Experimental Characterization of the Microwave-Discharge Water Ion Thruster for CubeSat

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Abstract: Water ion thruster was proposed as a candidate of a high delta-V thruster for CubeSats. The water has advantages on the safety and the storability, and it matches the concept of CubeSat. To increase performance of the water ion thruster, the dependence on the microwave frequency of the ion source and the neutralizer was experimentally investigated. As a result, for the ion source, the dependence of the plasma distribution was confirmed, on the other hand, the extract current does not depend on the frequency directly. For the neutralizer, the performance varied by changing the frequency, it is expected that the best operation point of the ion source and the neutralizer would be different.

I.Introduction

Importance of the propulsion system for CubeSats has been increasing with the number of launching CubeSat[1]. The higher performance is required to the propulsion system because the missions of CubeSats and CubeSats itself has been improved and complicated, and the requirement was also diversified to meet the various missions[1,2].

For examples, the satellite constellation is one of the well-known ways to extend the application of CubeSats, and the propulsion system with a high repeatability is an essential component in order to complete and keep an accurate constellation. The demand for the transportation between orbits increases because the ride-share of one rocket gets more popular to decrease the cost of the launch, which is the dominant cost of CubeSats. The deep space explorations with CubeSat are also planned, and some of them has been conducted[3,4]. In many cases, these have to achieve the much higher change of velocity with the limited power and volume, and the high system specific impulse is required for the mission.

The electric propulsion for CubeSats has been researched especially for the demand of a higher change of velocity because of its potential to achieve a high specific impulse such as a couple of thousand seconds. The Hall thrusters and the ion thrusters are widely used in the conventional satellite, and xenon is commonly used as a propellant. To applying them to CubeSats, this xenon is one of the problem because the high-pressure gas system with xenon is the heavy and large to be installed in a CubeSat. A couple of propellants, which are solid or liquid in room temperature and atmospheric pressure and could remove the high-pressure gas system, has been proposed and tested[5,6].

The suitable propulsion system especially for CubeSats has been also researched as another approach, and the Pulsed Plasma Thruster (PPT) and the Field Emission Electric Propulsion (FEEP) are the typical examples of such kind of system. PPT has a good feature to be miniaturized such as a simple structure and a solid propellant. On the other hand, the limitation of the propellant with the problem of the feeding system, the lifetime of the ignitor, and the electromagnetic interference should be the problem in the practical use and some researches has been conducted on these isues[7]. In these days, FEEP is made by MEMS technology and is essentially enough small thruster to install less than 1 U system[8]. The liquid metal or ionic liquid are used as propellant and it also has an advantage for miniaturization.

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The electromagnetic interference should also be problem and the neutralization is one issue of this thruster. However, the on-orbit operation of FEEP was already reported and the technology readiness level would be high level, such as eight or nine.

As a candidate of the propellant, water should be a strong one with considering its advantages, which are the safety and the storability[9]. It has no toxic, and can be stored under the room temperature and the atmospheric pressure. The handling is also a feature of the water, and it matches the concept of the CubeSat: short-term and low-cost development. Some water-propelled thruster has been proposed, and PPT and the resist jet thrusters are representative[10,11,12,13]. The liquid pulsed plasma thrusters using water were researched and its concept were proved on the ground, which has not been used in orbit. Some resist jet thrusters using water were researched and developed, however, there is a limitation of delta-V because of its low specific impulse.

We proposed the water ion thruster as one candidate, which has a possibility to achieve the high specific impulse with using water as the propellant, and already tested it on ground. Its thrust was 164 ± 13.4 μN, and the specific impulse was 387 ± 34 s while including the neutralizer[13]. The power consumption is approximately 30 W while considering the efficiency of the microwave and the direct current power processing unit. The range of the thrust and the power consumption are applicable for a 6U CubeSat, however, the specific impulse is much lower than expected, and it could not be said that the thruster can achieve a much higher change of velocity than the other thrusters for CubeSats.

We conducted the experiment on the water ion thruster while changing the frequency of the microwave and the strength of the static magnetic field. The dependence on the microwave frequency was already reported partially, and the further experimental results are reported in this paper. The performance of the thruster was measured by the beam current and the electron emission current.

II.Experimental Setup

A. Microwave-Discharge Miniature Ion Thruster

The thruster consists of the ion source and the neutralizer, and the ion source and the neutralizer was operated individually by connecting its electrical common to the Earth in this experiment. Both ion thruster and the neutralizer has the almost same design of the discharge chamber with the two ring-shaped magnets, the antenna and the side wall. The difference between them was that the ion source had the two grids, the screen grid and the accelerating grid, to extract the ion beam and the neutralizer had the orifice to extract the electrons. The schematics are shown in Fig.1. In the experiment of changing the frequency, the potential of the magnets, side wall, and the screen grid or the orifice was the same, and the antenna was electrically floated.

In this paper, the dependence of the performance on the frequency of the microwave was investigated with changing magnetic field. The frequency determines where the electron is mainly heated because the electrons are heated by ECR (Electron Cyclotron Resonance) heating and the resonance frequency is determined by the strength of the magnetic field. Since the magnetic field in the ion source and the neutralizer has a gradient in the axial direction as shown in fig. 4, the ECR region changes with the frequency in the axial direction. The plasma was expected to be existed on or near the ECR region because the ions are generated by the bombardment between the electron and the neutral particle, and the temperature of the ions would be low, around the room temperature.

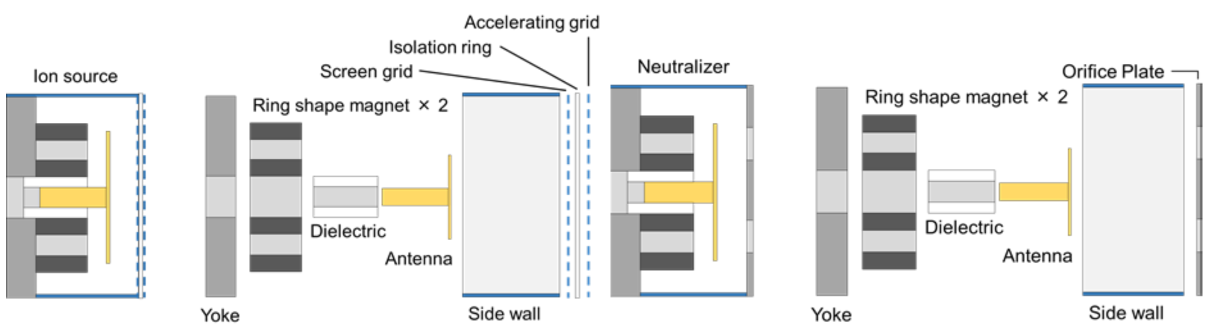

Figure 1 The schematic of the ion source and the neutralizer.

B. Vacuum Chamber, Power Source and Water Feeding System

The schematic of the experimental system is shown in Fig. 2. The experiments were conducted in a vacuum chamber, whose diameter is 1.0 m and its length is 1.2 m. It was pumped by a turbo-molecular pump, whose pumping speed was 800 L/s for nitrogen. The pressure in the chamber was kept below 2×10^{-2} Pa during the experiments.

The power sources were outside of the chamber, and the microwave and some DC voltages were supplied to the thruster via the flange of the chamber. The microwave power source consists of the wave source and the power amplifier. The wave source was able to output the 0 – 6.0 GHz signal, and the power amplifier could amplify the microwave in range of 3.0 – 6.0 GHz. The output power was controlled by the variable attenuator in the amplifier, which was calibrated in every frequency where the experiments were conducted because the output power was changed depending on the frequency if the attenuation was same. The DC voltages were supplied to the screen grid, the accelerating grid, and the neutralizer. The typical values were 1.0 kV, -200 V, and -40 V.

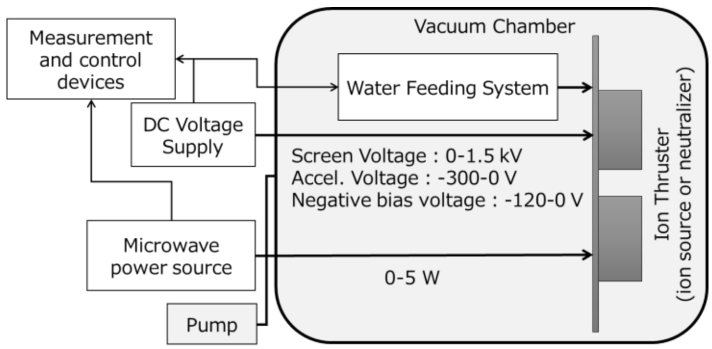

Figure 2 Schematic of the facility: vacuum chamber, power source and water feeding system

The mass flow rate of the water was controlled by the water feeding system. The schematic of the feeding system is shown in Fig. 3, and the picture of the feed system is Fig. 4. The size of the feeding system was 125 mm × 100 mm × 75 mm. It was in the vacuum chamber, and the operation and the calibration was conducted in the pumped vacuum chamber. The water was divided to the vapor and the liquid water in the tank, and the only vapor was used for the operation. The pressure of the vapor was a vapor pressure in the room temperature, which was around 2.9 kPa in 20 degrees of Celsius. To control the mass flow rate, the pressure of the accumulator was controlled to be constant by opening and closing the regulation valve. The typical trend of the pressure is shown in Fig. 5. While the water was regarded as an ideal gas, only the pressure determined the mass flow rate. The relation between the pressure and the mass flow rate was calibrated from the volume of the accumulator and the pressure history with the regulation valve close. This system achieved the accurate mass flow rate such as ±1.0 µg/s with 30 µg/s.

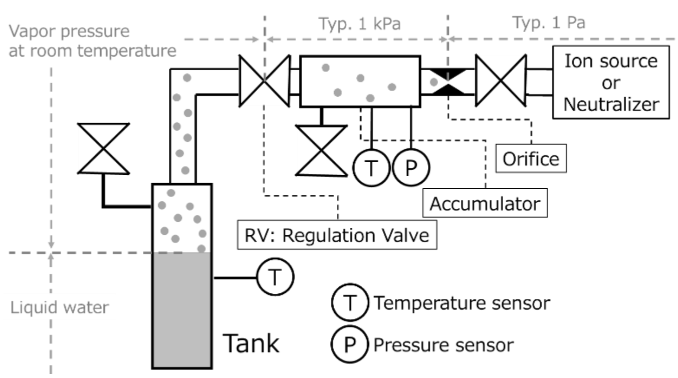

Figure 3 Schematic of the water feeding system

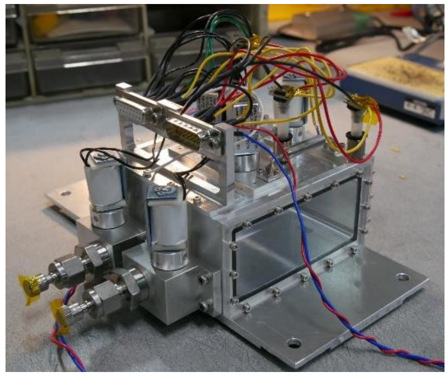

Figure 4 Picture of the water feeding system

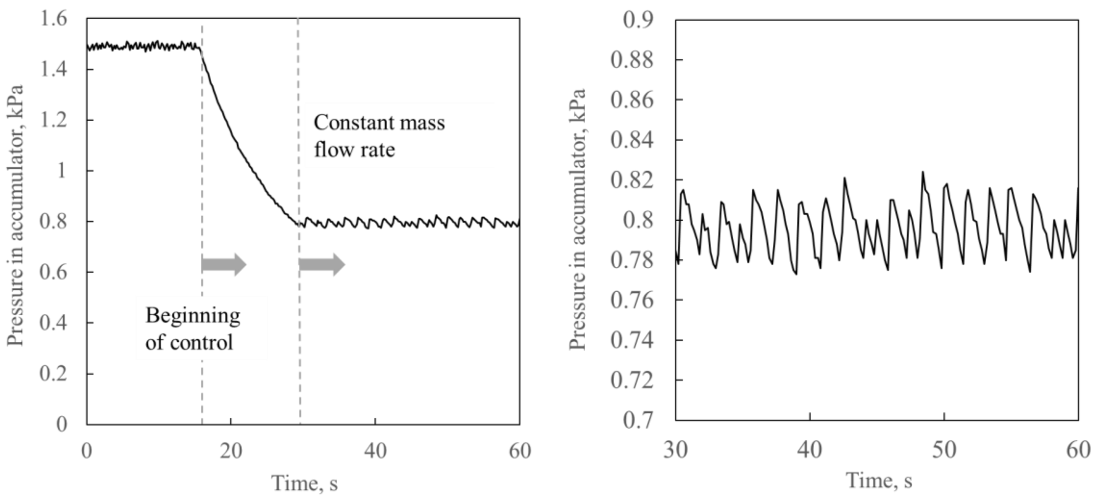

Figure 5 Typical pressure history of the accumulator (left) and the partial enlargement at a condition of constant mass flow rate (right). The standard derivative in right graph was 11.8 Pa and the mass flow was 31.0 ± 0.95 µg/s.

III.Experimental Condition

The experimental conditions are shown in Table 1 and Table 2. We tested two type of the ion source, one is with Samarium-Cobalt magnets, and the other is with neodymium magnets with changing the microwave frequency. A Samarium-cobalt magnet is commonly used in the ion thruster or other electric propulsions because of its tolerance to the demagnetization at high temperature. On the other hand, the neodymium magnet is weak to the high temperature. In this thruster, the temperature of the surface of the magnets are enough low and the demagnetization of the magnets was not observed by measuring the magnetic flux density before and after the operation.

For the neutralizer, the experiment was conducted only with the samarium-cobalt. The range in frequency was narrower than that of the ion source, and which is because the plasma could not be kept in higher or lower frequency than the frequency shown in Table 2.

Table 1 Experimental conditions of the ion source experiment

Material of ring-shaped magnet	Samarium-cobalt, Neodymium
Microwave frequency, GHz	3.0 - 6.0
Microwave power input, W	1.
Mass flow rate, µg/s	4×10^{1}
Screen grid voltage, V	800
Acceleration grid voltage, V	-100
Chamber pressure, Pa	$< 2\times10^{-2}$

Table 2 Experimental conditions of the neutralizer experiment

Material of ring-shaped magnet	Samarium-cobalt
Microwave frequency, GHz	3.6 - 5.0
Microwave power input, W	2.0
Mass flow rate, µg/s	1.2×10^1
Negative bias voltage, V	-50 – 0
Chamber pressure, Pa	$< 2 \times 10^{-2}$

IV.Results

A. Ion Source

The screen current with changing the microwave frequency are shown in Fig. 6 and Fig. 7. The operation range was changed by changing magnets, and the ion source with the neodymium magnet achieve the operation in higher frequency. The value of the screen current was not change so much. Figure 8 shows the effect of the reflection ratio of the microwave on the screen current. The reflection ratio is defined as the ratio of the reflected power and the forward power. The trend of the reflection ratio was the same over 4.2 GHz, and it causes the difference of the screen current.

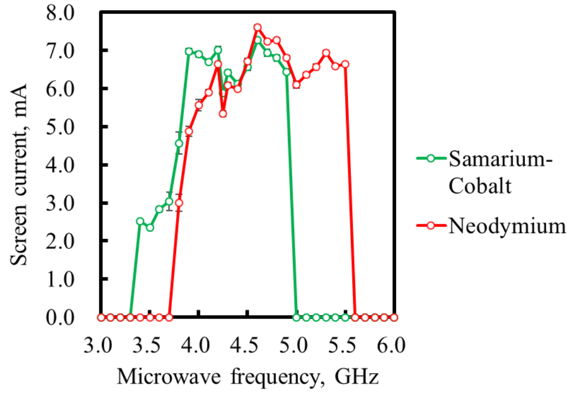

Figure 6 Screen current with changing the microwave frequency and the magnets.

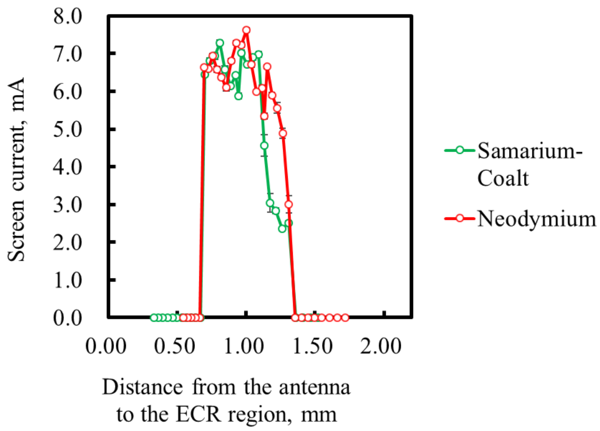

Figure 7 Dependence on the distance from the antenna to the ECR region of the screen current

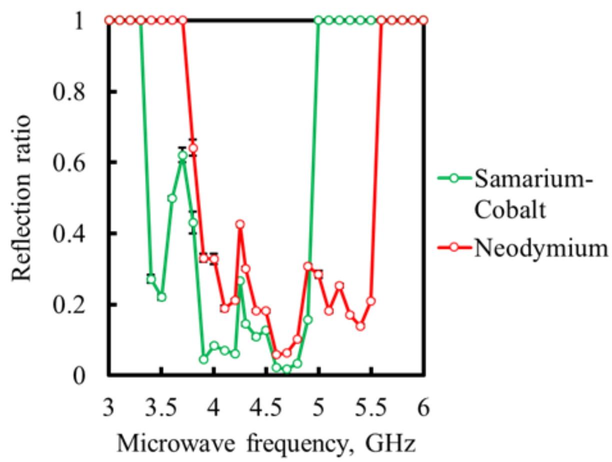

Figure 8 Reflection ratio of the microwave with changing the microwave frequency

B. Neutralizer

The electron emission currents with changing the frequency was shown in Fig. 9. The trends of the current were almost same in every frequency, and the current was almost saturated over 40 V of the negative bias voltage.

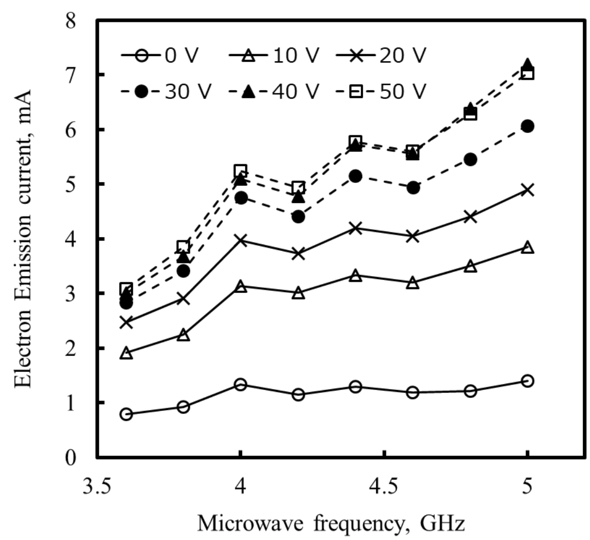

Figure 9 Electron emission current with changing the frequency. Legends shows the applied negative bias voltage of each plots.

V.Discussion

As shown in figure 6, the operation range was determined by the distance between the ECR region and the antenna. It suggested that the plasma distribution was changed with the ECR region and the loss of the plasma increased with moving to the antenna and the grid. The high frequency limit was the limit of the antenna, and the low frequency limit was that of the grid. On the other hand, the trend of the screen current was not determined from the distance but from the frequency, and this trend matched the trend of the reflection power shown in fig. 8. It suggests that the frequency does not have the large effect on the plasma density, and that changing the impedance of the microwave line with the frequency affect the plasma density and the performance of the thruster.

The reason why the frequency does not affect the performance so much was not revealed and additional experiments should be conducted. The distance between the grid and the plasma should affect the extraction and the shorter distance is the better. The distance between the antenna and the plasma should also affect the plasma density because of the distribution of the electrical field strength. It also prefers the shorter. One possible reason is that the balance of these two effect results this trend of the screen current.

The difference from the case of the ion source was that the frequency seemed to have a large effect on the performance especially when the negative bias voltage was the higher. It showed the effect that the plasma close to the orifice was relatively small than the case of the ion source at least, and it would be because the electron moves along the magnetic field, and it is more important that the electron is at which line of the magnetic force than what distance from the antenna in axial direction. In addition, this result matched the previous result from the 3D-PIC (Particle-In-Cell) simulation[15]. The simulation showed the motion of the electron in the neutralizer was determined by E×B drift induced from the electrical field of the circumferential direction, and the static electrical field does not affect the motion so much. These results suggest that the best operation points of the frequency were different between the ion source and the neutralizer. In this case, the performance as a whole system should be discussed because two microwave frequency should have a large impact on the power and the volume of the microwave source.

VI.Conclusion

The frequency dependence of the ion source and the neutralizer of the water ion thruster was tested. For the ion source, the dependence of the plasma distribution was confirmed by the difference of the operation range while changing the magnets. Although the extract current does not depend on the frequency directly, the performance varied because the frequency response of the power line affects the input power to the plasma. For the neutralizer, the electron emission current depended on the frequency and the higher frequency was the better. It matched the simulation results. For further discussion of the optimization of the frequency, the discussion as a system was essential in the case that the ion source and the neutralizer have the different best operation point of the frequency.

Acknowledgments

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References

[1] Poghosyan, A., and Golkar, A., CubeSat Evolution Analyzing CubeSat Capabilities for Conducting Science Mission, *Prog. Aerosp. Sci.* Vol. 88, 2017, 59-83.

[2] Lemmer, K., "Propulsion for CubeSats," *Acta Astronautica*, Vol. 134, May. 2017, pp. 231–243.

[3] Klesh, A., Clement, B., Colley, C., Essmiller, J., Forgette, D., Krajewski, J., Marinan, A., Martin-Mur, T., Stienkraus, J., Sternberg, D., Werne, T., and Young, B., MarCO: Early Operations of the First CubeSats to Mars, in: Small Satellite Conference 2018, SSC18-WKVII-04, Rogan, Utah, 2017.

[4]EQ

[5] Tsay, M., Frongillo, J., Zwahlen, J., Model, J., Barcroft, C., and Feng, C., Qualification Model Development of CubeSat RF Ion Propulsion System "BIT-3." *31st International Symposium on Space Technology and Science*, 2017-f-059, Matsuyama, Japan, 2017.

[6] Hoslte, K., Gartner, W., Zschatzsch, D., Scharmann, S., Kohler, P., Dietz, P., and Klar, P. J., Performance of an iodine-fueled radio-frequency ion-thruster, *European Physical Journal D*, Vol. 72, No. 9, 2018.

[7] Woodruff, C., King, D., Burton, R., Bowman, LJ., and Carroll, D., Development of a Fiber-Fed Pulsed Plasma Thruster for Small Satellites, in: Small Satellite Conference 2019, SSC19-WKVIII-06, Rogan, Utah, 2019.

[8] Jelem, D., Seifer, B., Buldrini, N., Horbe, T., Reissner, A., and Vogel, T., Performance Mapping and Qualification of the IFM Nano Thruster FM for in Orbit Demonstration, in: 35th International Electric Propulsion Conference, IEPC-2017-24, Atlanta, Georgia, 2017.

[9] Guerrieri, D. C., Silva, M. A., Cervone, A., and Gill, E., Selection and Characterization of Green Propellants for Micro-Resistojets, *Journal of Heat Transfer*, Vol. 139, Oct. 2017, 102001.

[10] Scharlemann, C. A., and York, T. M., Pulsed Plasma Thruster Using Water Propellant, Part I: Design and Investigation of Thrust Behavior, in: 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA-2003-5022, Huntsville, Alabama, 2003.

[11] Koizumi, H., Kakami, A., Furuta, Y., Komurasaki, K., and Arakawa, Y., Liquid Propellant Pulsed Plasma Thruster, in: 28th International Electric Propulsion Conference, IEPC-03-087, Toulouse, France, 2003.

[12] Lee, R. H., Bauer, A. M., Killingsworth, M. D., Lilly, T. C., Duncan, J. A., and Ketsdever, A. D., Free-Molecule-Microresistojet Performance Using Water Propellant for Nanosatellite Applications, *J. Spacecr. Rockets*, Vol. 45, 2008, 264-269.

[13] Asakawa, J., Koizumi, H., Nishii, K., Takeda, N., Funase, R. and Komurasaki, K., Development of the Water Resistojet Propulsion System for Deep Space Exploration by the CubeSat: EQUULEUS, in: Small Satellite Conference 2017, SSC17-VII-4, Rogan, Utah, 2017.

[14] Nakagawa, Y., Koizumi, H., Kawahara, H., and Komurasaki K., Performance Characterization of a Miniature Microwave Discharge Ion Thruster Operated with Water, *Acta Astronautica*, Vol. 157, 2019, pp. 294–299.

[15] Hiramoto, K., Nakagawa, Y., Koizumi, H., Takao, Y., Effects of E × B drift on electron transport across the magnetic field in a miniature microwave discharge neutralizer, *Physics of Plasmas*, Vol. 24, 2017, p. 064504.