Micro RF Ion Engine for Small Satellite Applications

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ABSTRACT

A xenon-fueled, micro rf ion engine suitable for small satellite propulsion was developed by Busek. Operating with a pair of grids that are 3 cm in diameter, the thruster demonstrates 1.4-2.1 mN thrust and 1500-2850 seconds Isp. Total power consumption ranges from 60 to 100 W. At the optimum Isp of 2500 seconds, the estimated thrust efficiency and propellant utilization is 49% and 47%, respectively. Total efficiency, including 90% dc-to-rf conversion, is estimated at 21%. The total efficiency can potentially be increased up to 27% by reducing rf coupling loss. Busek is dedicated to further miniaturize rf ion engines with the development of a 1-cm thruster equipped with a propellant-less carbon nanotube field emission neutralizer. Projected performance of the 1-cm micro rf ion engine is 0.15 mN thrust, 1570 seconds Isp and 14 W total power consumption.

INTRODUCTION

Radio-frequency (rf) ion engine belongs to the family of electric rockets used in spacecraft propulsion. It is categorized as an electrostatic thruster because it generates thrust by accelerating ions with the use of electric field between aligned grids. The rf ion engine creates the ions by electrode-less inductive discharge and does not require an internal cathode, eliminating a life-limiting component of a typical bombardment-type dc ion engines. Due to the absence of internal electrode and permanent magnetic structure, rf ion engines can be made much lighter and more efficient than dc ion engines of same size. In addition, rf ion engines are easier to scale down in size and power, making them attractive for small satellite propulsion. This paper documents Busek's effort in miniaturizing rf ion engines with the development of a 3-cm, 100W model. Laboratory results also pave way for the development of a 1-cm model suitable for nano-satellite applications.

Concept

The idea of incorporating inductive plasma source in an ion engine was first invented at the Giessen University of Germany in the 1960s. Since then, the European Aeronautic Defense and Space Company (EADS) Space Transportation GmbH has successfully developed and flown this type of rf ion engine. An rf ion engine of large scale (>10cm class) has similar performance compared to a dc ion engine with >3000 seconds Isp, >85% propellant utilization and >80% electric efficiency.[1]

A typical rf ion engine utilizes current induction method to generate plasma, as opposed to the direct electron bombardment method used in traditional dc ion engines. A conceptual view of a two-grid rf ion engine is shown in Figure 1. The rf coil initiates the ionization process by sending a high-frequency electromagnetic wave into the discharge chamber, which energizes any free electron along the azimuthally alternating electric field. This induced electron current carries tremendous amount of kinetic energy and subsequently ionizes some of the neutral particles upon contact.[2] Once the plasma is ignited, the inductive discharge is sustainable for a wide range of flow rate, rf power and grid extraction voltage.

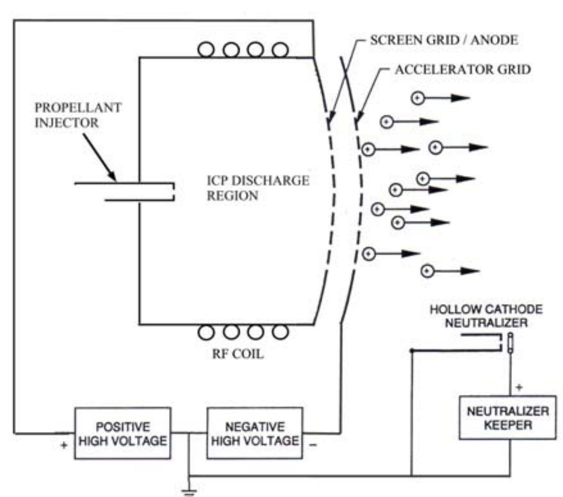

Figure 1: Conceptual View of an RF Ion Engine

Although rf ion engines have inherent advantages stemming from its method of plasma discharge, they require detailed design considerations. For example, the driving frequency and discharge pressure need to be carefully selected in order to prevent strong skin effect that impedes the induced electromagnetic wave penetrating into the plasma. In addition, the matching circuit, number of coil turns and chamber dimensions all need to be properly designed to minimize loss and maximize energy efficiency.[3]

Rapid and Precise Thrust Control

One significant advantage of an rf ion engine over competitors is its ability to rapidly and precisely vary thrust by adjusting the input rf power. This feature is critical for missions that require fine thrust control such as formation flights and missions that need fast thrust response such as drag cancellation. Busek has demonstrated such ability with a previously developed 7-cm rf ion engine. An interesting experiment was conducted during which the rf power was driven with the amplitude waveform of a music clip and the thrust response was recorded. Figure 2 shows the result. The original waveform of the music signal is shown at the top and the resultant thrust, estimated from the anode current, is shown at the bottom. It can be observed in Figure 2 that the recorded thrust waveform looks very similar to the driving music signal. By playing back the resultant thrust waveform as music, the original melody can be identified quite clearly. This demonstration proves that rf ion engines can indeed change thrust rapidly and precisely by programming the input rf power.

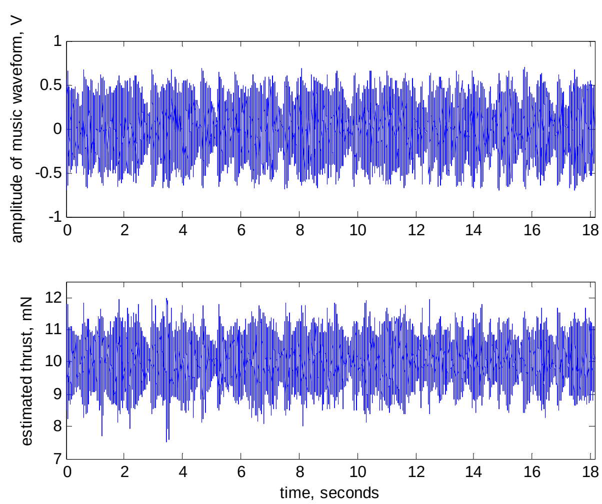

Figure 2: Rapid and Precise Change of Thrust by Modulating RF Power Programmed through a Music Waveform

Application of Micro RF Ion Engine

Miniaturizing rf ion engines has been an ongoing work in the electric propulsion community. Like many electric thrusters, nominal thrust and efficiency of an rf ion engine decrease as the size and power are reduced. Scaling often depends on the spacecraft size and payload limit. For example, for a micro-satellite that weighs 10-100 kg, a 3-cm class rf ion engine may be ideal. Previous theoretical work has shown the performance of a 3-cm rf ion engine can range 1-2 mN nominal thrust and 2000-3000 seconds Isp.[4] This performance is comparable to the MIXI micro dc ion engine developed by JPL.[5,6] For operating onboard a nano-satellite as a CubeSat, a 1-cm rf ion engine with 0.1 mN output would be the likely choice, albeit the lowered efficiency at the miniature size.

Applications of micro rf ion engines include many currently planned and future NASA missions that require precisely controlled and highly throttlable thrust for formation flights. These missions include Laser Interferometer Space Antenna (LISA), Space Interferometer Mission (SIM), Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), Space Astronomy Far Infrared Telescope (SAFIR), Terrestrial Planet Finder (TPF) and Stellar Imager. Furthermore, micro rf ion engines can serve as tip-off control for formation flying satellites. Tip-off refers to the de-tumbling of spacecraft upon separation from a launch vehicle.

Not only applicable to formation flight applications, micro rf ion engines are also the prime candidate for missions calling for zero drag. Zero drag can be achieved by varying thrust to counter the drag force measured from minute deceleration of the spacecraft. The thrust must be rapidly responsive and precise, which are the special features of rf ion engines. Example of a drag-less mission is the recently successfully Steady-State Ocean Circulation Explorer (GOCE) by the European Space Agency.[7]

BUSEK'S MICRO RF ION ENGINE

Busek's effort in miniaturizing rf ion engines began with the development of a 3-cm model labeled as BRFIT-3. Picture of the laboratory prototype is shown in Figure 3. The 3-cm refers to the diameter of the grid's hole pattern. Physical open fractions of the grids were designed to resemble the ones of the NSTAR ion engine flown on NASA's Deep Space 1 mission.[8] Actual ion transparency of the grid system varies depending on the grid voltage and plasma density; it typically ranges from 60 to 90%.

BRFIT-3 utilizes an RC parallel matching circuit to ensure more than 98% of the forward power is delivered to the load. A miniature capacitor bank (Figure 3) is mounted within the aft cylindrical casing.

Matching frequency with the use of this capacitor bank is around 2 MHz. A high-temperature ceramic material is used extensively for internal structures to relieve the deposition of rf power on conductive surfaces. Glass-ceramic is used for the laboratory prototype because of its machinability and relative strength. It however may not be tough enough to pass vibration testing. High-purity ceramics are typically used for flight applications.

Designed to operate with xenon, BRFIT-3 takes 30-50 W rf input power and produces 30-50 W dc beam power. This amounts to 60-100 W total power consumption. The beam power is mostly provided by the anode power supply, which in this case is the same as the screen grid power supply (Figure 1). Accelerator grid under nominal operation collects very low current and consumes less than 0.1 W. Figure 4 shows BRFIT-3 firing with 40 W rf power. Background pressure during testing is ~5×10^{-5} Torr.

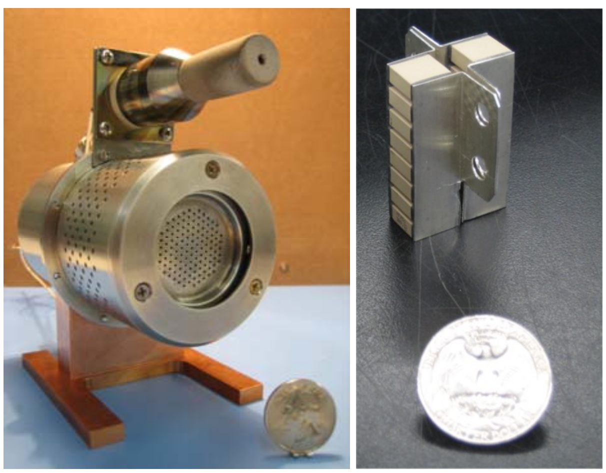

Figure 3: (L) BRFIT-3 with Busek 1/8" Hollow Cathode/Neutralizer; (R) Internal Capacitor Bank

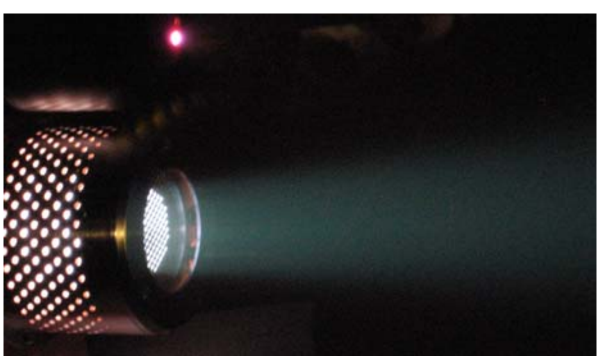

Figure 4: BFRIT-3 with Xenon and 40W RF Power (Shown with Veeco Cathode as Neutralizer)

EXPERIMENT

Definition of Performance Parameters

For the laboratory tests, thrust and Isp are estimated by the indirectly-measured beam current where $J_{beam} = J_{anode} - J_{accel}$. Equation for estimating thrust is shown in Eq. 1. Since the ion beams are well collimated, this method is widely used and accepted. Previous thrust-stand data showed 95% agreement with the estimated ones. Eq. 2 to 4 explains the efficiency parameters used in this paper. The thrust efficiency (Eq. 2) is important regarding spacecraft's thermal management because any power that is not converted into the production of ion beam is lost as heat. The propellant utilization efficiency (Eq. 3) is defined as the percentage of the neutral gas leaving as beam ions. This parameter is usually not as critical as the Isp is high and the propellant consumption is low regardless. The total efficiency (Eq. 4) is a combination of thrust and utilization efficiency and is generally used for comparing ion engines. Here a dc-to-rf conversion efficiency of 90% is also included in the total efficiency term. Note that the power and propellant consumption by the neutralizer are not included in the performance assessment.

$$F = \sqrt{\frac{2m_i}{e}} J_{beam} \sqrt{V_{screen}} \tag{1}$$

$$\eta_{thrust} = \frac{P_{beam}}{P_{beam} + P_{RF}} \tag{2}$$

$$\eta_{utilization} = \frac{J_{beam}}{\dot{m}(e/m_i)} \tag{3}$$

$$\eta_{total} = \eta_{utilization} \times \eta_{thrust} \times \eta_{DC\rightarrow RF} \tag{4}$$

Results

BRFIT-3 was tested with three flow rates (0.6, 0.8 and 1 sccm xenon) and 35-55 W rf power. These flow rates represent approximately 2.2 to 3.7 mTorr discharge pressure. Screen and accelerator voltage were set at 1800 and 100 V, respectively. For a given rf power, increasing flow rate generally increases thrust at the expense of propellant utilization and thus Isp. This tradeoff is shown in Figure 5 and Figure 6. Overall a wide range of performance is demonstrated here; thrust is recorded from 1.4 to 2.1 mN and Isp from 1500 to 2850 seconds. Note that full throttlability was not demonstrated. Previously tested 7-cm thruster exhibits throttlability in an order of magnitude.

Figure 7 shows the efficiency parameters as functions of Isp regardless of flow rates. Utilization and Isp have a linear relationship as they are both related to propellant usage. Electrical efficiency, at the other hand, decreases with increasing Isp. This trend is caused by the decreasing number of neutrals present in the discharge chamber when more of them are converted into ions and get extracted. As the result, probability for an rf-energized electron to collide with neutrals goes down, wall loss goes up, and the power required to create a beam ion increases. The cross-over between thrust and utilization efficiencies can be interpreted as an optimum point because it signals where the total efficiency curve starts to flatten. The optimum operating point in this case is around 2500 seconds Isp. The associated efficiencies are 49% for thrust, 47% for utilization and 21% for total. Total power consumption is 100 W (50W rf + 50W beam).

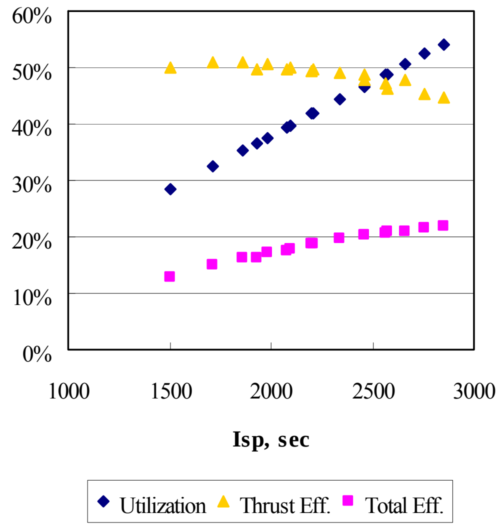

Figure 7: Efficiencies vs. Specific Impulse

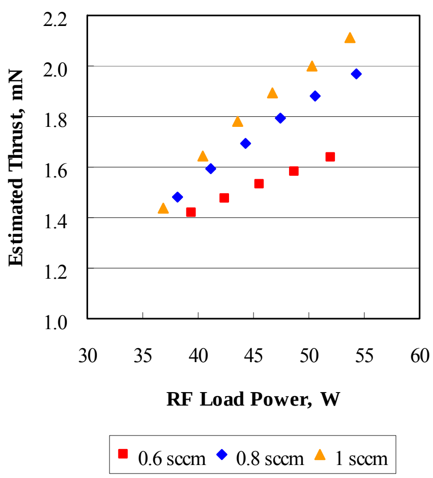

Figure 5: Thrust vs. RF Power

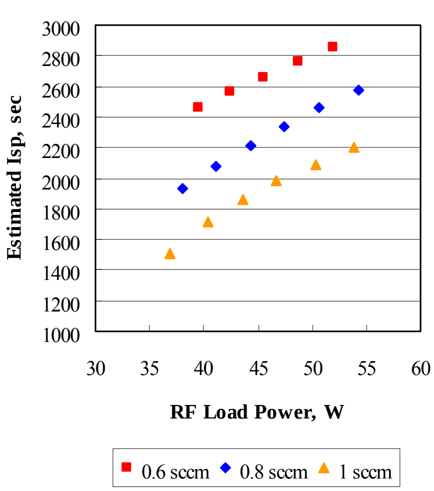

Figure 6: Specific Impulse vs. RF Power

Discussion

The 21% total efficiency of BRFIT-3 is lower than expected. One major cause is the loss of rf power to the surrounding conductive structure, thereby generating waste heat. The necessary standoff between the rf coil and other conductive surfaces could not be achieved within the available volume of the thruster. As the result, we estimate 30-40% of rf power was lost in the front grid structure and 15-20% of power was lost in the cylindrical metallic housing. The loss due to the grid structure is difficult to avoid, as moving the coil further away from the grids will increase ion wall losses. Reducing power loss to the grids is an active area of research. Potential solutions have been identified but not yet tested The power loss due to the metallic housing, on the other hand, can potentially be recovered by switching to a non-conductive material. Although the housing will lose its grounding ability, electrons are unlikely to enter the thruster as long as the housing does not have any opening. Figure 8 shows this proposed design labeled as BRFIT-3B. Preliminary test shows that by removing the metallic housing, thrust can be increased by as much as 20% because more power will be available to generate plasma. Predicted nominal performance of BRFIT-3B at 50 W RF power is 2.3 mN thrust, 2960 seconds Isp, 53% thrust efficiency and 27% total efficiency.

Figure 8: BFRIT-3B Design

WORK IN PROGRESS

With the successful development of BRFIT-3, Busek has shifted the focus onto a micro rf ion engine suitable for nano-satellite application. Supported by NASA/JPL, the work in progress is a 1cm-grid-diameter, 14W maximum-power thruster referred to as BRFIT-1. Two versions of BRFIT-1 are planned; one is designed to produce 50 µN and the other is designed for 150 µN and 1570 seconds Isp. One major attractive feature of BRFIT-1 is that as long as it operates under 150 µN, which is the equivalent of 2.1 mA beam current, the ion beam can be neutralized by Busek's space-qualified carbon nanotube field emission (CNTFE) cathode.[9] The CNTFE cathode requires no propellant and consumes less than 1 W of power. This innovative combination of micro rf ion engine and CNTFE cathode will give designers of nano-satellite a chance to incorporate an advanced electric propulsion system.

Figure 9 shows the BRFIT-1 prototype with Busek's space-qualified CNTFE cathode. Its predicted performance, along with the summary of BRFIT-3, is shown in Table 1.

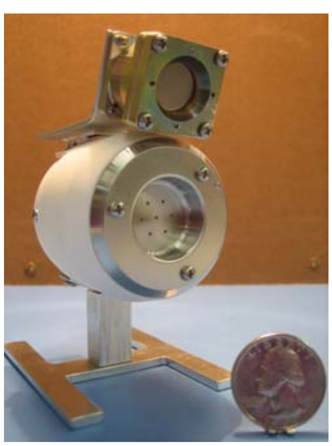

Figure 9: BFRIT-1 with Busek CNTFE Cathode

Table 1: Summary of Busek Micro RF Ion Engines

Thruster	BRFIT-3	BRFIT-3B (pred.)	BRFIT-1 (pred.)	BRFIT-1 (pred.)
Grid Size, cm	3	3	1	1
V_{screen}, V	1800	1800	1800	1800
RF Power, W	50	50	10	10
Thrust, mN	1.9	2.3	0.05	0.15
Isp, sec	2500	2960	1300	1570
Thrust Eff.	49%	53%	11%	28%
Utilization Eff.	47%	56%	25%	30%
Total Eff.	21%	27%	2.5%	7.50%

CONCLUSION

Demands for sophisticated electric thrusters grow as spacecraft missions become ever so complex. RF ion engines have the advantage of precise thrust control as well as rapid response. It is an ideal device for constellation flights and drag-less missions in LEO. Realizing such capabilities, Busek began to develop micro rf ion engines suitable for small satellite applications. The theory, setup and experimental data of a 3-cm, 100W class micro rf ion engine are presented. Highlights of its performance data include 1.4-2.1 mN thrust, 1500-2850 seconds Isp, total efficiency of 21% with the potential of increasing it to 27%. This development paves way to the current work of a 1-cm micro rf ion engine. The 1-cm thruster is projected to produce 150 µN thrust and 1570 seconds Isp. Armed with a propellant-less CNTFE neutralizer, the 1-cm thruster system is applicable to nano-satellites and can be perceived as a major advancement in micro propulsion.

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