Thrust Characteristics of Helicon Plasma Thrusters

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Operation of present electric propulsion such as ion thrusters has lifetime limitation due to electrode erosion. Future missions such as interplanetary flight and manned flight to the mars require high power and high thrust. These requirements make the lifetime issue severe. In order to solve the problem, we have been studied advance electric propulsion system by use of helicon plasma sources with Lissajous acceleration. In our previous work, experiments of plume investigation were carried out and preliminary thrust measurement was conducted. Direct thrust measurement for Lissajous acceleration is now required and we have developed a thrust stand which measures the sum of thermal thrust and the electromagnetic thrust based on pendulum method. In this study, as a first step, thrust measurement for plasma source (without Lissajous acceleration) was conducted. We measured the thrust directly for different thrust sizes (ϕ50 mm, ϕ100 mm) by the thrust stand and evaluated the thrust performance for carious input power (0.1 ~ 2.1 kW) and gas flow mass (10 ~ 70 sccm). Pulse high frequency (9.5 MHz) discharge (~200 ms) was input to double loops generating antenna in all conditions. Both the thrust and specific impulse increased with increasing the input power for ϕ50 mm and ϕ100 mm. However, with increasing the gas flow rate, the thrust increased and specific impulse decreased with increasing the gas flow rate for both thruster sizes. Improvements in thrust performance are observed for larger thruster size (ϕ100 mm). Maximum thrust (11$\pm$0.66 mN) was 2.4-times and maximum specific impulse ($8.4\times10^2\pm33$ s) was 2.2-times as much as ϕ50 mm each. We are now measuring the thrust characteristics with Lissajous acceleration.

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I. Introduction

For deep space missions, high specific impulse and a long lifetime are required. Electric propulsion [1] can meet those requirements. Combination of a helicon plasma production and electro-magnetic plasma acceleration which is powered by radio frequency waves could be a solution because the entire process is achieved with no physical contact between the plasma and electrodes. Various schemes have been developed to realize electrodeless electric propulsion: VASIMR [2], HDLT [3], and others [4].

We have been studying Lissajous acceleration method [5][6], one of the electrodeless thrusters, whose concept is shown in Fig.1. This study becomes a part of the HEAT (Helicon Electrodeless Advanced Thrusters) project [7]. The thruster consists of two sections, a plasma generation section by helicon plasma discharge and a plasma acceleration section by the Lissajous method. In the acceleration section, rotating electric fields are applied to the plasma in order to excite electron azimuthal currents. The Lorentz force, which is the product of the currents and the static magnetic field, accelerates plasma and produces thrust.

In our previous work, experiments of plume investigation were carried out and preliminary thrust measurement was conducted [8][9]. Thrust by this Lissajous method is not measured directly, and therefore the thruster performance is unknown. In this paper, we report thrust measurement experiments for helicon plasma source and evaluate thrust characteristics for different thruster sizes. This experiment is the first step toward the thrust measurement of helicon plasma thruster with Lissajous acceleration.

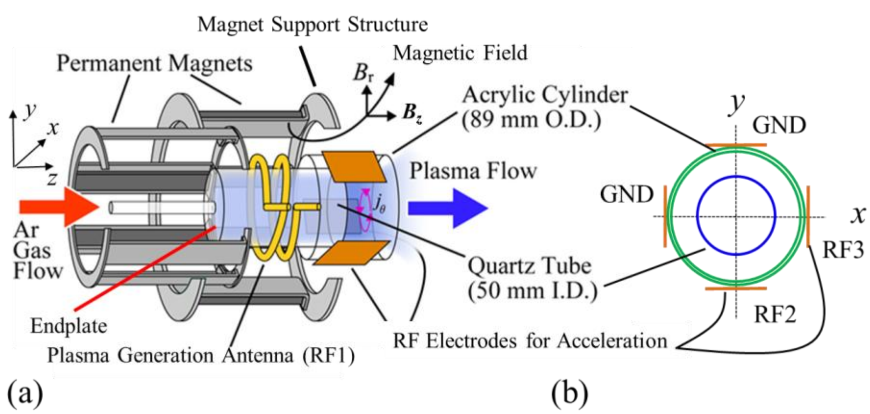

Figure 1. Laboratory model of Helicon thruster with Lissajous accelerator. *(a) side voew and (b)front view of thruster.*

II. Experimental Setup and Method

A. Experimental Setup

Experiments are conducted by the use of the "Large Helicon Plasma Device" (LHPD) [10] in the Institute of Space and Astronautical Science (ISAS). Experimental set up is shown in Fig.2. As shown in Fig.2, a quartz tube was placed inside the LHPD. Thrust is measured by a pendulum type thrust stand which is mentioned in section B below. Two inner diameters (I.D.) of 50 mm and 100 mm are used. Other experimental parameters are shown in Table I and configuration for power supply is shown in Fig.3. Pulse high frequency (9.5 MHz) discharge (~200 ms) was input to double loops generating antenna (RF1) in all conditions. Acceleration antenna (RF2 and RF3) were not used in this experiment. Dimensions of comportments for thrusters and the positions are shown in Fig.4. Gas mass flow is controlled by mass flow controller (HORIBA STEC, SEC-E440J) and monitored by mass flow controller monitor unit (KOEFLOC 3660). Input power is measured at monitor port of matching box (THAMWAY, T161-6013H-TN) by oscilloscope (Tektronix, TDS2014)

Table 1. Experimental Parameters.

Quartz Tube Dimensions	I.D. 50 mm length 50 mm	I.D. 100 mm, Length, 100 mm
RF Frequency	9.5 MHz	9.5 MHz
Input Power: P_{in}	0.1-2.1 kW	1.3-1.9 kW
Duration of RF Pulse	~200 ms	~200 ms
Chamber Pressure Before Discharge at Ar Flow of 0.89 mg/s	$< 6\times10^{-3}$ Pa	$< 2\times10^{-2}$ Pa
Gas mass flow	10-70 sccm	20, 30, 50, 70 sccm

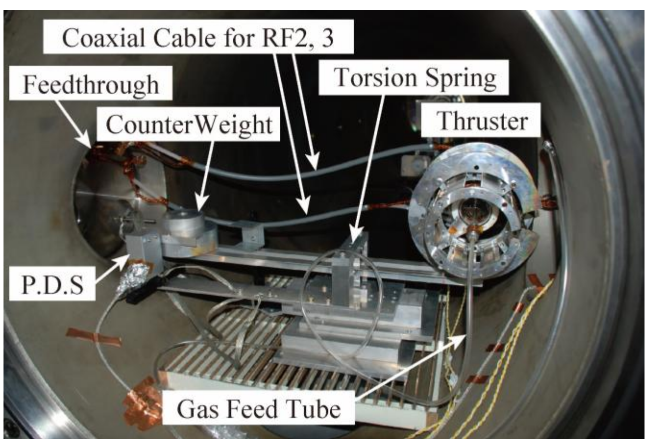

Figure 2. Configuration of thrust measurement.
(In case of thruster size 50 mm I.D.)

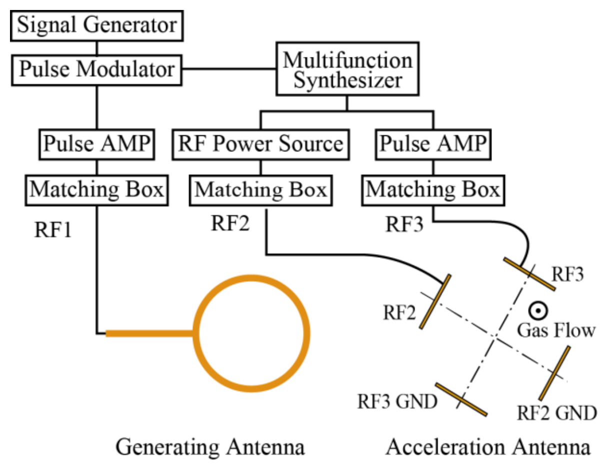

Figure 3. Configuration of power supply

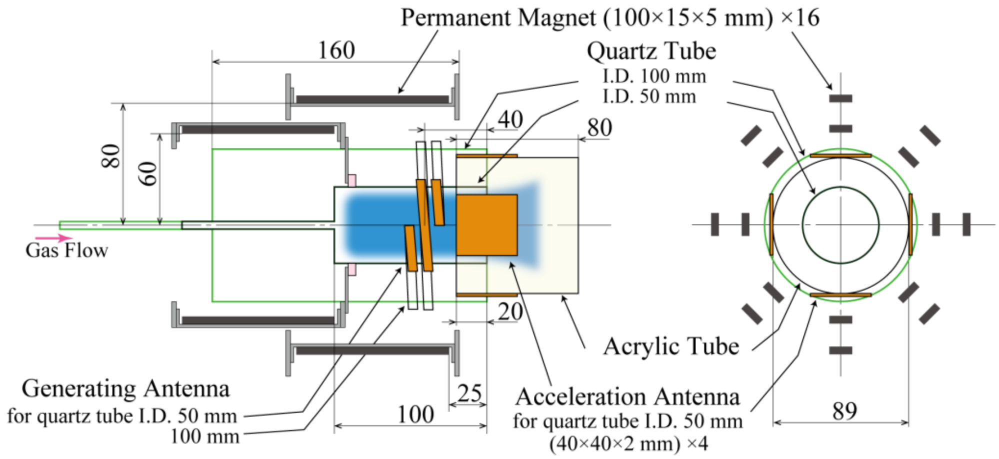

Figure 4. Dimensions for helicon thruster
(a) side view and (b)front view of thruster.

B. Thrust stand

Thrust stand is a micro thrust measurement system based on the pendulum method as shown in Fig.5. Two FLEXI-HINGEs (SDP/SI, S99FXS-031220) are used as a pivot of the pendulum. When the thruster produces the thrust, an impulse is imparted to the pendulum. This impulse drives damped oscillations of the pendulum as shown in Fig.0. The oscillation is detected by a photo displacement sensor (Omron, Z4D-F04A). An electromagnetic damper by the use of permanent magnets is placed to adjust the damping rate of the oscillation amplitude. In order to keep the balance of the thrust stand and increase the sensitivity of the thrust stand, counter weights are placed to cancel the gravitational force which acts on the thruster. Acceleration antennas (Fig.1) are suspended as surrounding the quartz tube contactlesslly and both the tube and circuit are mounted on the stand. Due to the fact that electromagnetic thrust and thermal thrust is given to the circuit and the tube, the sum of the electromagnetic thrust and thermal thrust is measured by the thrust stand. The response of the thrust stand to applied impulses is calibrated by striking a steel ball.

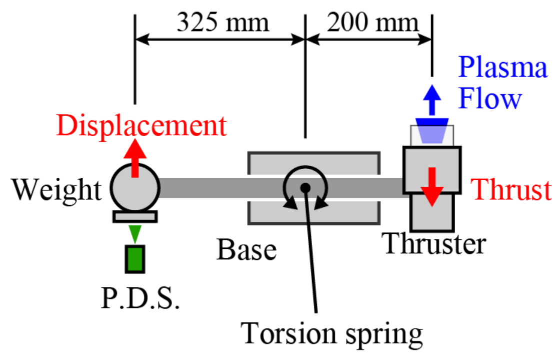

Figure 5. Experimental setup of thrust stand for thrust measurement.

III. Experimental Results and Discussion

The thrust, specific impulse for the 50 mm I.D. tube is shown in Fig.6 as a function of the mass flow rate for each input power. The maximum thrust (4.7 $\pm$0.12 mN) was measured at a parameter set: the mass flow rate of 60 sccm and input power of 1.5~1.7 kW. The maximum specific impulse (3.4×10^2 $\pm$4.9 s) was measured at a parameter set: the mass flow rate of 10 sccm and input power of 1.7~1.9 kW. The plasma ignition was not stable for the experimental parameters set of high gas mass flow and low input power. To elucidate the dependence of thrust characteristics for mass flow rate and input power, Fig.7 and Fig.8 are prepared. Fig.7 is the thrust and specific impulse for various gas flow rate (input power 1.3~1.9 kW). The thrust is proportional to the mass flow rate at a given input power. In addition, with the gas mass flow rate increase the brighter emission is observed. This suggests that the increase of the thrust could be caused by increase of the plasma density in the quartz tube. However, specific impulse decreases with increasing of gas mass flow. This indicates the rate of the thrust increase to gas mass flow increase is not enough to improve the specific impulse. Fig.8 shows the thrust and the specific impulse for the various input power (gas mass flow 30 sccm). Both the thrust and specific impulse are proportional to the input power. However, a rate of the thrust increase gradually decreases with increasing input power. Since the input power was measured at the output of a matching box, power loss through the coaxial cable from the matching box to the generating antenna (Fig.3) can be considered. The best performance is summarized in Table II in conclusion section.

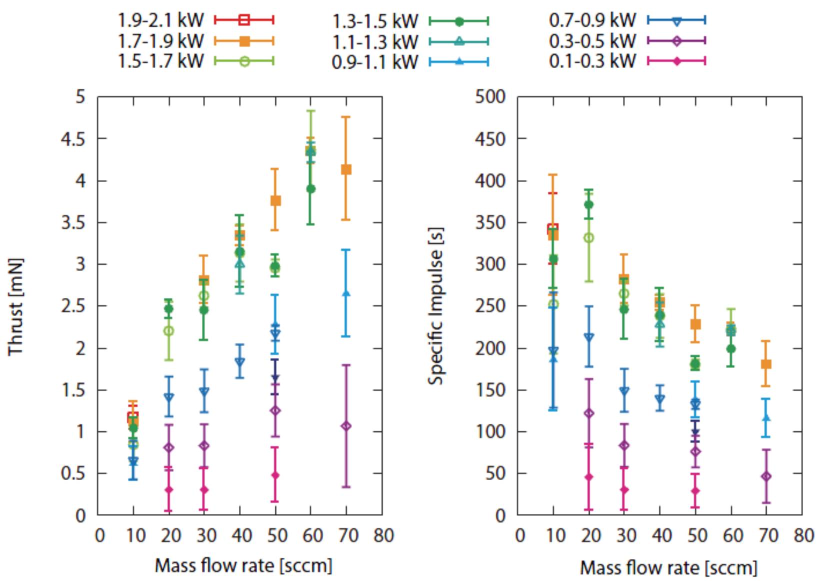

Figure 6. Thrust characteristics for 50 mm I.D.

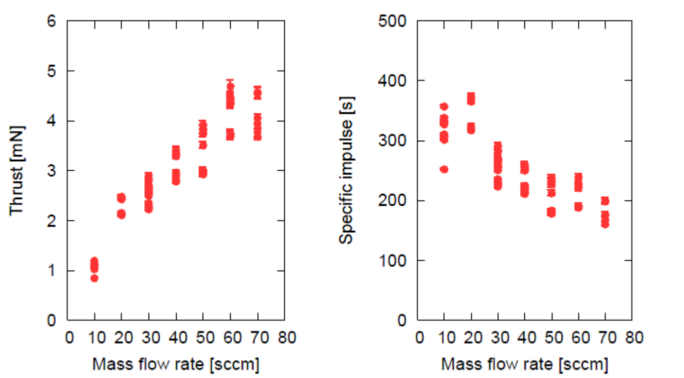

Figure 7. Thrust characteristics for various mass flow rate.
(*50 mm I.D., input power to generating antenna 1.3~1.9 kW)*

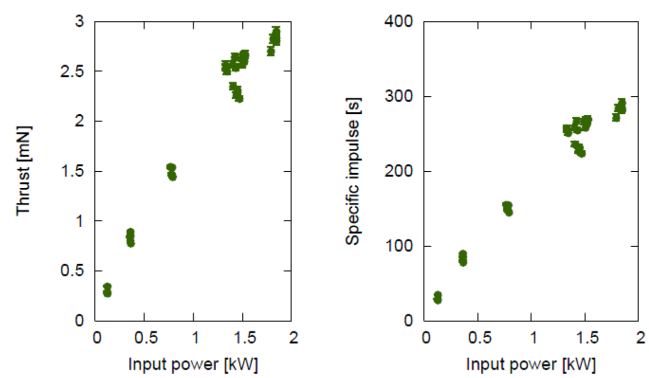

Figure 8. Thrust characteristics for varius input power.
(50 mm I.D., mass flow rate 30 sccm.)

The thrust and specific impulse for 100 mm I.D. is shown in Fig.9. Same trend as 50 mm I.D., the thrust increases and the specific impulse decreases with increasing of gas mass flow, was observed. Besides, improvement of thrust performance was measured. The maximum thrust (11 ±0.66 mN) was measured at a parameter set: the mass flow rate of 70 sccm and input power of 1.3~1.5 kW. The maximum specific impulse (8.4×10^{2} ±33 s) was measured at a parameter set: the mass flow rate of 10 sccm and input power of 1.3~1.5 kW. Compared with 50 mm I.D., maximum thrust is 2.4-times and maximum specific impulse was 2.2-times each. These improvements are considered to be caused by decreasing of plasma wall collision [11]. Since the distance between the plasma and the permanent magnetic get closer, larger quartz tube cause increase of magnetic field gradient in plasma and decrease the plasma wall collision due to the plasma confinement. The best performance is summarized in Table II in conclusion section.

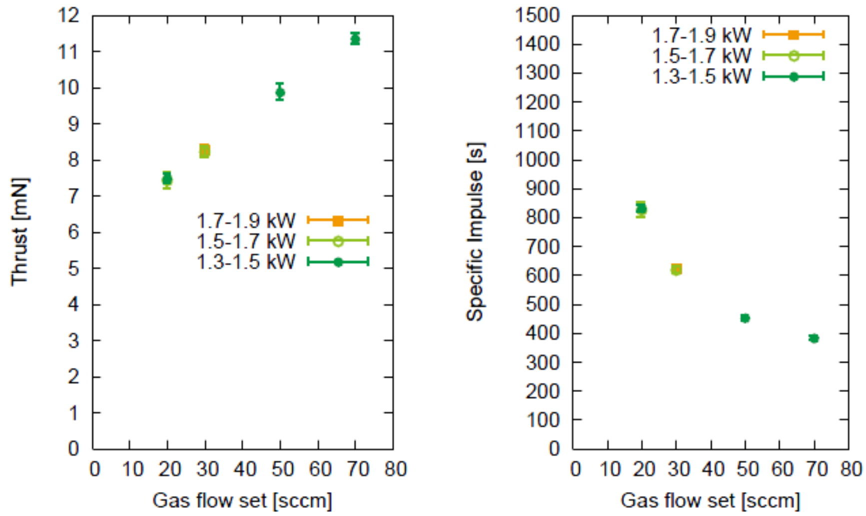

Figure 9. Thrust characteristics for 100 mm I.D.
(*input power to the generating antenna 1.3~1.9 kW, gas mass flow 20, 30, 50, 70 sccm)*

IV. Conclusion

Thrust measurement for helicon plasma source was conducted in two different thruster sizes (I.D. 50 mm and 100 mm) and thrust characteristics were evaluated. Both the thrust and specific impulse increased with increasing the input power. However, with increasing the gas flow rate, the thrust increased and specific impulse decreased. Same trend was observed for two different thruster sizes. And improvements in thrust performance were observed for larger thruster size (I.D.100 mm). Compared to I.D. 50 mm, maximum thrust (11±0.66 mN) was 2.4-times and maximum specific impulse (8.4×10^{2}±33 s) was 2.2-times each. The best performance is summarized in Table II. We are conducting thrust measurement with Lissajous acceleration for the laboratory model shown in Fig.1.

Table II. Thrust performance for two different thruster sizes.

	I.D. 50 mm w/o acceleration	I.D. 100mm w/o acceleration
Input power	< 2.0 kW	< 1.7kW
Max thrust	4.7 ±0.12 mN	11 ± 0.66 mN
Max specific impulse	3.7×102 ±4.9s	8.4×102 ±33s

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