Research and Development of High-Power, High-Specific-Impulse Magnetic-Layer-Type Hall Thrusters for Manned Mars Exploration

IEPC-2015-151／ISTS-2015-b-151

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

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Abstract: The Hall thruster is strongly required to space development in the future. This is because the Hall thruster has the characteristics of excellent propulsion performance, simple structure and small size. Therefore, the operational range of Hall thrusters will be hoped to be expanded for future orbital transfer vehicle and Mars exploration, i.e. for in-space propulsion. However, in order to apply to various space missions, high-power and high-specific-impulse performance of Hall thrusters must be improved. In this study, the basic performance characteristics were measured with typical made-in-Japan SPT-type Hall thruster THT-VI with discharge voltages of 300-1000 V in the large "HAYABUSA" space chamber system of JAXA, which was used for development of the HAYABUSA microwave ion engines, with high pumping performance. As a result, we obtained performance of thrust 102.05 mN, specific-impulse 3468.5 s, and thrust efficiency 63.4% with 2.1 kW. It was found that the thruster THT-VI is promising for the future missions although the operations were thermally severe.

I. Introduction

Activities of Hall thruster R&D are required to space development in the future. This is because the Hall thruster is suitable for excellent propulsion performance, simple structure and small size. Projects of electric propulsion for construction of large 1 GW-class solar power satellites, and for manned Mars or other satellites exploration, i.e. in-space exploration, have been proposed.[1-3] However, current Hall thrusters do not satisfy all performances, although when considering potentials of lifetime, efficiency, compact and performance, improvement is possible to meet it. In order to achieve various in-space missions, the performance of the Hall thruster was required to improve.

The final goal of this study is development of high-power and high-specific-impulse SPT-type (Stationary Plasma Thruster) Hall Thrusters for in-space propulsion. Performance measurement was performed using the SPT-type Hall thruster THT-VI developed at Osaka Institute of Technology. The THT-VI's discharge room outer-diameter is 100 mm. In order to design optimum Hall thrusters with large electric power, high specific-impulse, high thrust-efficiency, and long operating time, basic experiments were performed with a SPT-type Hall thruster. The

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operations were carried out at discharge voltage 300-1000 V. This is about two times of the conventional voltage. Then, the performance of the THT-VI was aimed at the achievement of specific impulse more than 3000 s.

II. Experimental Apparatus

THT-VI

The SPT-type Hall thruster was named THT-VI. Figures 1 and 2 show the schematic diagram of the THT-VI. Tables 1 and 2 show the specifications of discharge channel and coil. This thruster is classified as the magnetic-layer thruster, i.e. stationary plasma thrusters. The thruster has a discharge channel with an outer diameter of 100 mm and an inner diameter of 56 mm, i.e. with 22 mm in width, and the channel length is 40 mm. The channel dimensions are the same as those of SPT100 in Russia. The discharge channel wall is made of boron nitride (BN).[4] Figure 3 shows the calculated magnetic shapes.

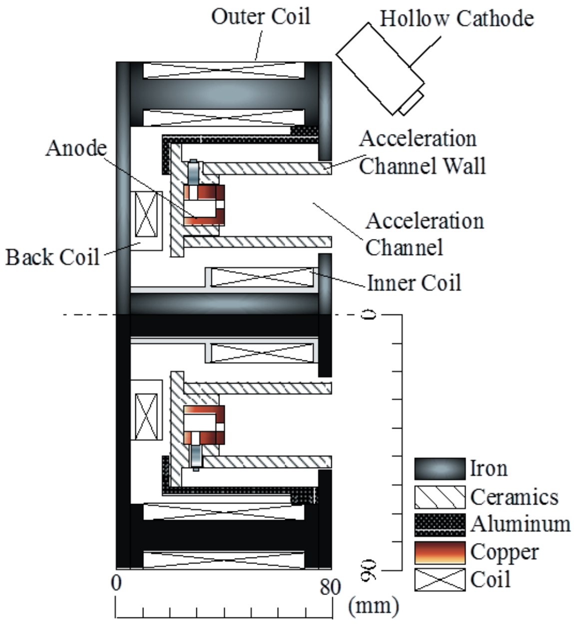

Figure 1. Cross-sectional view of SPT-type Hall thruster THT-VI.

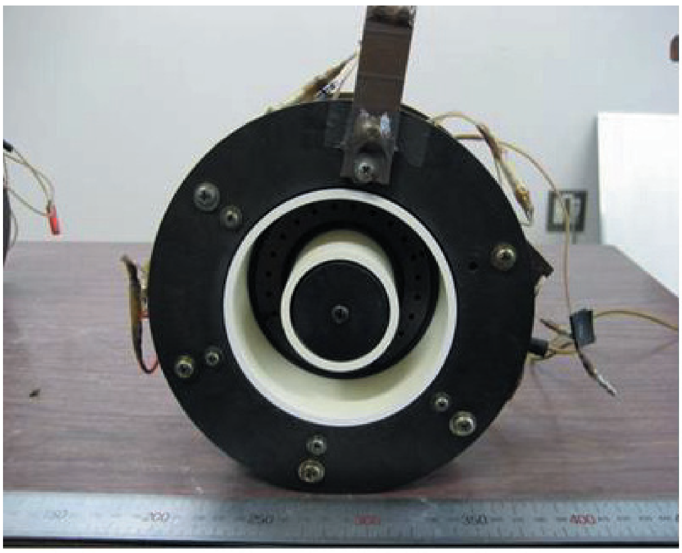

Figure 2. Overview of THT-VI.

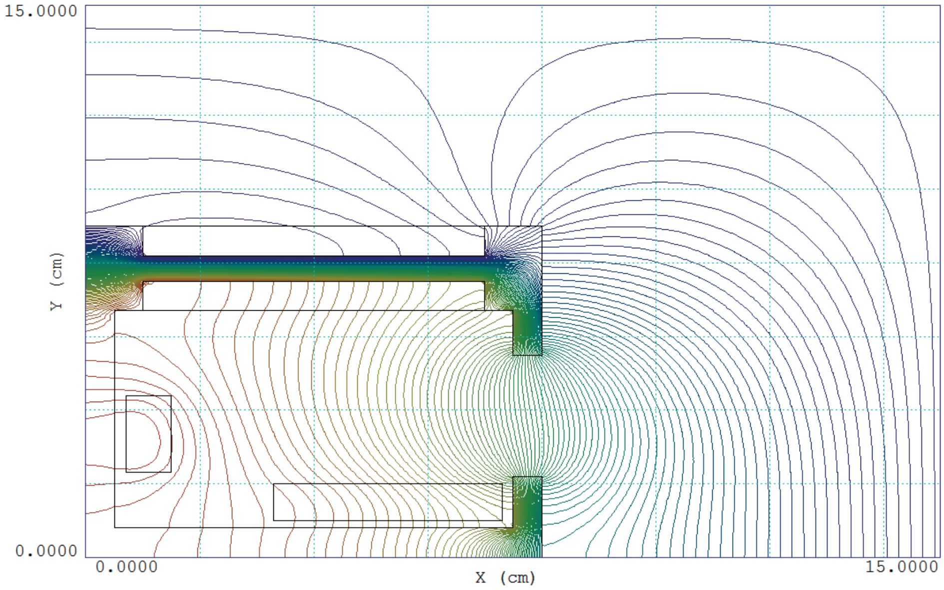

Figure 3. Magnetic field shape for THT-VI.

Table 1. Specification of discharge channel.

Discharge Channel	
Length	40 mm
Inner Diameter	56 mm
Outer Diameter	100 mm
Material	Boron nitride (BN)

Table 2. Details of THT-VI coil.

Coils	
Material	Copper φ0.5 mm
Inner Coil	
Number of Turns	1200
Quantity	1
Outer Coils	
Number of Turns	1400
Quantity	6
Trim Coil	
Number of Turns	350
Quantity	1

A. Vacuum facility

In this study, all experiments were conducted by using a large vacuum chamber system with a high pumping performance in the Institute of Space and Astronautical Science (ISAS), Japan Aerospace eXploration Agency (JAXA), in which microwave ion engines onboard the HAYABUSA and HAYABUSA2 were operated and developed. The experimental conditions are the same as experiments performed in our university OIT. Figures 4 and 5 show the overview and the sub chamber A, respectively, of the vacuum chamber. Figure 6 shows the positional relation of the laboratory instrument. The HAYABUSA vacuum chamber is consisted of main chamber, sub chamber A, sub chamber B. Our experiments with THT-VI Hall thruster were carried out in the sub-chamber A. The sub chamber A have a cylindrical shape of 0.7 m in diameter and 0.5 m in length. The vacuum pumps are a sub turbo molecular pump of pumping speed 140 l/s and a main cryo pump of pumping speed 28000 l/s. The vacuum chamber pressure is kept about 3.55×10^{-3} Pa under operation. Figure 7 shows thrust measurement system. Pendulum method is used in order to accurately measure thrusts. The thruster is mounted on a thrust stand suspended with an aluminum bar, and the displacement of the thruster is detected by an eddy-current-type gap sensor. As shown in Fig. 8, it has a high sensitivity and good linearity. Thrust calibration is conducted with a weight and knife-edge arrangement, which can apply a known force to the thruster under vacuum condition.[6-11]

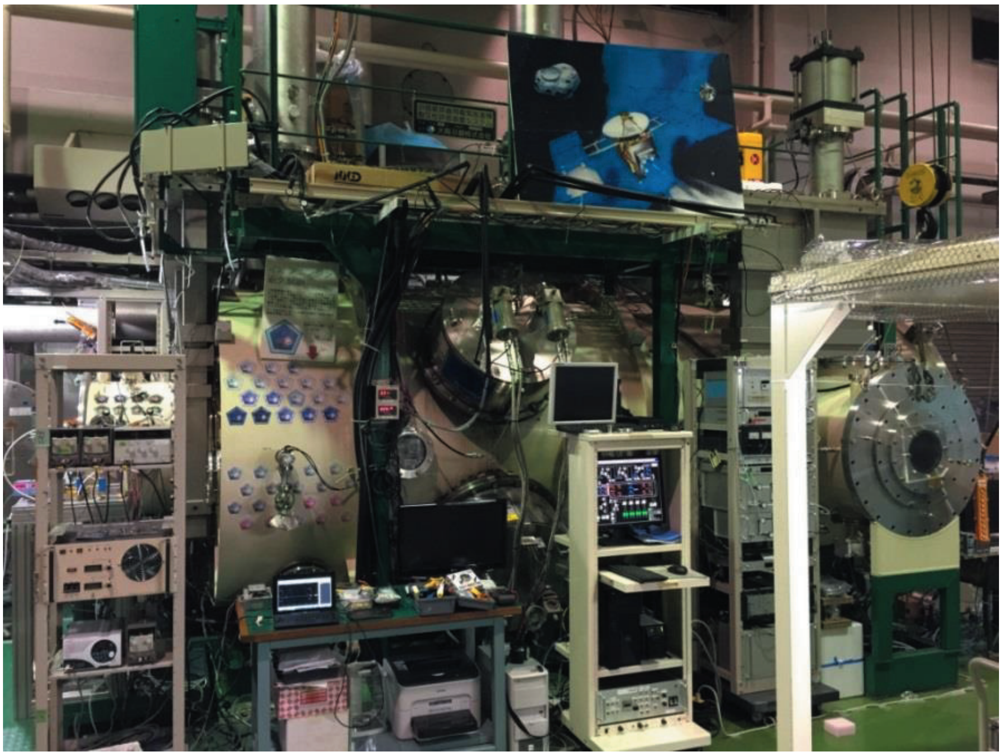

Figure 4. Experimental facility of HAYABUSA and HAYABUSA2 at ISAS, JAXA.

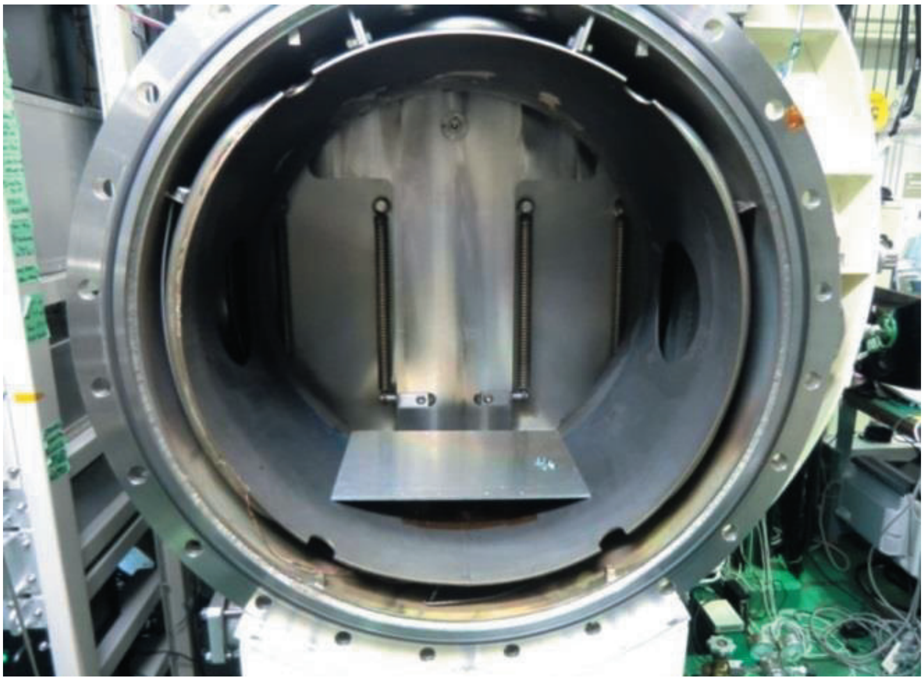

Figure 5. Overview of sub chamber A.

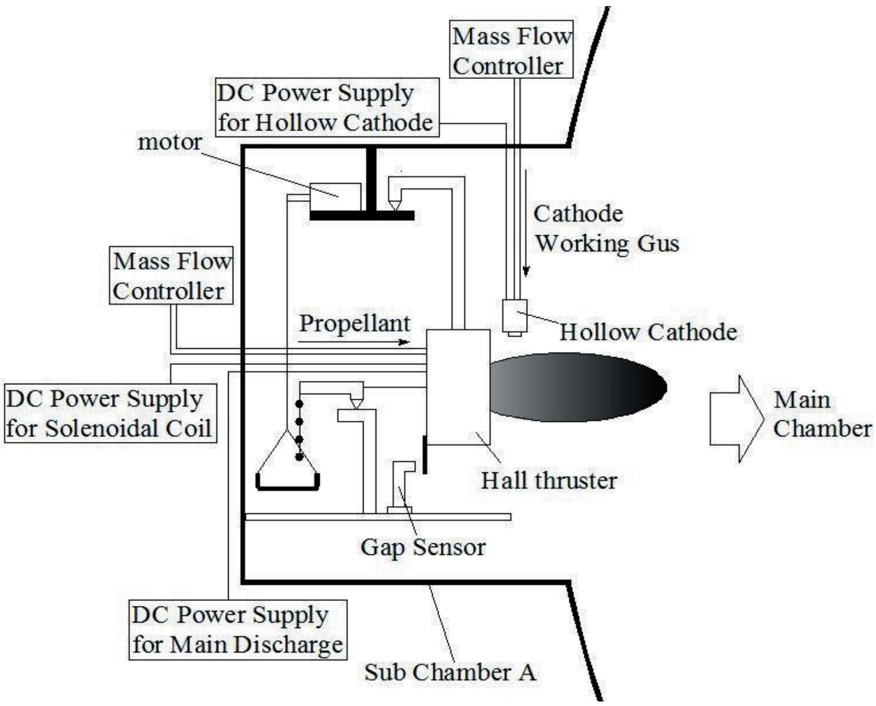

Figure 6. Positional relationship of laboratory equipment.

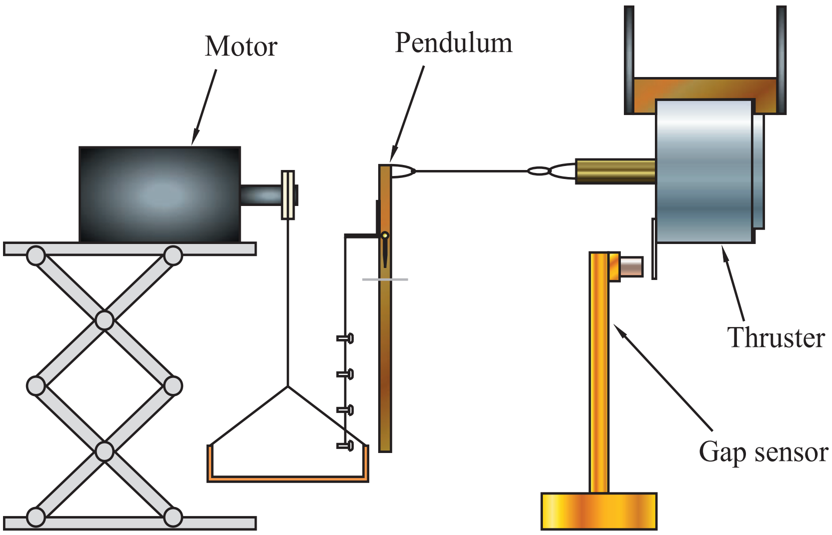

Figure 7. Thrust measurement system.

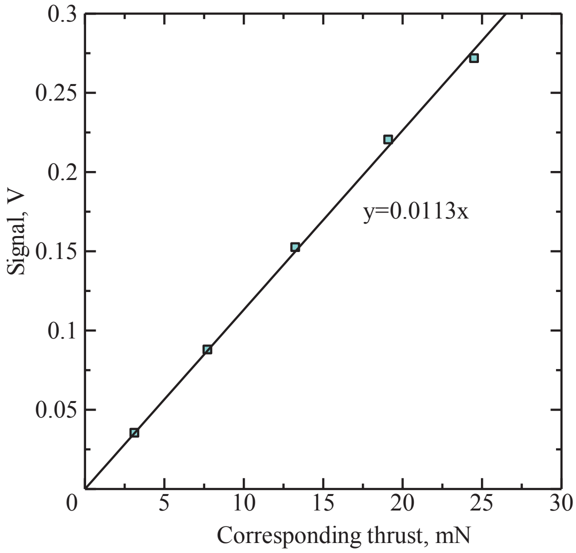

Figure 8. Thrust calibration plotting.

III. Experimental Conditions

Table 3 shows the experimental condition for the THT-VI thruster. [6-7] The operating condition is varied with discharge voltages of 300-1000 V. The xenon is used as the propellant. The thruster mass flow rate is 3.0 mg/s. The hollow cathode mass flow rate is 0.1-0.2 mg/s.

Table 3. Experimental conditions of THT-VI thruster**.**

Discharge Voltage	300-1000 V	
Propellant	Xenon	
Mass Flow Rate	THT-VI	3.0 mg/s
	Hollow Cathode	0.1-0.2 mg/s
Coil Current	0.3, 0.3, 0.9 A（Inner, Outer, Trim）	
Backpressure	3.55×10^{-3} Pa	

IV. Experimental Results and Discussion

Figures 9-11 show the characteristics of discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage. Figures 12 and 13 show the operation photos at discharge voltages of 300 and 1000 V, respectively. At discharge voltages of 950 V or more, the flow rate of the hollow cathode was required to increase because the operation of the thruster became unstable. Therefore, the hollow cathode flow rate was 0.1 mg/s at discharge voltages of 300-900 V and 0.2 mg/s at discharge voltages of 950-1000 V.

The discharge current is almost constant or slightly increases up to a discharge voltage of 900 V although it is intensively increases from 950 V. Both the thrust and the specific impulse linearly increase with discharge voltage up to 900 V. However, they decrease from a discharge voltage of 900 V. The operations were stable up to a discharge voltage of 900 V although they become unstable with the high discharge voltages. The rapid change at high voltage is considered because of overheating of the thruster body; that is, we could see a red-heating portion on the outer discharge channel.

In this study, the performance of the THT-VI thruster ranged a thrust of 47-110 mN and a thrust efficiency of 48-61% at specific impulses of 1600-3400 s with an input power of 0.7-3.6 kW.

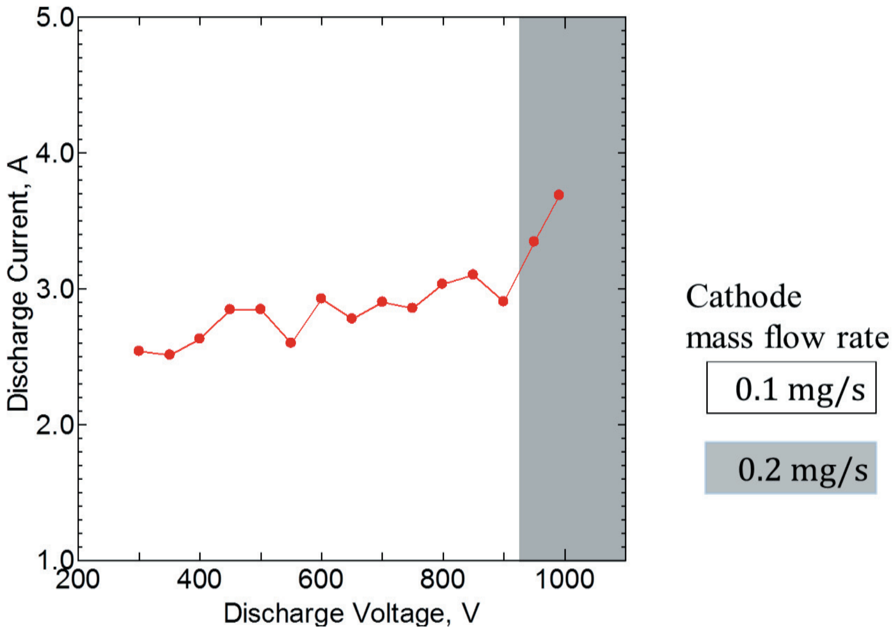

Figure 9. Discharge current vs discharge voltage.

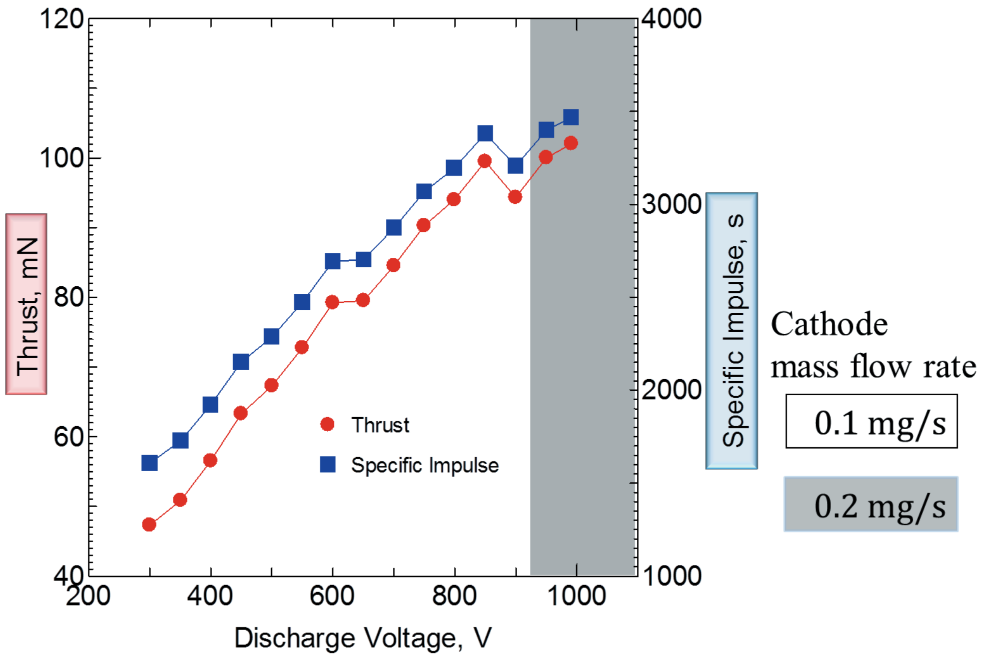

Figure 10. Thrust and specific-impulse vs discharge voltage.

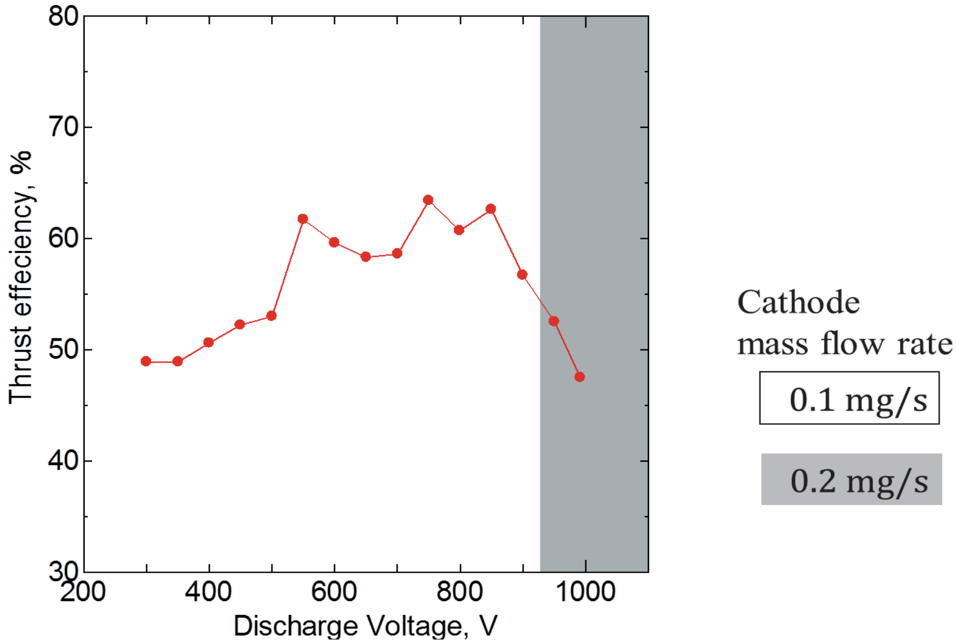

Figure 11. Thrust efficiency vs discharge voltage.

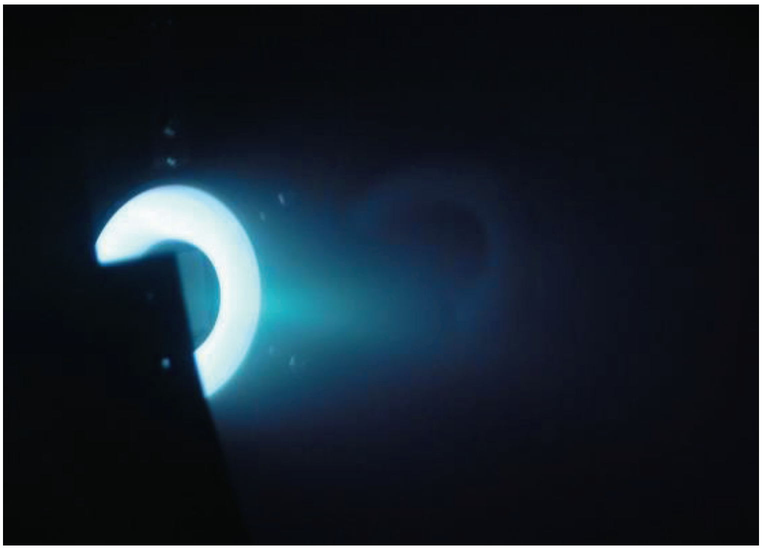
Figure 12. Operation photo at discharge voltage of 300 V.


Figure 13. Operation photo at discharge voltage of 1000 V.

V. Conclusion

The following results were mainly obtained.

1) The THT-VI Hall thruster achieved stable operations at a discharge voltage of 1000 V in the JAXA Hayabusa chamber system.
2) The performance at 1000 V was a thrust of 102.05 mN and a specific impulse of 3468.5 s at an input power of 3.6 kW.
3) The thrust efficiency reached the maximum of 63.4% at a discharge voltage of 750 V.
4) In the high-power operations we have seen red-heated portions on the outer discharge channel. Therefore, we are under improvement of thermal design of Hall thrusters for high-power operations.

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