

Performance Enhancement of Microwave Discharge Ion Thruster $\mu 10$

IEPC-2017-457

*Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017*

Yoshitaka Tani¹
The University of Tokyo, Bunkyo-ku, Tokyo, 113-8656, Japan

Kazutaka Nishiyama.²
Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan

Daiki Koda.³
Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan

and

Hitoshi Kuninaka⁴
Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan

Abstract: In this study, we focused on improving the performance of microwave discharge type ion thruster $\mu 10$ by experimental approach. We revealed the relation between the shape of the magnetic field inside the discharge chamber and the beam profile by probe measurement, and the highest beam current reaches 204mA optimizing the magnetic circuit. This corresponds to 13mN of thrust force and ion production cost is 166 W/A at the highest performance point. This is about 30% performance improvement comparing with HAYABUSA2's flight model thruster. This study firstly demonstrated exceeding 200mA beam current on 10cm class microwave discharge type ion thruster and showed the way to optimization of the magnetic circuit of $\mu 10$'s ECR ion source.

I. Introduction

THE ion thruster $\mu 10$ is the microwave discharge type ion thruster. It was mounted on the Japan asteroid explorer "Hayabusa", and its successor "Hayabusa 2" as the main thruster unit, and has still been operated in the space. The most characteristic feature of this thruster is electrodeless plasma generation with electron cyclotron resonance (ECR) discharge. Because of this, $\mu 10$ is fundamentally free from the electrode erosion, and achieved the long lifetime^{1,2}. The ECR discharge type ion thruster has some advantages as follows: (1) easy to use because of cathodeless structure, (2) simple power supply system, and (3) only one microwave power supply can feed power both ion source and neutralizer. On the other hand, its thrust is approximately 40% lower than the other ion thrusters of the same size³⁻⁶. Table 1 shows the comparison of the performance with the other major ion thrusters. For the application of future deep space missions, thrust enhancement is essential, and the aim of thrust level is 15 mN.

In this study, we changed the shape of the magnetic field inside the $\mu 10$, and measured and compared its performance change.

¹ Graduated School of Engineering, Department of Aeronautics and Astronautics, tani@ep.isas.jaxa.jp

² Associated professor, Institute of Space and Astronautical Science, nishiyama@ep.isas.jaxa.jp

³ Researcher Fellow, Institute of Space and Astronautical Science, koda@ep.isas.jaxa.jp

⁴ Professor, Institute of Space and Astronautical Science, kuninaka@isas.jaxa.jp

Table 1. Comparison of performances of 10cm-class ion thrusters.

	$\mu 10$	RIT10	T5	XIPS13
Type	ECR	RF	DC	DC
Diameter, mm	10	10	10	13
Thrust, mN	10	15	18	17.2
Specific impulse, s	3080	3000	3000	2507
Power, W	405	459	476	421
Lifetime, hour	15,000	10,000	10,000	—
Thrust efficiency, %	38	52	55	50

II. Concept of performance improvement

A. Microwave discharge type ion thruster⁷

The schematic diagram of the microwave discharge type ion thruster $\mu 10$ is shown in Figure 1. The ion thruster $\mu 10$ is composed of four components: (1) waveguide, (2) discharge chamber (magnetic circuit), (3) grid support ring, and (4) neutralizer. External input resources are only propellant gas, microwave power, and acceleration power. Because $\mu 10$ doesn't need hollow cathodes unlike DC discharge type ion thrusters, expended materials are only propellant gas. The microwave is input from the bottom of the waveguide and heats electrons by electron cyclotron resonance (ECR) discharge in the discharge chamber. The discharge chamber is composed of the ring shape the samarium cobalt magnet magnets and the magnetic yoke. The magnetic circuit also confines electrons by the mirror magnetic field and prevents them from losing to chamber wall. By the mirror magnetic field trapping and the ECR, electrons that have been sufficiently reciprocally heated ionize propellant gas, xenon, and plasma is generated. Three grids fixed to the grid support ring electrostatically accelerate ions from the generated plasma and release them to the downstream. The ions are neutralized by electrons extracted from neutralizer and become a stable plasma state.

In the first "Hayabusa" model $\mu 10$ propellant gas was fed only from the bottom of the waveguide. In "Hayabusa 2" model, the gas feeding method was revised and the propellant gas was distributed and fed from waveguide and discharge chamber. This method improved propulsion performance by 30% compared with the first model of $\mu 10$.⁹

B. Performance improvement method

Propulsion performance of $\mu 10$ was improved in "Hayabusa 2" model, but there is still room for improvement. The propulsion performance of $\mu 10$ correlates with the propellant mass flow rate to be fed. Figure 2 shows the characteristics of the net ion beam current depending on propellant supply rate¹⁰. When the propellant supply rate is at a relatively low rate, the extraction beam current monotonically increases as the propellant supply rate increases. However, when the propellant supply rate exceeds a certain amount, the beam current suddenly decreases (we call this "stall" mode). It is considered that the stall mode is due to microwave cutoff caused by plasma density increase inside the discharge chamber. In order to increase the maximum beam current, there are two plans: (1) to prevent the stall phenomenon from occurring even at a larger propellant supply rate, or (2) enhance the propellant utilization efficiency closer to 100%. Plan (1) is not realistic because a large-scale design change of the entire thruster including the shape of waveguide is necessary. Therefore, we examined performance improvement under the plan of (2).

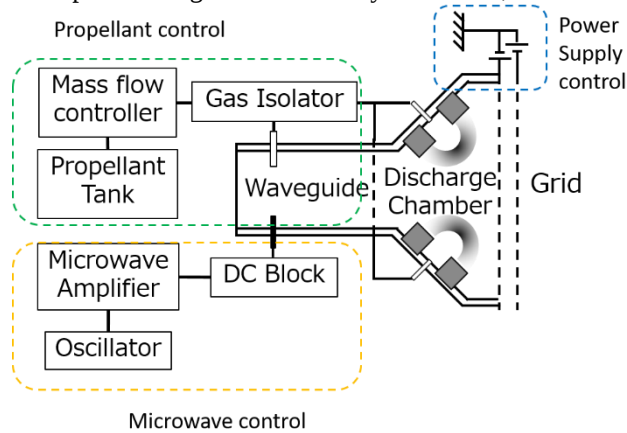


Figure 1. The schematic diagram of the microwave discharge type ion thruster $\mu 10$

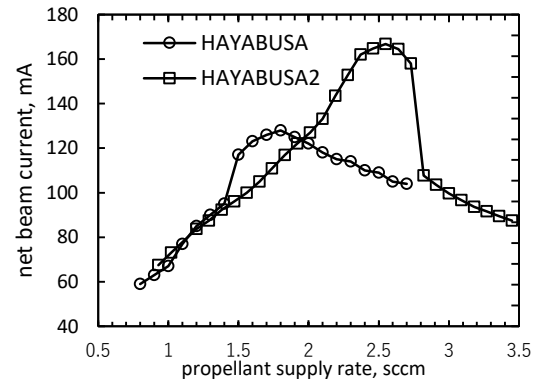


Figure 2. Characteristics of the net ion beam current depending on propellant supply rate of Hayabusa and Hayabusa 2 mode.

C. Magnetic circuit optimization

Figure 3 shows the radial distribution of the beam current density measured at 20mm-downstream from the screen grid of $\mu 10$. It can be seen that the beam current density distribution is like an axisymmetric “M” shape distribution having a peak at approximately 30 mm outside from the center. It has been known that this distribution correlates with the discharge chamber length, and the peak position is the same point where the magnetic lines of force contact with the screen grid¹⁰. Based on this result, we changed the magnetic circuit of $\mu 10$. The comparison of the original magnetic circuit ($\mu 10$ yoke) and the redesigned magnetic circuit (new type yoke) is shown in Figure 4. As a result of this change, it is considered that the peak position of the beam current density distribution moves outward in the radial direction, and the total beam current is expected to increase because the beam extractable area increases.

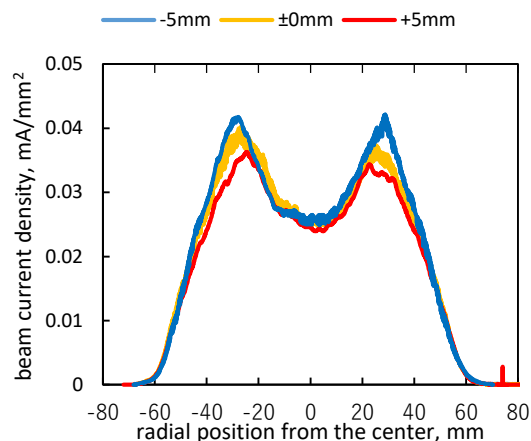


Figure 3. 20mm downstream beam current density distribution of the $\mu 10$ yoke operating Hayabusa 2 mode.

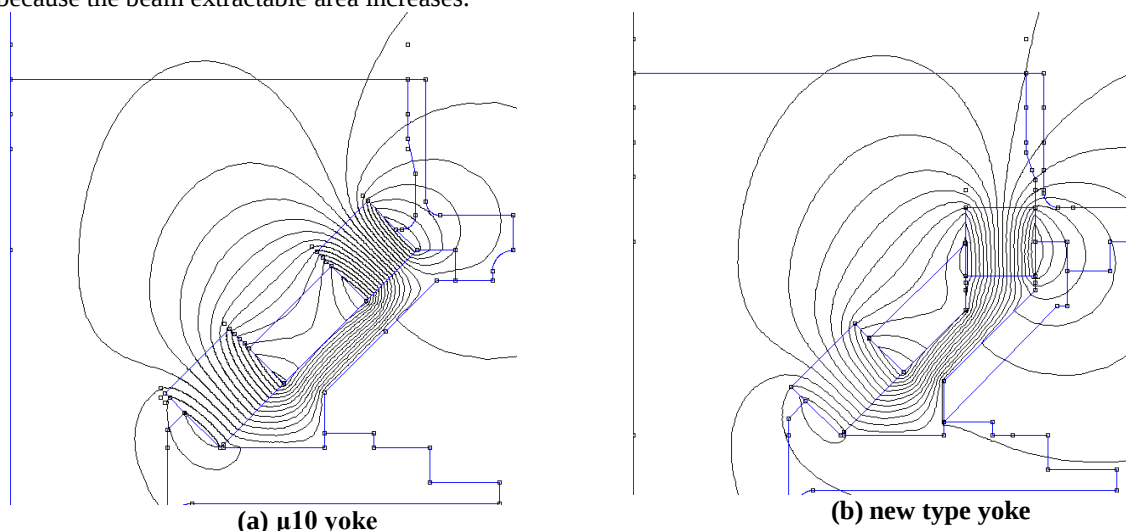


Figure 4. Schematic diagram and magnetic lines of force of the discharge chamber

III. Experimental apparatus

Table 2 shows experimental conditions. The discharge chamber length is a parameter, and the other conditions are the same as the nominal operating point of the original $\mu 10$. Thruster characteristics of the net beam current depending on the propellant supply rate were obtained when the supply rate was changed from 1.0 sccm until the stall mode occurred (1.0 sccm = 0.098 mg / s). The beam current density distribution was obtained by using a molybdenum planar probe with $\phi 1.0$ mm diameter, and it was swept on a radial axis passing through the grid center position. Measurements were conducted at 1.0, 1.5, 2.0, and 2.5 sccm for each discharge chamber length.

The experiment was carried out in the ion thruster experiment chamber at JAXA Sagami-hara campus¹¹. The vacuum chamber has the structure where two sub chambers (80 cm diameter) are connected to a main chamber (200 cm diameter and 500 cm overall length). The main chamber is maintained at a high vacuum of about 2.0×10^{-5} Pa by four cryogenic pumps. After setting the ion thruster in the sub chamber, connecting both chambers with the gate opening, and ion thruster experiments can be conducted under a high vacuum back pressure environment.

Table 2. Experimental conditions.

Screen grid voltage	1500V
Acceleration grid voltage	-350V
Discharge chamber length	-10, -5, ± 0 , +5, +10 mm (difference from the original length)
Microwave power	34 W
Microwave frequency	4.25GHz
Propellant supply rate	1.0 – 3.5 sccm
Propellant gas	Xe
Beam current density measurement point	20mm downstream from the acceleration grid

IV. Experimental results

The results of the characteristics of net beam current depending on propellant supply rate for each experimental condition are shown in Figure 5. And Figure 6 shows the graph of propellant utilization efficiency versus ion production cost. According to Figure 5, when the length of the discharge chamber is shorter than that of the original $\mu 10$, the maximum beam current is approximately 170 mA, which is almost the same performance as the $\mu 10$ of the "Hayabusa 2" mode. On the other hand, when the discharge chamber length is longer than the original $\mu 10$, its performance is remarkably improved. The graph of Figure 6 is a general graph for evaluating the performance of the ion thruster, and the performance is better at lower right region. The ion production cost, which was about 200 W/A on $\mu 10$ of the "Hayabusa 2" mode, improved to approximately 166 W/A by redesigning of discharge chamber. Figure 6-10 show the results of the downstream beam current density distribution. Each graph shows the radial distribution from the axial symmetry center of the grid. As mentioned pervious section, the beam current density distribution of $\mu 10$ has an M shape, and the same distribution is shown also on the new type yoke. It is also seen that the peak position of the current density distribution varies in the radial direction due to the discharge chamber length.

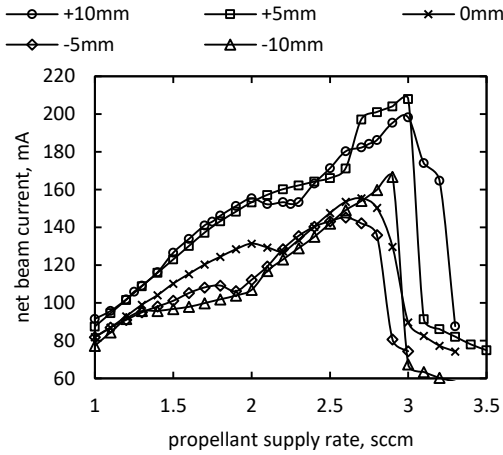


Figure 5. Characteristics of net beam current depending on propellant supply rate.

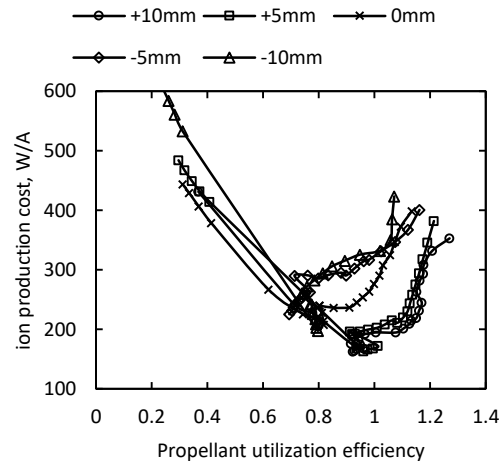


Figure 6. Propellant utilization efficiency versus ion production cost.

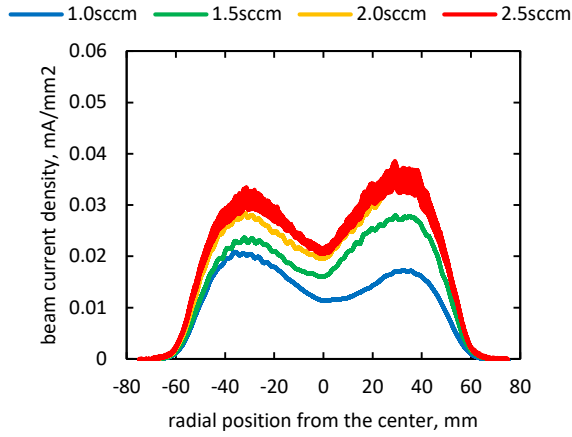


Figure 7. Results of the beam current density distribution of +10mm discharge chamber length.

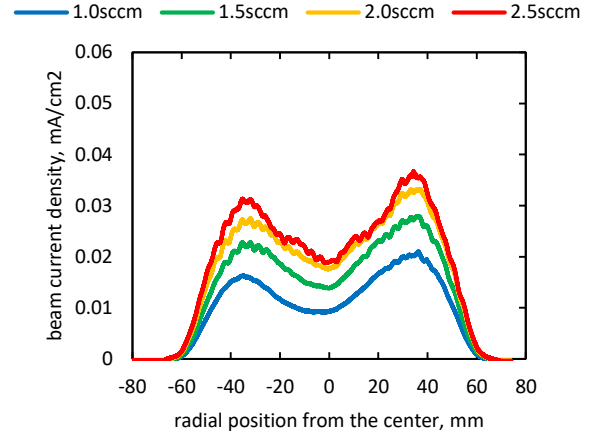


Figure 8. Results of the beam current density distribution of +5mm discharge chamber length.

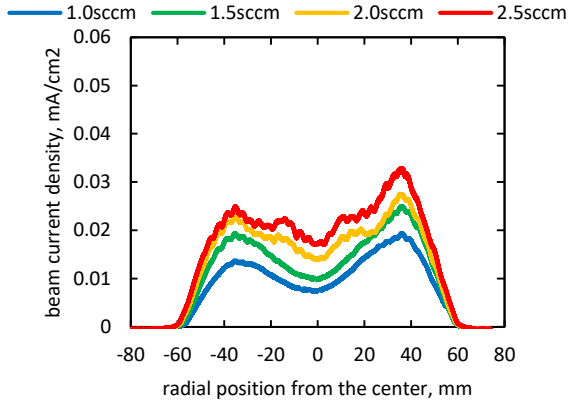


Figure 9. Results of the beam current density distribution of original discharge chamber length.

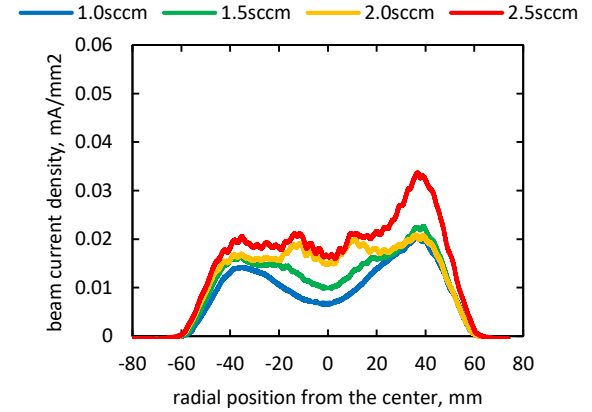


Figure 10. Results of the beam current density distribution of -5mm discharge chamber length.

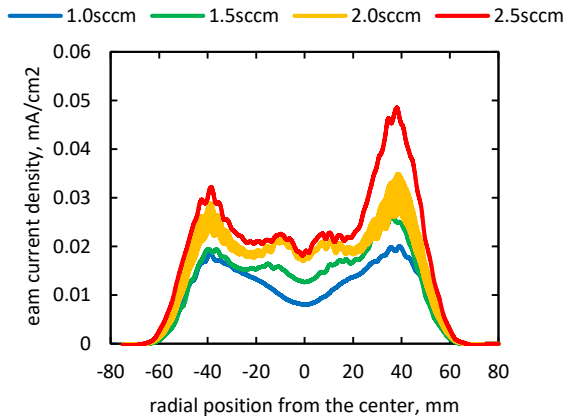


Figure 11. Results of the beam current density distribution of -10mm discharge chamber length.

V. Discussion

Consider the correlation between the current-mass flow characteristics and the discharge chamber length. The results obtained this experiment show a tendency that the maximum beam current is increased as the discharge chamber length is. These results are opposite tendency to that obtained when changing the discharge chamber length on the $\mu 10$ yoke. According to the result of the current density distribution, as shown in Figure 3, on the $\mu 10$ yoke the shape of the beam current density distribution doesn't change dramatically except for the peak position even when the length of the discharge chamber is changed. On the other hand, on the new type yoke, in the case where the length of the discharge chamber is longer than +5 mm or shorter, the shape of the beam current density distribution is different; the shape near the center axis is flat on the short discharge chamber. This seems to be due to the change in the method of extracting ions from the plasma.

Figure 12 shows a schematic diagram of the inside of the discharge chamber. It is considered that the region inside the discharge chamber is divided into four regions: open magnetic field region where the electrons are not trapped (region A), ions extractable region (region B), the region ions are not extractable (region C), and non-heating region (region D). Each region are divided by three magnetic lines of force: the magnetic line contacting with the screen grid (magnetic line ①), the magnetic line on which the Larmor radius of ions are enough large that the ions can contact with screen grid (magnetic line ②), and the magnetic line contacting with the ECR region (magnetic line ③). It is considered that plasma generation is dominant at region B+C.

In order to increase the beam current of the ion source, it is considered to widen the region B and decrease the area of region C. Increasing the length of the discharge chamber leads to increase the area of region B, and shortening the discharge chamber length conversely leads to decrease that of the region B. Therefore, if the length of the discharge chamber is increased, the performance will be improved (Effect 1).

On the other hand, when the length of the discharge chamber is lengthened and the region B + C is increased, the electron flight distance per path becomes longer, and it is considered that the high energy electrons lost by excitation neutral particles will be frequent (Effect 2). Therefore, if the length of the discharge chamber is shortened, ions can be extracted from the higher density region, and the ion source performance is considered to be improved.

Because of this contradiction of Effect 1 and Effect 2, it is considered that there is an optimum grid position for the magnetic field shape. On the $\mu 10$ yoke, the influence of Effect 2 is considered to be large. On the other hand, on the new type of yoke, it is considered that there is a boundary between Effect 1 and Effect 2 around at the discharge chamber length +5 mm. The beam current density distribution is also considered to be due to this influence. However, not only this factor but also a change in the length of the discharge chamber with respect to the magnetic field shape causes a change in the current density peak position, a change in the microwave electric field intensity, etc., so that a more complicated effect is considered to have occurred.

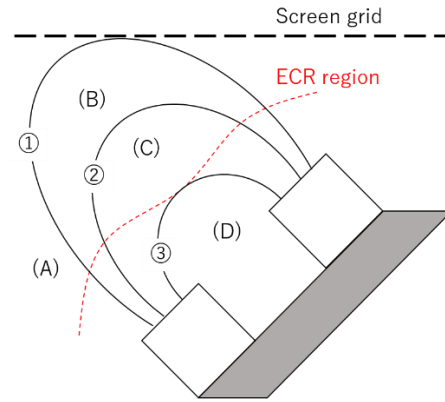


Figure 12 Schematic diagram inside the discharge chamber

VI. Conclusion

Table 2 shows the performance comparison between the maximum performance obtained from this research result and the "Hayabusa 2" mode. By the new type of yoke, the maximum beam current increased by 34 mA compared to "Hayabusa 2". This is about 13 mN in terms of thrust, and thrust increases by 30% from "Hayabusa 2". Propulsion efficiency improved to 46%.

This time, we improved the performance of the ion thruster by changing only thruster head without adding equipment. This means that you can use the space-proven equipment used in $\mu 10$ as it is, which is a great advantage.

Table 2. Comparison of the thruster performance between Hayabusa 2 and this research

	Hayabusa 2	This research
Thrust, mN	10	13
Beam current, mA	170	204
Specific impulse, s	3320	3765
Power consumption, W	444	505
Ion production cost, W/A	200	166
Thrust efficiency, %	40	46

Acknowledgments

This work was financially supported by JSPS KAKENHI Grant Number 16J08096.

References

- ¹Kuninaka, H., “Development and Demonstration of a Cathode-less Electron Cyclotron Resonance Ion Thruster,” *Journal of Propulsion and Power*, Vol. 14, No.6, 1998, pp. 1022–1026.
- ²Nishiyama, K., Hosoda, S., Ueno, K., Tsukizaki, R., Kuninaka H., “Development and Testing of the Hayabusa2 Ion Engine System,” *Joint Conference of 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, IEPC-2015-333/ISTS-2015-b-333, 2015.
- ³Bassner, H., Berg, H. P. and Kukies, R. “Recent Results on Qualification of the RITA Components for the ARTEMIS Satellite,” *28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics, AIAA1992-3207, 1992.
- ⁴Gray, H., Smith, P. and Fern, D.G.”Design and Development of the UK-10 Ion Propulsion System,” *32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA 96-3084, 1996.
- ⁵Goebel, D. M. and Katz, I.,” Fundamental Electric Propulsion,” *JPL Space Science and Technology Series*, Wiley, New Jersey, 2008.
- ⁶Notarantonio, A., Killinger, R. and Amorosi, L.”Ion Propulsion System Saves ARTEMIS Satellite, IAC-03-S.4.01,” *54th International Astronautical Congress of the International Astronautical Federation*, the International Academy of Astronautics, and the International Institute of Space Law, Bremen, Germany, 2003
- ⁷Hitoshi, K., and Shin, S., “Development and Demonstration of a Cathodeless Electron Cyclotron Resonance Ion Thruster,” *Journal of Propulsion and Power*, Vol. 14, No.6, 1998, pp. 1022-1026
- ⁸Ryudo, T., Yuta, Y., Satoshi, H., Kazutaka, N., and Hitoshi, K., “Effects of Segmented Chamber Walls in a Microwave ion Thruster on Thrust Performance,” *Journal of the Japan Society for Aeronautical and Space Sciences*, Vol. 65, No. 1, 2017, pp. 17-20 (in Japanese)
- ⁹Ryudo, T., Toshiyuki, I., Hiroyuki, K., Hiroyoshi, T., Kazutaka N., and Hitoshi K. “Thrust Enhancement of a Microwave Ion Thruster,” *Journal of Propulsion and Power*, Vol.30, No.5, 2014, pp. 1383-1389
- ¹⁰Yoshitaka T., Daiki K., Kazutaka N., Satoshi H., Ryudo T., Hitoshi K. “Performance Improvement of Microwave Discharge Ion Engine”, *Space Transportation Symposium*, STEP-2016-0036, JAXA, Sagamihara, 2017 (in Japanese)
- ¹¹Ikkoh, F., Hitoshi, K., Kyoichiro, T., Yukio, S., and Shin, S., “Development of an Endurance Test Facility for Microwave Discharge Ion Engine System,” *Journal of the japan Society for Aeronautical and Space Sciences*, Vol. 47, No. 550, pp. 411-418 (in Japanese)