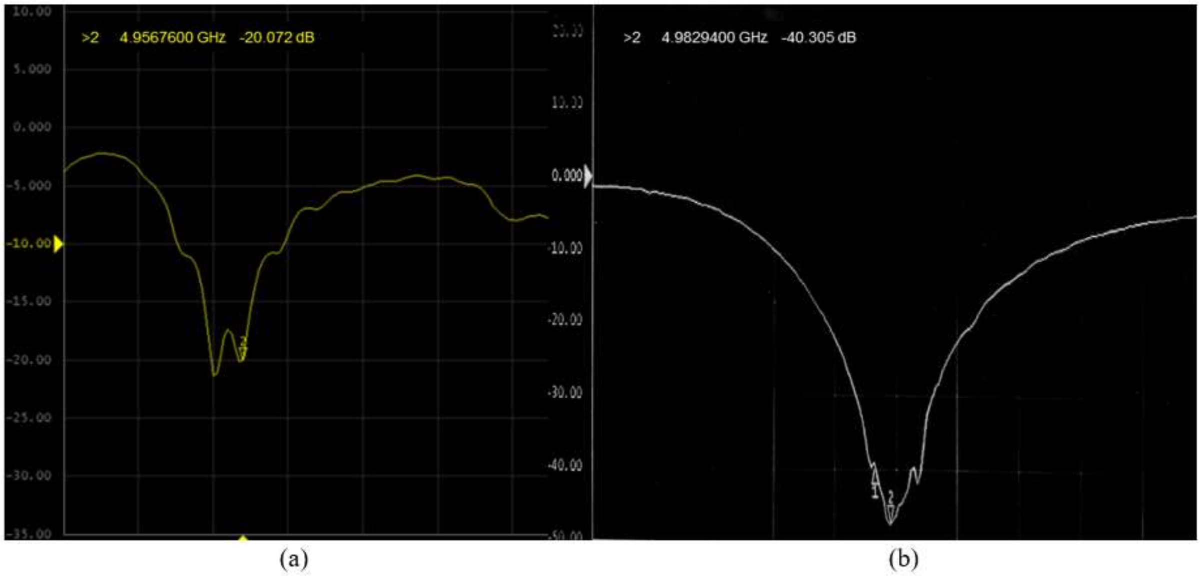

Figure 5. S_{11} Plots (a) previous design[8] and (b) current design.

results after the changes were implemented along with appropriate changes made to the microwave tuning setup to account for better impedance matching. Both the plots show resonance at around 4.9 GHz, but the new design keeps reflections below −40 dB, rather than −20 dB for the previous iteration.

The new design has been successful in generating plasma at input powers as low as 2.6–3.3 W with only 0.1 W power required to sustain plasma once ignited (power requirements fluctuate due to the minor differences in setup for each experiment). These variations in input power requirements are expected to be reduced as the thruster progresses to a more stable experimental version and ultimately the flight version.

Initial testing of this version of the MMIT produced arcing between the grids and between the screen grid and the antenna. Occasionally, the arc would jump from the acceleration grid over to the rear section of the thruster. This was a destructive process when generating plasma and attempting extraction. Several grids and antennas had to be replaced due to sputtering of plasma on the surfaces and other damages from arcing. These were problems that existed in the previous design and had to be mitigated to obtain ion beam extraction. The outer arc was a result of a design flaw in shaping the grid connectors with squared extensions, which caused arcing from the corners. The spacers were deformed due to arcing damage and an accumulation of sputtered material from the initial round of testing. These problems were resolved by eliminating sharp edges in the design and using Kapton insulation to serve as a redundancy in case of deformations due to unaccounted errors. Figure 6 shows the grids after the first set of experiments to determine the nature and severity of the arcing problem. Although running the arc test was a destructive process, it served as a way of revealing leaks in the system during the postprocessing of data, allowing these problems to be successfully eliminated.

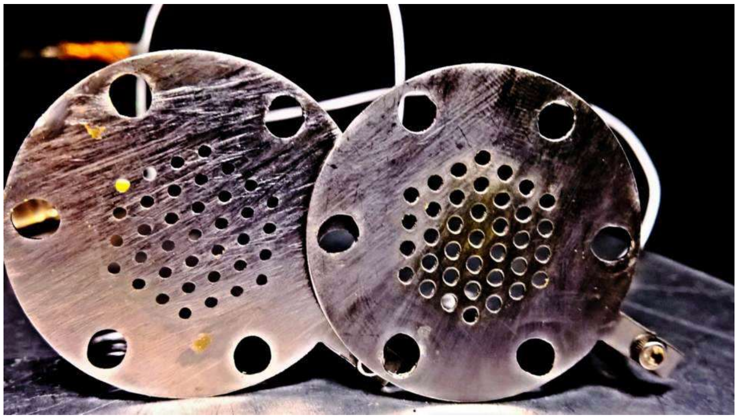

Figure 6. Extraction grid set after arc testing.

The experimental procedures involved testing the generation of plasma at different mass flow rates ranging from 0.1 sccm to 0.3 sccm. The power requirements for generating and sustaining plasma were found by incrementing the input power at a rate of 0.2 W (for generation) and decreasing the power at a rate of 0.1 W (for sustainment) until the plasma dies. The characteristics of the plume were analyzed by using the Langmuir probe to acquire the necessary data to calculate thrust, specific impulse, and efficiency. The calculations were made based on the equations provided in Section II. To limit the complexity of our calculation, we combined certain variables into ratios to help make changes in the system with fewer complications in the processing of our data.

The ion beam currents were measured as shown in Figure 7e by using the Langmuir probe placed a few centimeters away from the grids. Exhaust plume under various throttle settings were observed; (a) shows the thruster operating at zero throttle; (b) and (c) are intermediate; and (d) at the maximum experimental throttle before breakdown occurs. We observe that with changes in the throttle setting coupled with the difference in input power, we clearly have different ionization levels at (e) as indicated by the visual changes in the plume. To fully characterize the behavior of the ion beam characteristics and determine the level of ionization in the system will require further analysis.

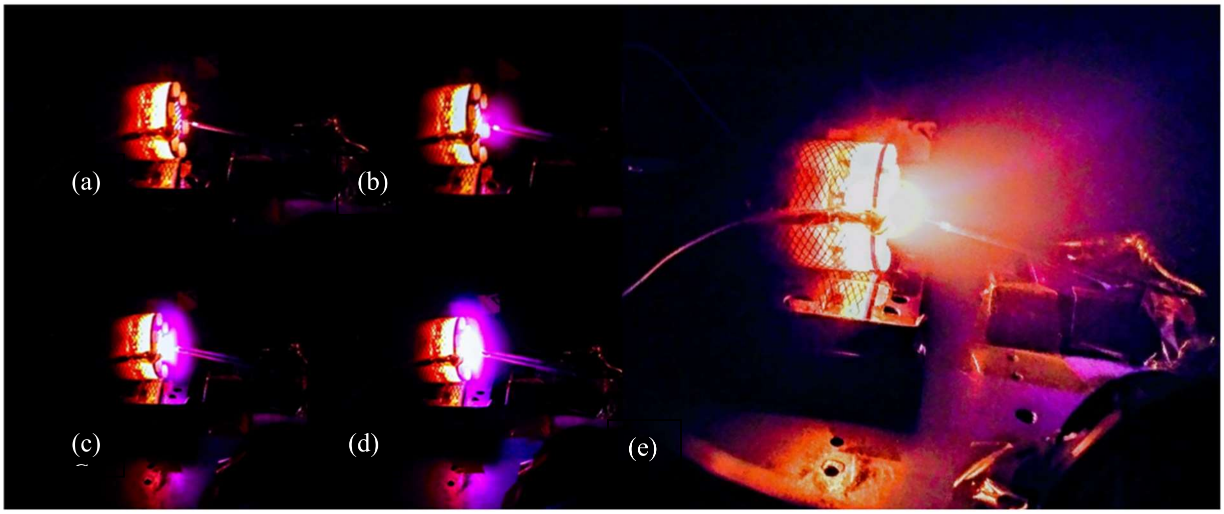

Figure 7. Exhaust plume under various throttle settings.

The values shown in Table 1 are the projected and experimental values for specific impulse at different mass flow rates. The results shown in Table one and Figure 8 indicate a specific impulse of 2470 s and thrust of 0.1 mN at 0.25 sccm mass flow rate of argon with total efficiency of 36 % at 3.3 W of input power. Lowering the mass flow requirement would increase the total efficiency and specific impulse of the thruster at a similar range of thrust. Although the efficiency and specific impulse are lower than the projected values, further optimization should allow us to reach targeted thrust, specific impulse, and efficiency by the next iteration of the MMIT.

Table 1. Mass flow rate vs. Specific impulse

	Mass Flow Rate (sccm)	**Thrust (mN)**	**I_{sp} (s)**
Projected	0.15	0.10	4080
Experimental	0.25	0.10*	2470*
Experimental	0.15	0.063*	2570*

*Calculated from experimental data

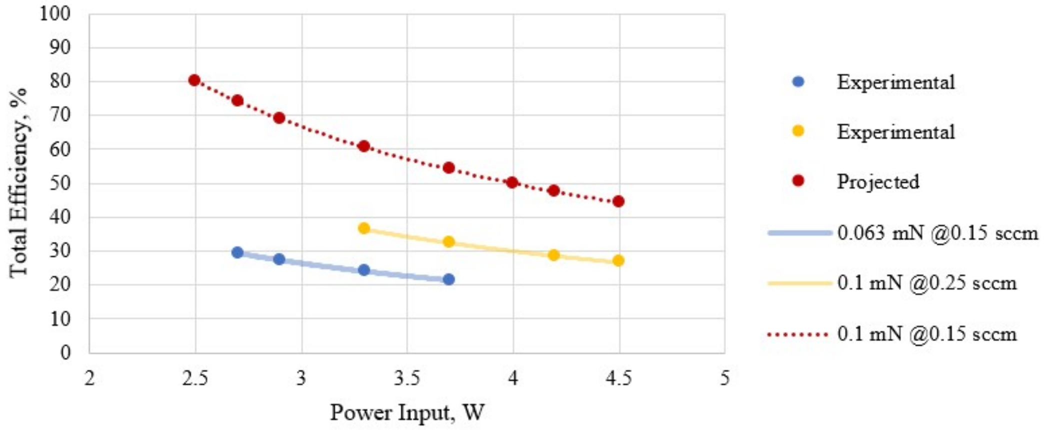

Figure 8. Input power vs. total efficiency

VI.Conclusion

A successful MMIT prototype has been designed and significant improvements to the MMIT's performance have been demonstrated. The current MMIT version uses a microwave ring antenna with neodymium permanent magnets to create plasma via an ECR discharge with the addition of a Faraday cage around the new design. This updated version has demonstrated extraction of the ion beam, which was a major issue with the previous version. We presented calculations based on experimental values for exhaust velocity, thrust, specific impulse, and efficiency. The work done on the MMIT has been an iterative process between experimental and computational research. Each iteration has brought us closer to the desired end goal of the MMIT project, which is to build a fully functional flight thruster suitable for applications on microspacecraft, such as CubeSats. There are four aspects that have played a key role in optimizing the microwave circuit for the thruster: antenna design, orientation, and position; installation of a Faraday cage; tuning the microwave setup using the double stub tuner; and eliminating arcing. Experimental results at 4.9 GHz show calculated thrust values in the range of 0.06 mN to 0.10 mN with a specific impulse ranging from 2500 seconds to approximately 4500 seconds. The propellant used is argon at flow rates of 0.15 sccm to 0.25 sccm with input microwave power as low as 2.6 W for creating plasma and 0.1 W for sustaining the plasma. Even though the current efficiency is lower than the estimated value, we expect to be able to increase it in the next MMIT iteration.

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