Development of Helicon Electrostatic Thruster (HEST)

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Abstract: Helicon plasma can be utilized to high power electric propulsion thruster because it can produce high density plasma (~10^{19}m^{-3}) using high frequency discharge. Past studies about helicon plasma thrusters are mainly focused on electrode-less accelerations, but we propose and develop a new electrostatic acceleration of helicon plasma using by electrode. In this study, we measured ion energy distribution function, ion beam current and thrust to evaluate the performance and investigated the characteristics of the electrostatic acceleration of the helicon plasma.

Nomenclature

B	=	magnetic flux density at the coil center
e	=	elementary charge
E_i	=	ion energy
F	=	thrust
g	=	gravitational acceleration
I_b	=	ion beam current
I_d	=	discharge current
I_{sp}	=	specific impulse
$\dot{m}_{hc}$	=	mass flow rate through the hollow cathode
m_i	=	mass of the ion
$\dot{m}_i$	=	mass flow rate of the ion beam
$\dot{m}_{rf}$	=	mass flow rate through the helicon source
n_e	=	electron density
P_d	=	discharge power

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P_{rf}	=	radio frequency (RF) power
P_{total}	=	total power without coil and hollow cathode
r	=	radical distance from center axis
u_i	=	average velocity of ion beam
V_d	=	discharge voltage
z	=	axial distance from the coil center
η_t	=	thrust efficiency

I. Introduction

Helicon plasma is useful plasma sources for various applications because it has high density plasma (10^{19} m^{-3} order) and it can be generated by a relatively simple arrangement. Helicon plasma is generated by radio frequency (RF) power supply through antenna and magnetic field. Since helicon plasma production does not need any electrode, the plasma is also known as long lifetime plasma source.[1]

At the thought of the helicon plasma use as a plasma source of the space propulsion, the acceleration method can classify two types, one is the electrodeless acceleration and another one is the electrode acceleration. There are some investigations about both electrodeless and electrode acceleration. Variable specific impulse magneto-plasma rocket, VASIMR (Ad Astra Rocket Company),[2] Helicon Electrodeless Advanced Thruster, HEAT (Tokyo University of Agriculture and Technology),[3] and Helicon Double Layer Thruster, HDLT (Australian National University)[1] use electrodeless acceleration. These thrusters can achieve electrode-erosion-free acceleration because they do not have any electrode in plasma source or acceleration region. Hence, these thrusters are expected long lifetime comparing with other thrusters with electrode. On the other hand, Helicon Hall Thruster, HHT (The University of Michigan),[4] and helicon magneto plasma dynamic thruster (Tohoku University)[5] use electrode acceleration. The target of using helicon plasma for these thrusters is both higher efficiency and higher thrust performance than conventional thrusters. The favorable feature of electrodeless plasma production with helicon wave never excludes the possibility of developing an efficient thruster using electrode acceleration region. So the thruster using helicon plasma source and electrode acceleration region is the possible candidate to achieve better performance than conventional ones.

Now, Hall thrusters are used for many satellites to correct the altitude and to attitude control.[6] The conventional Hall thruster is structure with annular acceleration channel and channel center core to produce the magnetic field of the radial direction. To decrease the loss with the center core, cylindrical hall thruster is developed in Princeton University.[7] As for this thruster, the annular part close to the exit becomes the ionization region of the propellant by equaling the length of the annular part and the ionization mean free path. The ions are accelerated and exhausted by the electric field of the rapid potential drop in the region without the center core. In this configuration, it is thought that the influence of the center core can be lowered.

Helicon electrostatic thruster (HEST) which electrostatically accelerates helicon plasma by the use of electrode. This magnetic field shape is similar to cylindrical type hall thruster and there is not a center core, so HEST does not have the reduction of the thrust by the friction with it. Moreover, the electric field has center direction component by the magnetic field shape, so we consider that HEST can suppress the friction with the outer wall, too.

In this study, the characteristics and the performance of HEST are investigated by measuring ion energy distribution, discharge current, ion beam current and thrust.

II. Experimental setup

A. Thruster Head Overview

The schematic of the HEST is illustrated in Fig. 1(a). The upstream section is helicon plasma production part. The helicon plasma is placed on the center axis of a water-cooled solenoid coil. The magnetic field is 100 mT at the coil center. We employ a copper helical antenna with a length of 170 mm that was first proposed by Shoji et al.[8] The radio frequency (RF) power is supplied to the antenna with 13.56 MHz, and helicon plasma is produced by the interaction between RF power and the magnetic field. In this study, the propellant is argon gas and mass flow rate is ranged in 0.21-0.84 mg/s. The helicon source tube is made of ceramic, and the inner diameter is 27 mm.

The helicon plasma shift to expanded tube at the downstream, plasma acceleration part. The expanded tube is made of ceramic, and the inner diameter is 80 mm. A ring shape anode, whose inner diameter is 27 mm and its thickness is 10 mm, is placed z = 25 mm, where the coordinates r (radial) and z (axial) originate at the coil center. A hollow cathode (DLHC1000, Kaufman & Robinson, inc) is placed at z = 180 mm, r = 70 mm to the diameter direction. Working gas is supplied in hollow cathode (0.15 mg/s, argon), and applied current of 2 A between the cathode and the keeper.

The details of the acceleration part is illustrated in Fig. 1(b). Downstream from the expanded tube, the magnetic field is formed as shown by solenoid coil, 16 cylindrical Nd-permanent magnets and a soft iron yoke. The permanent magnets are arranged with even azimuthal separation angles. In this way, there is few magnetic field near the hollow cathode. When electric discharge voltage V_d is applied between the anode and cathode, electron ejected from hollow cathode is trapped by these magnetic fields and electric fields are maintained. The ions are accelerated electrostatically, and neutralized by hollow cathode.

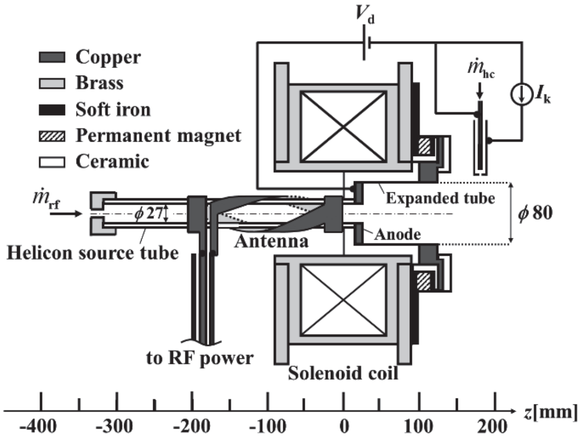

Figure 1(a) Schematic of the HEST.

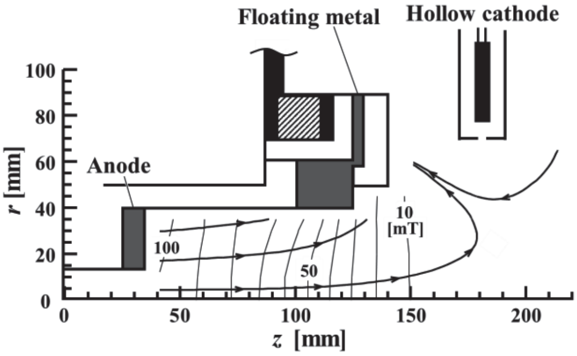

Figure 1(b) The detail of plasma acceleration part.

B. Experiment Apparatus and Measurement Method

The experiments in this study were conducted in a vacuum chamber whose diameter and length are 1.2 m and 3.2 m, respectively. The vacuum chamber was evacuated using a cryogenic pump (8400 L/s), which was backed by a dry pump (116.7 L/s). The ambient pressure in the vacuum chamber was measured by an ionization vacuum gauge and pirani gauge, and vacuum condition is kept less than 1.5×10^{-2} Pa.

Ion energy distribution function (IEDF) was measured by retarding potential analyzer (RPA)[9] which was fixed to the position of z = 390 mm, r = 0 mm. Ion beam current was measured by 400 mm × 400 mm quadrate copper ion collector which is applied to -50 V from cathode to reject electrons. This collector was located at z = 590 mm and the center of the collector corresponds to the center of the thruster. The collector should be placed close to the thruster because ion beam has a large divergence angle, but if the collector was placed at closer position, the collector affect the discharge characteristics. Therefore, there is a possibility that this configuration cannot capture the all ion beam current emitted from thruster. Thrust was measured by an inverted pendulum type thrust stand. The displacement of the stand is measured by a laser displacement sensor.

III. Operation characteristics

A. Operation condition

The operation conditions are shown in Table 1.

TABLE 1 Experimental condition

Control parameter	Symbol	Value
Mass flow rate (helicon tube)	$\dot{m}_{rf}$	0.21, 0.84 mg/s
Mass flow rate (hollow cathode)	$\dot{m}_{hc}$	0.15 mg/s
RF power	P_{rf}	0 - 1500 W
Discharge voltage	V_d	0 - 300 V
Keeper current	I_k	2 A
Magnetic field at coil center	B	100 mT

B. Operation characteristics

Dependency on V_d

Figure 2(a) shows ion energy E_i as a function of V_d, when P_{rf} is 300 W. The dotted line means $V_d = E_i$, i.e. ions are entirely accelerated by electric field between anode and cathode. In $V_d = 0$ V, ions have some energy because of RF power which is used to make plasma, and this energy is inverse proportion to mass flow rate. As shown in this figure, E_i depend on $\dot{m}_{rf}$. There is the knee point that a slope of E_i as a function of V_d turns into when V_d is increased. This point about E_i is linked with the knee point about I_d and I_b which is shown in Figs. 2(b) and (c). In addition, it becomes the problem that I_d is greater than the equivalent current of the propellant, and the acceleration efficiency is less than 0.2 with $V_d = 300$ V.

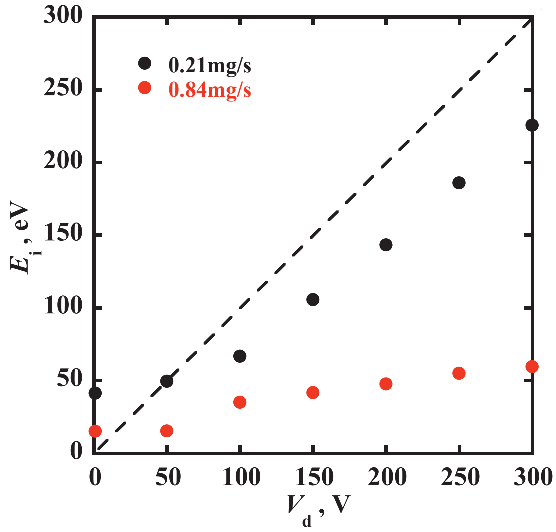

Figure 2(a) E_i as a function of V_d, *$\dot{m}_{rf}$ = 0.21–0.84 mg/s, P_{rf} = 300 W.*

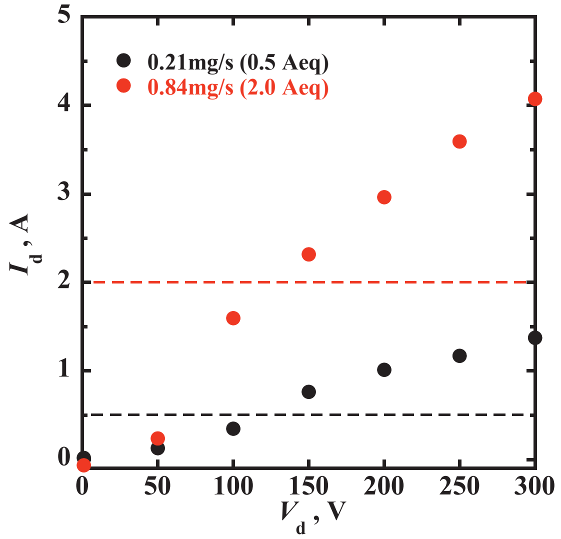

Figure 2(b) I_d as a function of V_d, *$\dot{m}_{rf}$ = 0.21-0.84 mg/s, P_{rf} = 300 W.*

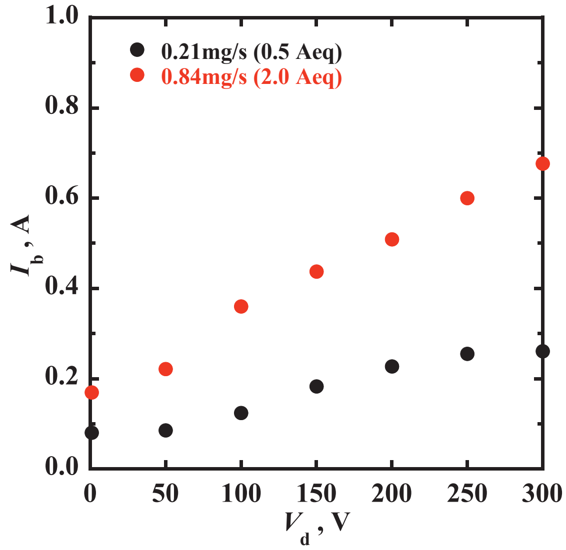

Figure 2(c) I_b as a function of V_d, *$\dot{m}_{rf}$ = 0.21-0.84 mg/s, P_{rf} = 300 W.*

Dependency on Power

Figure 3(a) shows ion energy E_i as a function of P_{rf}, when V_d is 300 V. A positive jump of E_i was seen with the low mass flow rate of 0.21 mg/s in 50 ~ 100 W. This jump accorded with a density jump when we measured electron density in a helicon plasma source without acceleration which is showed in Fig. 4. This tendency is also shown in Fig3. (b), I_d as a function of P_{rf}. Accordingly, when P_{rf} is small power, plasma is produced and accelerated by discharge between anode and cathode without RF power. And then, this result was able to confirm what ion energy was able to raise by helicon plasma generation with the low mass flow rate.

However, when there was large mass flow rate, E_i decreased sharply even if RF power was supplied. When looking at Fig3. (a), E_i increases to apply several dozen of P_{rf} with 0.21 mg/s of mass flow rate, though it needs several hundred or more RF power in order to increase E_i with more mass flow rate. From these result, an effect of the RF power tends to weaken if mass flow rate increases.

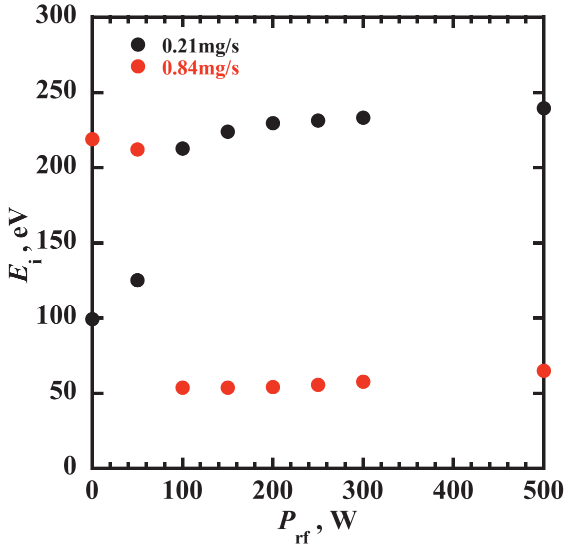

Figure 3(a) E_i as a function of P_{rf}, *$\dot{m}_{rf}$ = 0.21-0.84 mg/s, V_d = 300 V.*

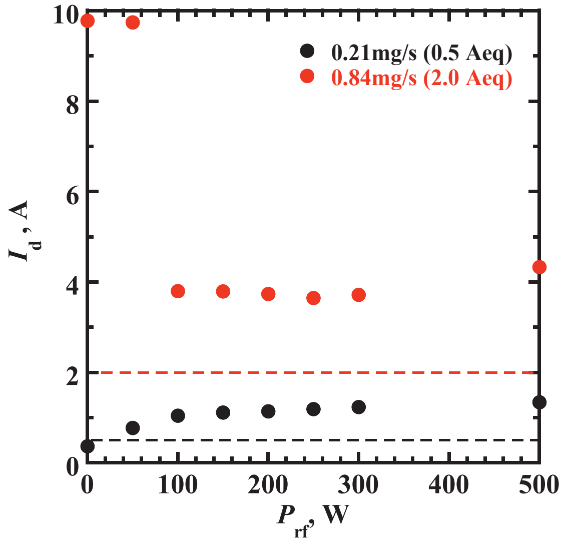

Figure 3(b) I_d as a function of P_{rf}, *$\dot{m}_{rf}$ = 0.21-0.84 mg/s, V_d = 300 V.*

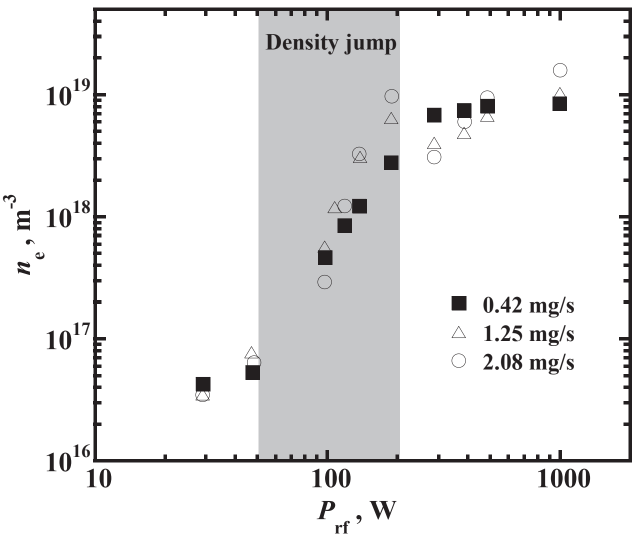

Figure 4 Electron density jump by increasing P_{rf}, *$\dot{m}_{rf}$ = 0.42-2.08 mg/s, P_{rf} = 0-1000 W, z=40 mm.*

Figure 5 shows E_i as a function of P_{total}, which means the consumed total power in plasma production and discharge while that is not include the power of the coil and the hollow cathode. From this figure, it tends to increase E_i and P_d ($=V_dI_d$) linearly. These slopes quite decrease with increasing the mass flow rate.

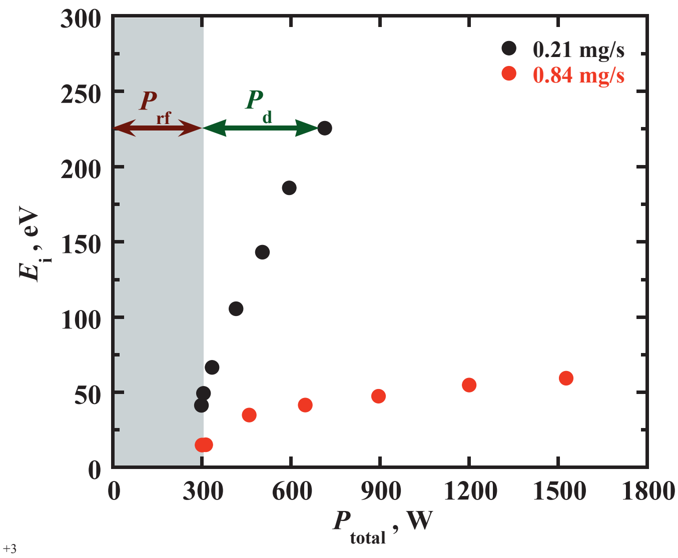

Figure 5 E_i as a function of P_{total}, *$\dot{m}_{rf}$ = 0.21-0.84 mg/s, P_{rf} = 300W, V_d = 0-300V.*

Thrust performance and efficiency

Figure 6 shows F as a function of V_d, when P_{rf} is 1500 W. However, sensitivity of the thrust stand which we used was not enough and we were not able to measure all conditions. The closed circles were measured by thrust stand and opened ones estimated by E_i and I_b, which were measured by RPA and ion collector, for Eq. (1). The curved lines mean ideal thrust when the propellant utilization efficiency equals to 100% and E_i equals to V_d.

$$F = \dot{m}_i u_i = I_b \sqrt{\frac{2 m_i E_i}{e}} \tag{1}$$

where, $\dot{m}_i$ is mass flow rate of the ion beam, u_i is average velocity of the ion beam, m_i is mass of the ion and e is an elementary charge.

The difference between the calculated thrust by Eq. (1) and measured thrust is likely to be caused by the ion current measurement, the captured ion beam currents were underestimated.

The maximum measured thrust was about 16 mN under these conditions and the measured thrust was close to an ideal thrust in the case of mass flow rate of 0.21 mg/s.

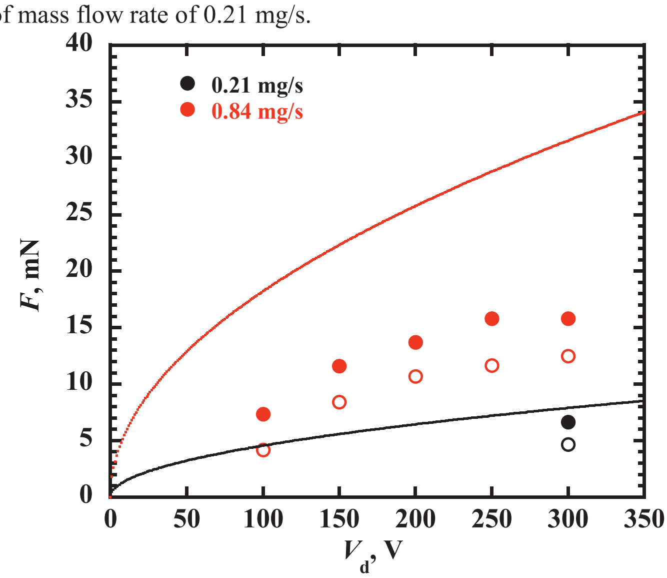

Figure 6 F as a function of V_d, *$\dot{m}_{rf}$ = 0.21-0.84 mg/s, P_{rf} = 1500 W, V_d = 100-300 V, ● shows the thrust measured by thrust stand, ○ shows the thrust estimated by E_i and I_b, solid lines are obtained by Eq. (1).*

Then, thrust efficiency η_t and specific impulse I_{sp} are estimated by the measured thrust. Figure 7 shows η_t as a function of I_{sp}. The equations of η_t and I_{sp} are shown Eqs. (2) and (3).

$$\eta_t = \frac{F^2}{2\dot{m}_i P_{total}} = \frac{E_i I_b}{P_{rf} + V_d I_d} \tag{2}$$

$$I_{sp} = \frac{F}{\dot{m}_{rf} g} \tag{3}$$

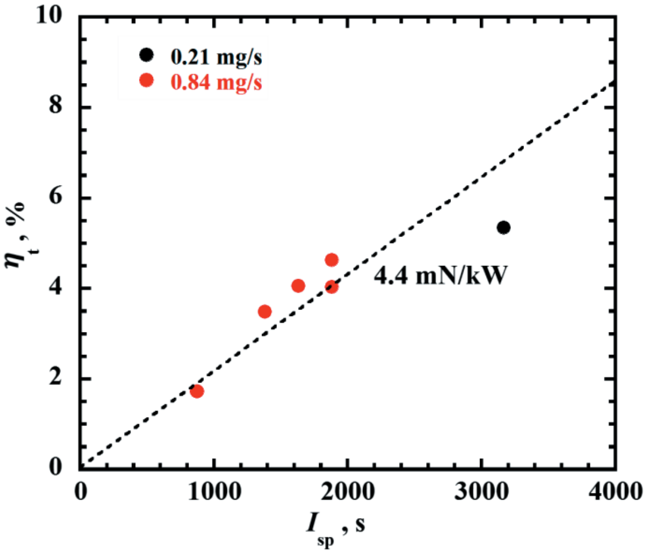

Figure 7 η_t as a function of I_{sp}, *$\dot{m}_{rf}$ = 0.21-0.84 mg/s, P_{rf} = 1500 W, V_d = 100-300 V.*

In the range of these experimented conditions, η_t was 5.4%, and I_{sp} was about 3200 s with mass flow rate of 0.21 mg/s. As a result, we find that there are a lot of power loss to accelerate ions by discharge voltage. There are two factors. One factor is many power that was applied to helicon source. The P_{rf} contributes to plasma production and not to increase in E_i.[9] Therefore, it is necessary to lower it as much as possible. The second factor is that the discharge current I_d is too large. The I_d is more than twice the equivalent current of the propellant with 300 V of discharge voltage, and this decreases the efficiency of the thruster.

IV. Conclusion

The thruster which helicon plasma source is accelerated electrostatically have been developed. For evaluating the thruster performance, the thrust, ion energy distribution and ion beam current was measured. From the measured results of the acceleration characteristics, both the ion energy and the discharge current had almost constant or small increment and increasing tendency with the discharge voltage. Although the separation of the plasma source and the acceleration region had an advantage for ion energy under the lower mass flow rate condition, this did not work well under the larger mass flow rate. The evaluated thrust efficiency was up to 5.4% under the measured condition. This lower efficiency is caused by both too large RF power for plasma production and, large discharge current compared with equivalent current of the propellant.

Acknowledgments

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