DEVELOPMENT AND CHAMBER TESTING OF A MINIATURE RADIO-FREQUENCY ION THRUSTER FOR MICROSPACECRAFT

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ABSTRACT

The high specific impulse provided by electric propulsion devices make them highly desirable for space missions in which the propellant mass budget is limited. The ion thruster is of particular interest because of its simplicity and its ability to make rapid changes in thrust by modifying input power level and acceleration grid potential. With respect to micro- and nanosatellites, a miniature ion thruster could provide an attractive method for changing spacecraft attitude and spin rate, as well as for enabling formation flying. A miniature radio frequency ion thruster (MRIT) is being developed and tested at The Pennsylvania State University. It consists of a radio frequency coil operating at a frequency of 13.56 MHz surrounding an ionization chamber capped with accelerating grids. This paper discusses the ongoing development work and testing of the MRIT for inclusion on the LionSat nanosatellite.

1 INTRODUCTION

For the past 40 years, the numerous studies performed on radio-frequency (RF) ion thrusters have demonstrated their potential and attractiveness as propulsion devices. The benefits that these devices offer over traditional chemical and electric thrusters include the opportunity of varying the specific impulse, operating without a hot cathode, and gas ionization by electromagnetic fields [1,2]. Another advantage of ion engines over more conventional propulsion systems is their high specific impulse. A typical chemical thruster’s specific impulse is on the order of 300 s, whereas ion thrusters can achieve specific impulses on the order of 3000 s [2]. Hence, ion engines are of particular interest for a number of missions, e.g., to increase the operational life of propellant-limited satellites [3].

The two main processes within a typical ion thruster are, first, the ionization of the propellant and, second, acceleration of the ionized propellant using electrostatic forces through the exit grids. The independent nature of these two steps allows the beam velocity to be controlled by setting the grid voltage [1].

The performance of electric propulsion (EP) thrusters has always been limited by the power available to ionize and accelerate the propellant. With increasing availability of high performance solar cells, however, available electric power has increased and is no longer a limiting factor [1]. This has increased the interest for developing high specific impulse EP thrusters. The types of missions for which these thrusters are being designed include north–south station keeping (NSSK), compensating for aerodynamic drag, formation flying, and de-orbiting of satellites.

1.1 Previous Designs

A 10-cm RF Ion Thruster (RIT–10) that runs at an ionization frequency of 1 MHz with a cylindrical ionization vessel was developed at Giessen University, Germany [1,3,4]. The RIT–10 research focused on the performance of this thruster at different power levels, which were set to produce different specific impulses. The RIT–10 was tested on board the retrievable carrier *Eureca* that launched in 1992. It was designed to work for more than 1000 hours at an altitude of ~500 km for a one-year mission with a thrust between 5 and 10 mN. When tested, the thruster worked for about 240 hours until a soldering connection broke [5]. It achieved a power-to-thrust ratio of 25 to 30 W/mN at specific impulses between 3000 and 4000 s.

The 10-cm thruster was later modified to have a conical shaped ionization chamber in order to reduce the occurrence of collisional recombination by minimizing the surface area of the walls. This new engine, called the RIT XT, was designed as a 100–200-mN-class ion thruster, and was tested over this range of thrust levels [4,6]. Using this configuration, with a propellant efficiency between 80 and 96%, the ion production cost was reduced to 232–190.8 W/A for specific impulses from 2987–4600 s. This conical

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shape also presented better mechanical properties with respect to vibration loads and shock resistance during launch [4].

Following the RIT–10, the RIT–15 was developed, followed by the RIT–35. These thrusters were capable of producing a thrust of 20 and 250 mN, respectively [1,2,7]. The performance characteristics of the 15-cm RF Ion Thruster (RIT–15), which was designed to run at a frequency of 880 kHz, were also examined. The main goals of the research were to increase the ionization efficiency and to lower the power-to-thrust ratio to the range achieved by Kaufman and Hall-effect electrostatic thrusters by using high perveance carbon–carbon. Their earlier designs evolved from a cylindrical ionization vessel to a spherical vessel in order to reduce the area for wall recombinations without lowering the probability for ionization. With this new configuration they were able to achieve an ionization production cost of 275 eV/ion with an optimum specific power consumption of 25.5 W/mN and a propellant utilization efficiency of 92% [1,2].

The first engines—i.e., RIT–10, –15, and –35—were initially designed to use mercury as the primary propellant; however, the RIT–35 was adapted in 1988 to use xenon instead. The main reason for this change was the limited reactivity of this gas, minimizing spacecraft damage and environmental concerns [2]. Ground processing safety considerations were also decreased.

2 DESCRIPTION OF EXPERIMENTAL APPARATUS

The overall MRIT system design consists of a gas reservoir with flow controller feeding to an ionization chamber as well as a neutralizer. An RF source with matching network excites a discharge in a ceramic ionization chamber. Ions are accelerated out the end via a two-grid system with static potential maintained by a high voltage. The chemically milled accelerating grids are located at the downstream end of the ionization chamber. The system as it is being implemented for ground testing in a vacuum chamber is shown in Fig. 1.

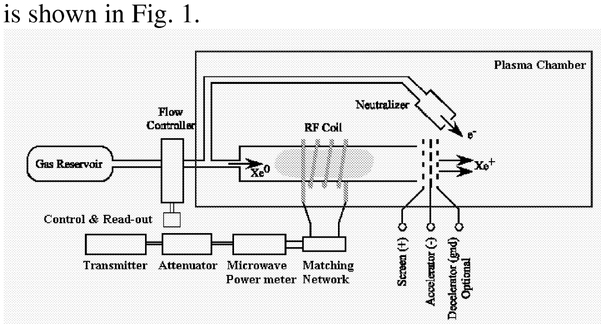

Fig. 1. Diagram of the MRIT system

2.1 Vacuum Chamber Testing Facility

Within the Communications and Space Sciences Laboratory of Penn State, two vacuum systems are available for MRIT testing. The smaller of these systems can achieve an absolute pressure of 10^{-5} torr via a turbo pump (Fig. 2). The larger chamber can achieve 10^{-7} torr via a cryopump. The first tests conducted here were performed in the smaller chamber due to availability of experimental time.

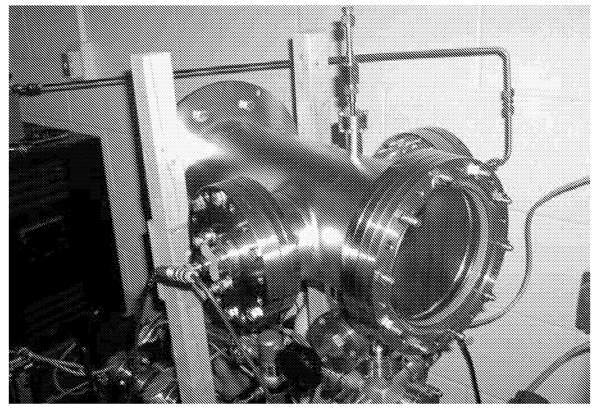

Fig. 2. Picture of the smaller vacuum chamber

The MRIT experimental ionization chamber was placed horizontally in the vacuum chamber shown in Fig 2. The chamber was made of quartz tubing for ease of fabrication and an 11-turn, 18-gauge (AWG), RF- ionization coil was wrapped around it. Different lengths of ionization chamber were fabricated in order to perform a parametric study.

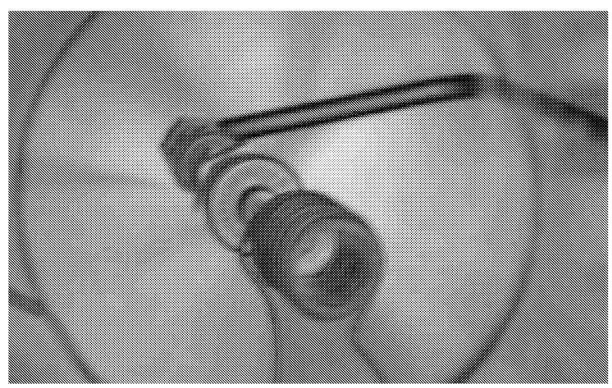

Fig. 3. Ionization chamber with RF coil inside vacuum chamber in Fig. 2

The set of grids being used for these experiments are made from chemically milled molybdenum. It consists of a positively charged grid (screen) located directly at the exit of the ionization chamber followed by a negatively charged grid (accelerator). No decelerator is used on this system. A static electric field is created between the grids by applying a –1000-V DC voltage, which accelerates the xenon ions thus creating thrust.

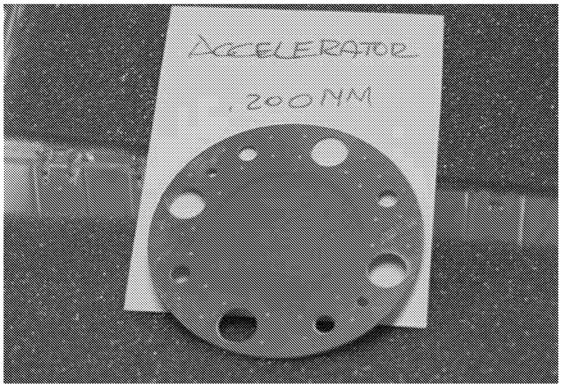

Fig. 4. Picture of the 0.200-mm accelerator grid

3 THEORY

3.1 RF Inductive Discharge in the Chamber

As mentioned above, the process of generating thrust in an ion thruster consists of two processes. The propellant is first ionized and then the thrust is generated via the acceleration of the electrically charged particles by static electric fields. In an RF ion thruster, the ionization chamber is made of an insulating material that is surrounded by an RF coil. When energized with RF power, the coil induces an axial (z-directed) magnetic field

$$B_z = \frac{NI}{\mu_0} e^{j\omega t}, \quad (1)$$

where μ_0 is the permeability of free space, N is number of turns per unit length, I is the current in the coil, and ω is the angular frequency. This time-varying magnetic field creates a corresponding time-varying azimuthal (θ-directed) electric field given by

$$E_\theta = -\frac{j\omega r}{2} B_{z0} e^{j\omega t}, \quad (2)$$

where r is the distance from the center axis, and $B_{z0} = NI/\mu_0$. The electric field generates a circumferential current in the plasma. The electrons are consequently accelerated, which increases their temperature and sustains the plasma during the ionization process. This inductively coupled process sustains the plasma discharge.

3.2 Plasma Initiation

Since there are no free electrons initially within the xenon gas to respond to the induced electric field, a different process is used to cause plasma ignition. Since there is no plasma before ignition, there is also no power dissipation from the coil to the gas, which implies a larger stored reactive power. The voltage across the coil is then increased and, with an appropriate matching network, some of the voltage is capacitively coupled to the inner wall of the chamber creating an electric field strong enough to break down the gas. Even though it was an unanswered question for over 50 years, it is now generally agreed that an RF discharge is capacitive at lower densities with a transition to mainly inductive at high densities [8].

The voltage necessary to initiate a discharge is roughly a function of the product of the spacing between "electrodes" and the pressure. For xenon, the minimum voltage occurs at a product of about 1 torr·cm (Fig. 5). At higher pressures, the required discharge voltage increases, making it difficult to start the plasma if the electrode spacing is large. At very low pressures (or more properly pressure–distance product), there are too few collisions and electrons traverse the chamber and strike the walls without ionizing. For typical chamber geometries, it is very difficult to initiate a capacitive discharge at pressures less than 10–20 millitorr, though it is often possible to "strike" the discharge at higher pressure and then operate at only a few millitorr. In our initial experiments, we had to resort to a Helmoltz coil to strike the discharge in the chamber, after which the inductive discharge mode from the RF coil took over immediately. It is clear that additional work on a low-power "strike" function is needed for a flight version of the thruster.

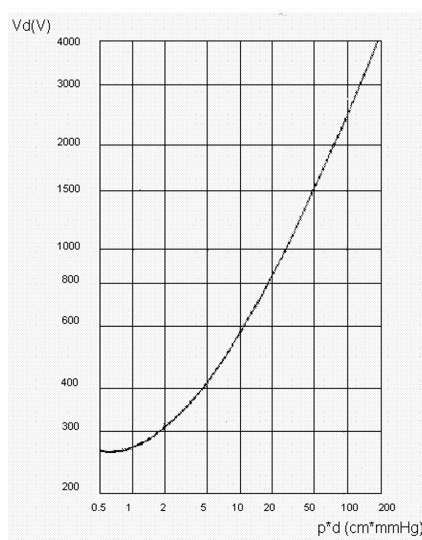

Fig. 5. Paschen curve for xenon (after Ref. [9])

If the discharge is driven directly by an RF power source, then power is not transferred efficiently from the source to the discharge. Therefore, a matching network between the source and the ionization coil is required. Additionally, one of the benefits of an RF ion thruster is that it can make fast changes (on the order of milliseconds) in thrust level simply by changing the applied RF power level. The mass flow can be subsequently changed until it reaches an optimum value. Our design is being optimized for a flow rate of 5 sccm.

4 RESULTS AND DISCUSSION

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 in the 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 about ~30 W. A stable plasma can be maintained for incident power in the coil (after matching network) of ~9 W. Fig. 6 shows the plasma as developed in the MRIT ionization chamber.

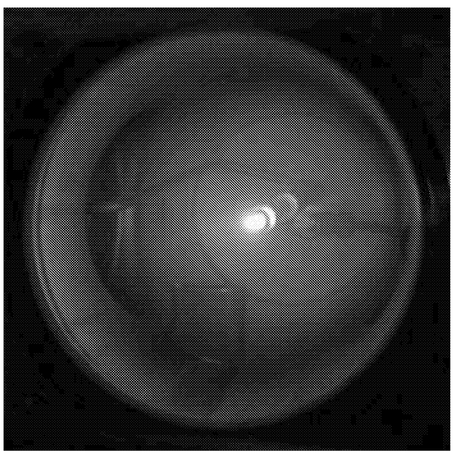

Fig. 6. MRIT ionization chamber in operation in the vacuum chamber

After plasma initiation via the aid of a Helmoltz coil, the sustaining inductive discharge took over almost instantaneously. Previous studies on a similar diameter (but longer) MRIT ionization chamber did not require the application of an external electric field due to, what we suspect, is the different configuration of the power source and matching network [10].

As mentioned above, inductive discharges, in general, start in a capacitive mode at low plasma density and then transition to an inductive mode at higher densities [8]. Most processing gases are molecular and electronegative; hence they are easier to induce discharge. 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. We also have to consider that the description of the ionization process in an RF discharge is particularly complex. In our discussions here, we have considered first-order processes.

5 FLIGHT OPPORTUNITY: LIONSAT

The miniature RF ion thruster has been baselined as the propulsion system on the nanosatellite mission called LionSat (Local Ionosphere Measurements Satellite) [11], which is part of the University Nanosatellite 3 (UN–3) program sponsored by AFOSR, NASA GFSC, and AIAA. These three organizations established the University Nanosatellite program to perform space experiments, demonstrate new technologies, and develop operational systems via low-cost spacecraft. Because it is geared towards universities, it is an educational program that prepares students for careers in the space industry. The program seeks to establish strong relationships between university, industry, and government. The Air Force Research Laboratory Space Vehicles Directorate is currently developing low-cost solutions for the small satellite launch problem by exploiting excess payload capacity on several launch vehicles [12]. LionSat must fit within a envelope of 47.5 cm in both diameter and height, and have a mass of less than 30 kg [13].

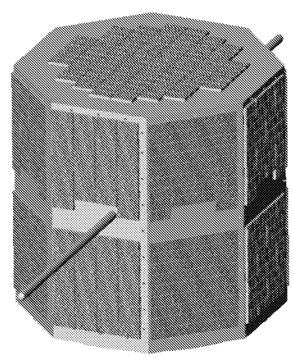

Fig. 7. LionSat with plasma booms deployed

The primary engineering goal of the LionSat mission is to investigate spin maintenance of the spacecraft using a pair of MRITs. 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. 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. A minimum of twenty-four hours of operation is expected including at least one hour of continuous operation. 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.

6 FUTURE WORK

Clearly, much work remains to develop an operational MRIT system; however, we are very encouraged by the results of our initial experiments. Concurrently, we are developing the RF electronics, propellant feed system, and propellant storage system, which will be somewhat limited in total volume due to safety considerations (100 psia maximum vessel pressure). As for the flight version of the MRIT, a conical shape is being considered for the ionization chamber in order to minimize the loss rate of ions on the walls. Different sizes and shapes are being machined from MACOR ceramic and will be tested. Another issue we are considering is the neutralization of the flow of positive ions being exhausted from the engine. Several candidate neutralizers are being considered.

7 CONCLUSIONS

The development of a miniature RF ion thruster is well underway at Penn State. We have demonstrated the ability to sustain an inductively-coupled plasma discharge at a power level of <10 W with a flowrate of 5 sccm of xenon. As a system, the MRIT is being developed for flight test on LionSat, a nanosatellite being designed and built by students at Penn State as part of the NS-3 program. A number of open items remain before the thruster is ready for flight, which we are actively pursuing. Our hope is to approach the calculated values of performance, which are an Isp of ~3800 s and a thrust of ~0.6 mN.

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