Design and Performance Testing of a 1-cm Miniature Radio-Frequency Ion Thruster

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This paper presents the design and performance testing of the 1-cm Miniature Radio-Frequency Ion Thruster (MRIT) currently under development at The Pennsylvania State University. The primary goal of the MRIT program is to produce progressively smaller, micronewton range, RF ion propulsion thrusters for use in high precision spacecraft attitude control and on miniaturized spacecraft. The MRIT is an inductively coupled RF ion thruster currently using argon gas as a propellant. The latest MRIT model is the smallest iteration to date with a conical plasma chamber that is 1 cm in both diameter and length. The total thruster diameter and length are each just over 2 cm. The thruster has been tested in a cylindrical vacuum chamber at pressures between 10^{-4} and 10^{-6} Torr. The MRIT produces a maximum thrust and specific impulse of 59.0 μN and 5480 s, respectively. The overall performance of this MRIT iteration was characterized by a series of tests conducted at PSU from 2008–2009. Selected data and results are presented here.

I. Introduction

Miniature ion propulsion devices show great promise as a means of providing finite attitude control for satellites and other spacecraft due to their high specific impulse and operational efficiencies as well as their exceedingly low fuel consumption.[1] A small RF ion thruster, like the Miniature Radio-Frequency Ion Thruster (MRIT) under development at The Pennsylvania State University, could produce low levels of thrust, on the order of 1 to 50 μN, at a precise thrust resolution providing consistent and accurate positioning capability over the lifetime of a spacecraft. These micronewton-scale thrusters could be used for applications such as routine satellite station keeping, precise attitude control in formation flying spacecraft, or potentially as a primary propulsion device on a miniature spacecraft. Specific uses such as drag compensation, orbit control and reconfiguration, disturbance cancellation, and controlled formation flying are commonly noted.[2]

The objective of the MRIT program is to produce progressively smaller, micronewton range, radio frequency (RF) ion propulsion thrusters. The previous iteration of the MRIT was a cylindrical thruster whose plasma chamber measured 1.25 cm in both diameter and length. It used a two-grid extraction system operating at a total voltage of 1200 V to produce approximately 75 μN of thrust with an I_{sp} of 2400 s.[3]

Concerns with the previous MRIT design included the accelerator grid directly intercepting ions accelerated by the screen grid and beam steering that was occurring due to grid misalignment and slight inaccuracies in grid construction. Solving these optics problems was one of the primary goals of this MRIT iteration. In addition, the change from a cylindrical to conical plasma chamber was made in an effort to increase the chamber volume to surface area ratio and thereby decrease discharge losses to the chamber walls and increase thruster efficiency.[4] The MRIT iteration presented in this paper continued the miniaturization of the previous MRIT and produced a smaller, more efficient, and more reliable thruster.

The MRIT design presented in this paper is shown in Fig. 1. It has a conical plasma chamber 1.0 cm in both diameter and length. Total thruster length and diameter are each just over 2.0 cm. It is an inductively coupled RF ion

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thruster with a two-grid, 7-apertures-per-grid, extraction system. A schematic overview of the thruster is shown in Fig. 2.[5] During the previous MRIT iteration it was shown that the thruster operates at a higher efficiency using an RF frequency of 1.0–1.5 MHz rather than the previously used 13.56 MHz.

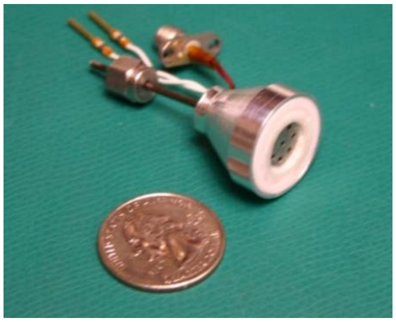

Figure 1. MRIT size comparison.

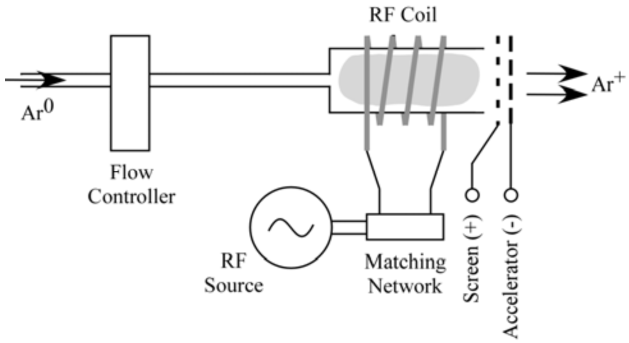

Figure 2. MRIT system diagram.

In order to reduce costs, the laboratory model of the thruster was constructed from materials somewhat different from those typically used in ion thrusters. Most notably, the extraction grids were constructed from stainless steel and the assembly that houses them was constructed from several pieces of Teflon. The flight model of the MRIT will utilize molybdenum extraction grids and alumina ceramic extraction assembly components. The MRIT plasma chamber and Faraday cage surrounding the thruster were constructed from an alumina ceramic and 6061 aluminum alloy. It is likely these materials will remain the same in the flight model thruster.

Testing with xenon propellant was also postponed to reduce costs. Argon is significantly cheaper and easier to obtain. The results presented in this paper were obtained using argon gas as a propellant, but testing using xenon gas will be carried out in the near future. Xenon gas is the intended thruster propellant.

II. Testing Facility and Experimental Setup

A. Test Facility

The facility used to test the MRIT system is located at Penn State. The vacuum chamber used is shown in Fig. 3. The chamber is approximately 0.6 m in diameter and 1.0 m in depth. The vacuum system is a two-stage system that uses a BOC Edwards IPUP scroll pump and a CTI-Cryogenics Cryo-Torr 10 series cryopump to reach an ultimate pressure as low as 1.0×10^{-6} Torr.

B. Experimental Equipment

The pressure inside the vacuum chamber is measured using an MKS Series 999 Multi Sensor Pressure Transducer and an Inficon CC3 cold cathode vacuum gauge. The MKS Series 999 Sensor measures pressures from atmosphere to 10^{-10} Torr with an accuracy of 0.01×10^{n} Torr, where n is the order of magnitude at which work is being conducted. The Inficon CC3 measures pressures from 10^{-3} to 10^{-8} Torr with similar accuracy. Both sensors were used and their readings compared to ensure accurate pressure measurements.

A Horiba Stec mass flow controller (MFC) was used in combination with an MKS 147B control box to regulate the flow of propellant into the thruster's ionization chamber. Cold flow tests were conducted frequently to ensure proper propellant flow rate within the plasma chamber. The MFC was set to various flow rates and the change in chamber pressure was recorded.

Two Bertan 205B series high voltage sources were used to provide the positive and negative high voltage used on the screen and acceleration grids, respectively. The high voltage sources are internally grounded and, in addition, the cables carrying the high voltages are grounded to the metallic vacuum chamber via their

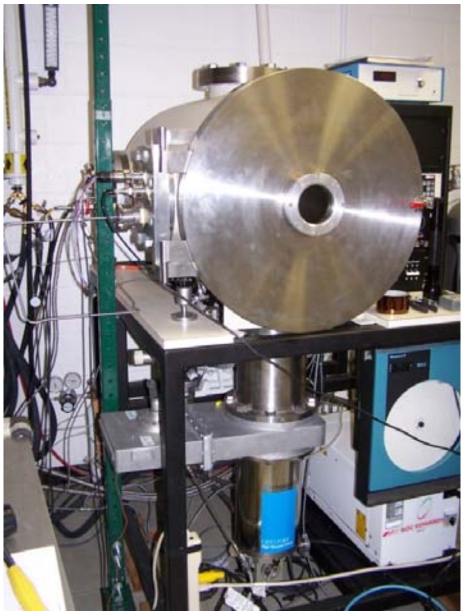

Figure 3. Thermal–vacuum chamber.

respective feed-throughs.

To generate the RF field, a Hewlett Packard 33120A Arbitrary Waveform Generator was used to produce the necessary signal at a frequency of 1.5 MHz. It was then amplified by an RF Power Labs Model ML50 RF amplifier to provide the necessary range of RF power levels. The signal was tuned using an MFJ Deluxe Versa Tuner V and a 4:1 matching transformer to provide the lowest possible SWR.

C. Experimental Setup

The MRIT exhaust plume was analyzed using a 3.5-cm-long Faraday cup with a 0.1-cm^2 aperture. The cup was placed 5 cm downstream of the MRIT exit grids and aligned axially with the center of the thruster. The Faraday cup was placed in this position to make all beam current density measurements except for those associated with beam divergence testing.

To test for beam divergence the Faraday cup was placed 5 cm downstream of the thruster exit in a radial pattern from 0 degrees to 24 degrees on either side of its initial position. Beam current density measurements were taken every 2 degrees throughout this range to produce a two dimensional beam current density profile for the MRIT exhaust plume.

All other thruster parameters (e.g., total ion current, accelerator grid current, etc.) were recorded from the various laboratory power supplies, power meters, and mass flow control systems listed above. Thruster operational parameters were then calculated from this data and the beam current density profile attained from the Faraday cup testing.

To test for proper beam neutralization a Langmuir probe was placed 5 cm and 10 cm downstream of the MRIT. The probe was excited by a potential of −50 to +50 V and the collected probe current was recorded. At each throttle point the required current through the neutralizer to produce a neutral beam (no current reading at LP location) was recorded.

III. Experimental Results and Discussion

A. Operational Parameters

Before analysis of the MRIT exhaust plume and other performance characteristics could begin, the operational limits of the thruster and a reliable operating procedure had to be established. The primary characteristics that needed to be known were: functional propellant flow rates, minimum operational RF power level, and functional exit grid potential. A photograph of the operational thruster can be seen in Fig. 4.

To determine the functional flow rate, first the necessary flow rate to achieve a chamber pressure between 10^{-2} and 10^{-3} Torr was calculated using Poiseuille's equation.[6] A flow rate of 0.03 sccm to 0.04 sccm was calculated for the current MRIT geometry. The MRIT successfully sustained operation with flow rates ranging to as low as 0.02–0.1 sccm. Maximum propellant efficiency occurred at the lowest functional flow rates.

A 4:1 matching transformer was used between the RF amplifier and the thruster coil, with SWR values as low as 1.5 consistently obtained. It was found that, at an SWR of 2.0, the thruster could function with as little as 10 W of delivered power.

Figure 4. MRIT firing.

The two sets of tests above were both conducted with a total exit grid potential of 1200 V. The screen grid was charged to +1000 V and the acceleration grid was set to −200 V. These were the standard potentials used on the previous iterations of the MRIT and produced consistent operation here. Arcing occurred between the grids at total voltages above 1700 V and the thruster would lose stability at total voltages below 500 V. In the results presented herein, the steady state operating conditions for the MRIT are: +1000 V and −200 V screen and acceleration grid potential, respectively, 0.035 sccm propellant flow rate, and a delivered RF power level of 15 W.

B. Exhaust Plume Characteristics

The exhaust plume of the MRIT was analyzed using the Faraday cup setup outlined in Section II.C. The average beam current density at steady state conditions was on the order of 2.0 mA/cm^2. At these conditions the MRIT produces a calculated thrust of 22.5 µN at a specific impulse of 2096 s.

A two dimensional beam current density profile for the MRIT is shown in Fig. 5. This profile was used to determine the beam divergence of the MRIT exhaust plume. The beam divergence is approximately 17 degrees.

Thrust values reported in this paper are calculated from the beam current measurements and the beam divergence value determined via experimentation.

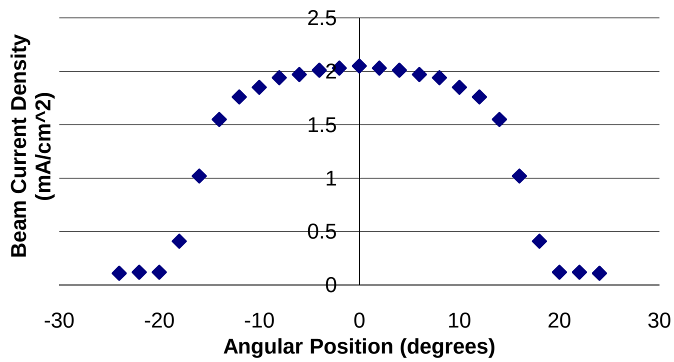

Figure 5. Two-dimensional beam current density profile.

C. Neutralizer

A simple tungsten filament 1 mm wide by 1.5 cm in length was used to neutralize the ion beam expelled by the thruster. As is typical with electric propulsion systems, the neutralizer self-biases to automatically expel the required number of electrons to effectively neutralize the thruster exhaust beam.[7] A current of 3.75 A to 6.03 A at a potential of 3.11 V to 5.27 V was fed through the filament in order to neutralize the MRIT ion beam at all throttle points (on the order of 10^{14}–10^{17} electrons/m^3). This is a simple, yet effective, method for neutralizing the exhausted ion beam.

D. Electron Backstreaming Tests

Testing was done to determine the electron backstreaming limit on the MRIT optics. The backstreaming limit was defined as the acceleration grid voltage at which a 1% increase in screen grid current was seen (due to backstreaming electrons).[8] Figure 6 below shows the results of these tests and the identified backstreaming limit acceleration grid potential of −60 V.

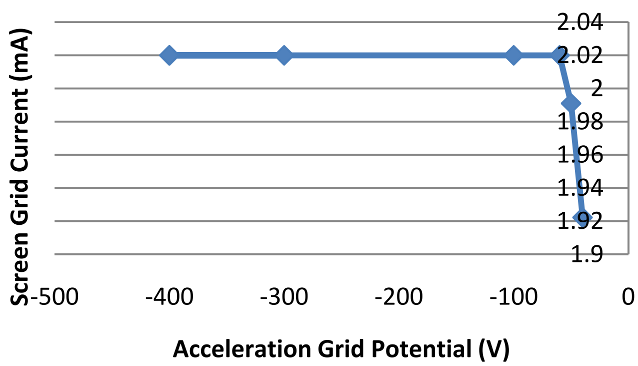

Figure 6. Electron backstreaming limit.

E. Throttling

MRIT throttling is accomplished by varying the total voltage applied to the exit grids. Throttling by varying the delivered RF power was also investigated, but it was found that better thrust control and resolution was achieved when using the optics. Throttling using both systems will continue to be investigated as the MRIT electronics evolve. Results from the optics throttling tests are shown below in Fig. 7. The minimum and maximum thrust levels were 1.45 µN and 59.01 µN, respectively. Thrust intervals ranged from 4 µN to 10 µN.

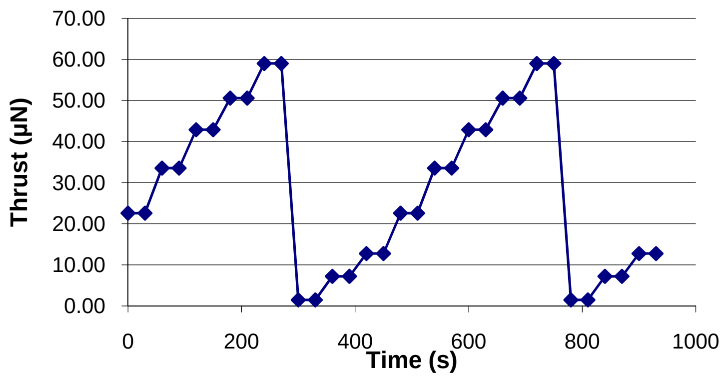

Figure 7. MRIT thrust vs. time (demonstrating throttling).

IV. Performance Analysis

The current MRIT iteration functioned more reliably than any previous iteration. The thruster produced a maximum calculated operational thrust of 59.0 µN with a specific impulse of 5480 s and a mass efficiency on the order of 60% to 80% depending on propellant flow rate. Figure 8 gives the propellant efficiency as a function of thrust at multiple propellant flow rates.

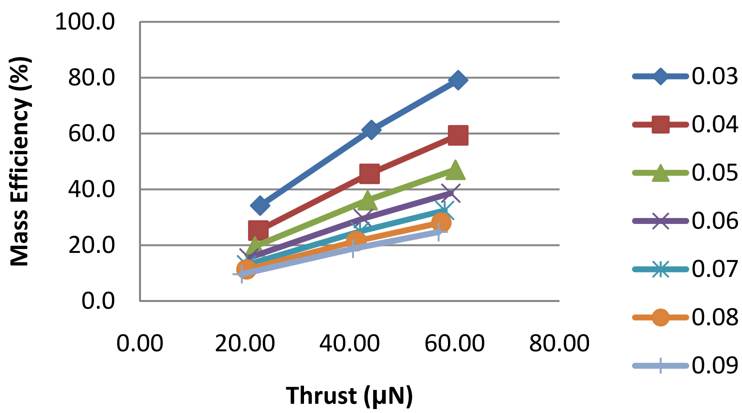

Figure 8. MRIT mass efficiency vs. thrust at multiple propellant flow rates.

The MRIT operated continuously for over 50 hours without any incident or fault in operation. During these 50 hours, the thruster was throttled up and down over the entire operational thrust range, shut down and re-ignited numerous times, and subjected to various changes in propellant flow rate, exit grid potential, and delivered RF power. In every case the MRIT operated without fail provided these parameters remained within the bounds of the operational parameters outlined in Section III.A. This is the longest and most successful series of testing any MRIT iteration has undergone.

The power-to-thrust ratio was 300 W/mN with an electrical efficiency of 15.2%. The power to thrust ratio is high and the electrical efficiency suffers accordingly. This is due in part to the exceedingly small size of the MRIT; however, as the MRIT flight electronics evolve and the transition from laboratory electronics is made, a more power efficient thruster is a primary goal.

Total efficiency was 12.84%. The total efficiency suffered as a direct result of the low electrical efficiency. Once again, it is hoped the total efficiency will increase with advancements in the MRIT support systems.

V. Conclusions and Future Work

Initial testing of the current iteration of the MRIT showed that the MRIT thruster can operate at RF input power levels as low as 13 W and mass flow rates from as low as 0.02 to 0.1 sccm. Steady-state operational testing was conducted with an RF input power level of 15 W, a mass flow rate of 0.035 sccm, and a total exit grid potential of 1200 V. Faraday cup testing conducted under these conditions produced results consistent with theoretical predictions. The MRIT produced 1.45 µN to 59.0 µN of thrust at throttling intervals ranging from 4 µN to 10 µN. At maximum thrust the thruster achieved an I_{sp} of 5480 s.

The maximum mass efficiency of the MRIT was just under 80%. Far lower electrical and total efficiencies were produced, and while reduction in these efficiencies is expected with reductions in scale, there is room for improvement. It will be a primary goal of subsequent MRIT iterations to produce more efficient flight electronics.

Future work should focus on improving thruster efficiency, conversion to flight materials, and production of MRIT specific flight electronics. Flight model electronics will allow further RF and optic throttling testing to be done and will allow a better prediction of the practical performance of the thruster as these properties are primarily related to the design of the support electronics and not the thruster itself.

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