Vacuum Testing of the Miniature Radio-Frequency Ion Thruster

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Abstract: A miniature RF-ion thruster (MRIT) is being designed and developed at The Pennsylvania State University. It is a complete 2-grid ion thruster, composed of a xenon gas reservoir flowing into an ionization chamber surrounded by a RF coil, connected to a matching network, and fed by RF source. The MRIT has been tested in a vacuum chamber for plasma discharge power levels on the order of ten watts. A 13.56-MHz industrial unregulated frequency is used as the excitation frequency. With an input power of approximately 15 W and an acceleration grid voltage of approximately 1 kV, we estimate being able to obtain a specific impulse of approximately 3800 s and thrust in the 100s of μN. Estimates of thrust are calculated from measurements of the ion beam current, which are made via a Faraday cup. This paper describes the tests made to date on the MRIT. The MRIT is to be flight tested onboard LionSat, a Penn State student-designed satellite. The mission requirements for LionSat are a minimum of one hour of continuous operation for the RF-Ion thruster and a measurable change in the satellite rotation rate.

Nomenclature

A	= surface area seen by the ion beam (m^2)
e	= unsigned charge of an electron (1.602×10^{-19} C)
J	= beam current density (A/m^2)
M	= xenon ion mass (kg)
n	= particle density (m^{-3})
T	= thrust (N)
V_a	= discharge voltage between the grids (V)

I. Introduction

Large scale RF ion thrusters have shown their potential on several successful missions. We are applying the concept to much smaller scales via the design of the miniature RF-ion thruster (MRIT). This thruster will allow the small satellite community to benefit from the advantages offered by RF ion thrusters, such as higher specific impulse, operation without a hot cathode, and gas ionization by electromagnetic fields.[1]

A. MRIT Description

The MRIT tested here is composed of a MACOR®ionization chamber surrounded by an RF ionization coil. The 18-gauge RF-ionization coil is fed by a 13.56-MHz RF source through a capacitive matching network. At the downstream end of the chamber are located a set of two chemically milled molybdenum grids. A

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DC voltage is applied between the grids creating an electric field that accelerates the ionized propellant. It consists of a positively charged grid (screen) located directly at the exit of the ionization chamber followed by a negatively charged grid (accelerator). Testing of the MRIT is being done in the smaller chamber available in the Communications and Space Sciences Laboratory at Penn State.[1] Figure 1 shows the system diagram of the MRITs to be implemented onboard LionSat.[1]

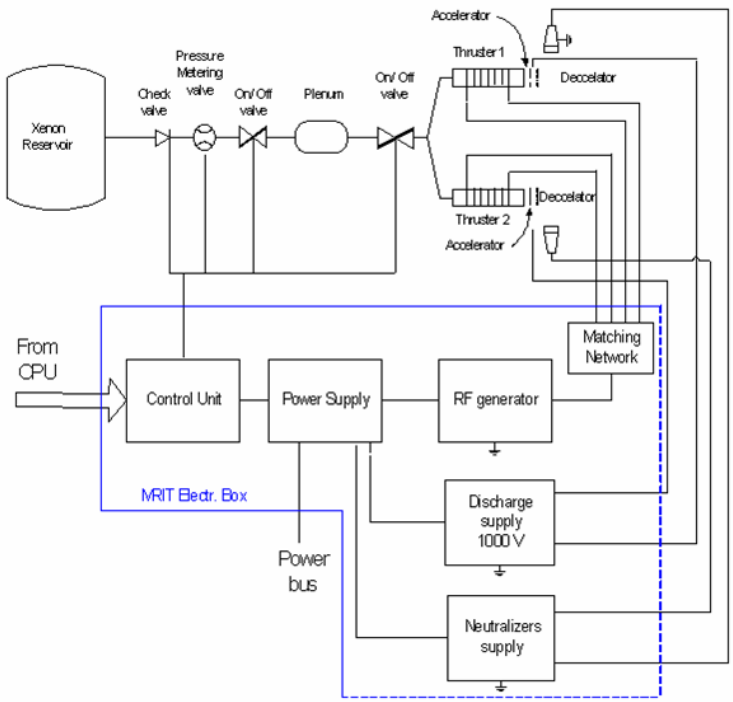

Figure 1. MRIT system diagram

B. Previous Results

A parametric study of the input power delivered to the coil was conducted in order to establish the conditions for creation and maintenance of the plasma within the MRIT's ionization chamber. The minimum power required to start a plasma for a 5-sccm flow rate at 9.44×10^{-5} torr in the vacuum chamber was $\sim$ 30 W.

A stable plasma can be maintained with incident power in the coil (i.e., after matching network) of about 9 W. A Helmholtz coil was required for the initiation of the plasma within the ionization chamber, which was instantaneously followed by a sustained inductive plasma discharge. Inductive discharges start in a capacitive mode at low plasma density and then transition to an inductive mode at higher densities. Most processing gases are molecular and electronegative; hence, it is easier to induce discharge within them. Xenon, however, being a noble gas does not have the free electrons required for initial discharge; thus, the initial ionization has to be produced by a breakdown obtained by increasing the electric potential in the gas.[1]

C. Thrust Measurements Method

A limited number of methods are available to measure the small thrusts produced by electric propulsion devices. Among these are the torsional balance, the nano-newton stand, the interferometric proximeter system (IPS).[3,4,5] A Faraday cup can also be used as a thrust measurement device. It consists of a metallic chamber, or cup, that intercepts the plasma beam, which is connected by an electrical lead to a current measuring instrument. By evaluating the current in a beam of charged particles, an estimate of the thrust becomes possible according to the following equation:

$$T = \sqrt{\frac{2}{(e/M)}} J V_a^{1/2} A \tag{1}$$

Because it was simple to implement within the confines of the small chamber (Figure 2), a Faraday cup was chosen as the thrust measuring method. Also, measurements made with Langmuir probes were shown to be less conclusive than the ones made using the Faraday cup.

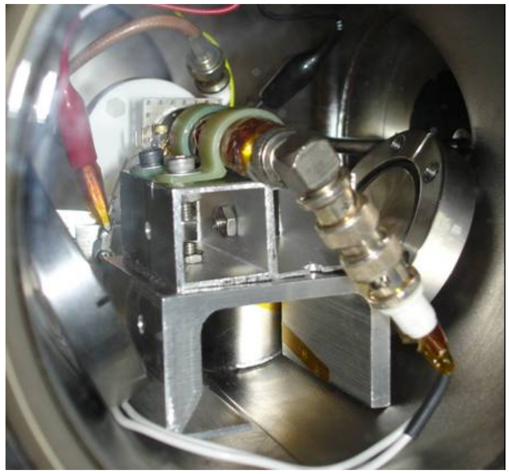

Figure 2. Faraday cup and MRIT in vacuum chamber

II. Experimental Results and Discussion

A. Intermediate RF-Ion Thruster

An intermediate RF-thruster with slightly larger dimensions than the flight-version MRIT was developped and tested concurrently. This RF-thruster was about 2″ (about 5 cm) in diameter with a length about 5″ (about 13 cm). A picture is shown in Figure 3. Testing of the intermediate RF-thruster was performed with a grid voltage of 1000 V and an input power of 45 to 55 W. A set of results is presented in Table 1. For power levels of the order of 40 W, a thrust of about 0.25 mN was estimated using Equation 1.

The intermediate thruster was found to be functional at a wide range of RF power levels, grid voltages, and gas flow rates. RF power levels as low as 13 W, grid voltages as low as 300 V, and gas flow rates as low as 1.4 sccm were all successfully achieved. This thruster allowed us to address many of the key issues involved with sustaining an ion plasma as well as properly matching RF networks on small scales. This knowledge is used then in the design of the flight-version of the MRIT.

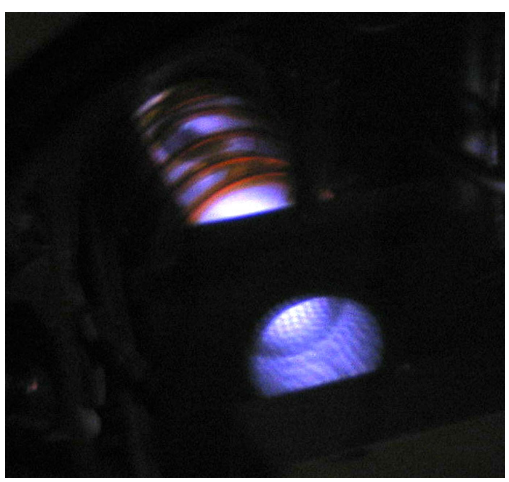

Figure 3. Firing of intermediate thruster

Table 1. **Faraday cup measurements**

Grid Voltage (V)	Grid Current (mA)	Faraday Cup Current (A)	Ion Density (ions/m^{-3})
300	0.013	0.00290	4.72×10^{11}
400	0.015	0.00400	5.64×10^{11}
500	0.018	0.00528	6.66×10^{11}
600	0.020	0.00600	6.91×10^{11}
700	0.022	0.00660	7.04×10^{11}
800	0.023	0.00710	7.08×10^{11}
900	0.024	0.00780	7.33×10^{11}
1000	0.025	0.00825	7.36×10^{11}

B. MRIT

Unlike the intermediate thruster, the MRIT was found to be much more sensitive to changes in RF power levels, grid voltages, and gas flow rates. Testing was conducted over the past several months with the goal of establishing a sustainable ion plasma as well as to define the parameters at which full thruster fuction could be maintained.

Initially, some experimental difficulties appeared for the initiation of the plasma within the discharge chamber requiring an external voltage source. As such, a Helmholtz coil was needed to strike the discharge in the earlier stages of the experiment.[1] Through the use of a better matching of the RF-coil with the source, as well as the combination of the grid discharge voltage and the RF power, we can now create a self-initiated discharge. A picture of the firing thruster is shown in Figure 4, which was achieved with an RF power of 36 W and a grid voltage of 1000 V.

Figure 4. Firing of MRIT with grids

III. MRIT onboard LionSat

The MRIT is designed to be flight tested onboard LionSat (*L*ocal *Ion*ospheric Measurements *Sat*ellite), which is a nanosatellite being built by Penn State University.[1,6] Initially part of the University Nanosat3 (NS3) program and designed for a launch onboard the Space Shuttle, LionSat will be launched on an expendable launch vehicle. The general physical envelope of LionSat remains 47.5 cm in both diameter and height, and a mass of less than 30 kg. The mission requirements for the pair of MRITs are the following: a minimum of one hour of continuous operation and a measurable change in the satellite rotation rate. The scientific goal of the LionSat mission is to explore the ram/wake structure via placement of its plasma probes on the outside of the spacecraft as it rolls along the orbit.

The opportunity to flight test the MRIT as part of the LionSat mission is currently set for 2007. The

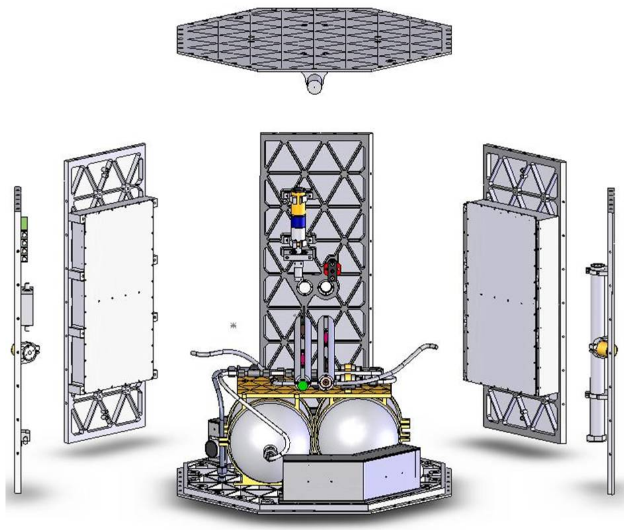

Figure 5. Exploded view of LionSat

two ion thrusters will be placed at the belly band of the satellite, 180° apart, and once in action will create a tangential thrust, which by reaction will induce a rotational motion in the opposite direction (Figure 5). By orienting the moment arm of the thrusters through the center of mass of the payload, the roll rate of whole spacecraft can be adjusted as needed. Through measuring the increase in satellite spin once the operational roll rate has been obtained, the LionSat team will verify MRIT operation and thrust levels. A minimum of twenty-four hours of operation is expected, including at least one hour of continuous operation. The pair of MRITs will be fed by two xenon tanks through a flow control module.[1]

IV. Summary and Future Work

Calculated thrust values of the order of 0.25 mN were found for an intermediate size RF-ion thruster using Faraday cup current measurements. A self-initiated discharge within the MRIT was also shown to be possible with the presence of the chemically milled accelerating grids at the downstream end of the chamber. The MRIT will now have to go trough a similar series of tests as the ones performed on the intermediate size RF thruster in order to deduce thrust values. At the same time, the following MRIT components are being developed and improved: the RF electronics, propellant feed system, and propellant storage system, for which the latest version is shown in Figure 5. With these new systems, testing will be conducted on the MRIT to define ion beam current, ion density, and thrust values for the functioning thruster. These parameters will then allow the MRIT to be integrated into the LionSat spacecraft. Also under development is a theoretical and computational model of the RF-ionization processes occuring within the MRIT.

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