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Chapter 1 Introduction

1.1 Microsatellite

Nowadays, space usage is an important theme for our life. There are many technologies being used using in spaces such as, communication, GPS, weather observation, military defense etc. The key technology is satellites. Satellites are launched from the earth by rockets and used in the space. The missions have wide range such as from orbiting around the earth to planetary probe. Among the importance of the satellites, micro satellites are being attracted.

Recently, launches of microsatellites has been increasing. The launches of less than 100 kg thrusters are over 100 in 2013[1)]. Around 13 years have passed since first cubesat was launched, number of recent launches is shown in the fig1-1[2)]. The increase in launches of micro satellites are being caused by low cost and that the constructing time is short. Also the difficulties in developing and designing are becoming less. By these, not only the space companies and space agencies can develop, but educational industries and venture business companies can also take part of it. The parts of the microsatellites kitting are advancing recently. That is why number of launches of microsatellites is increasing and by the advancing in technology even more, it would increase in the future. As challenging microsatellites have a thruster like the “Hodoyoshi-3&4” and “PRoximate Object Close flYby with Optical Navigation (PROCYON)” in these days[3,4)].

The attractive microsatellites also have disadvantages like size restriction and electric power generating restrictions. Micro satellites don’t have much space inside to take things with it. So most of the satellites don’t have thrusters with it. Also the solar panels are small causing restriction in the amount of electricity able to use. On the other hand, thrusters can make the satellites to be used in wide range of missions. Thrusters are used to control the attitude and the orbital movement. As missions which thrusters are required, there is Super low Altitude Satellites “SLATS” project[5)]. It is a project requiring thrusters to cancel out the drag force, since it is made to move at low altitude. They move around the height of around 200 km to detect the surface of the earth with high resolution by a detector.

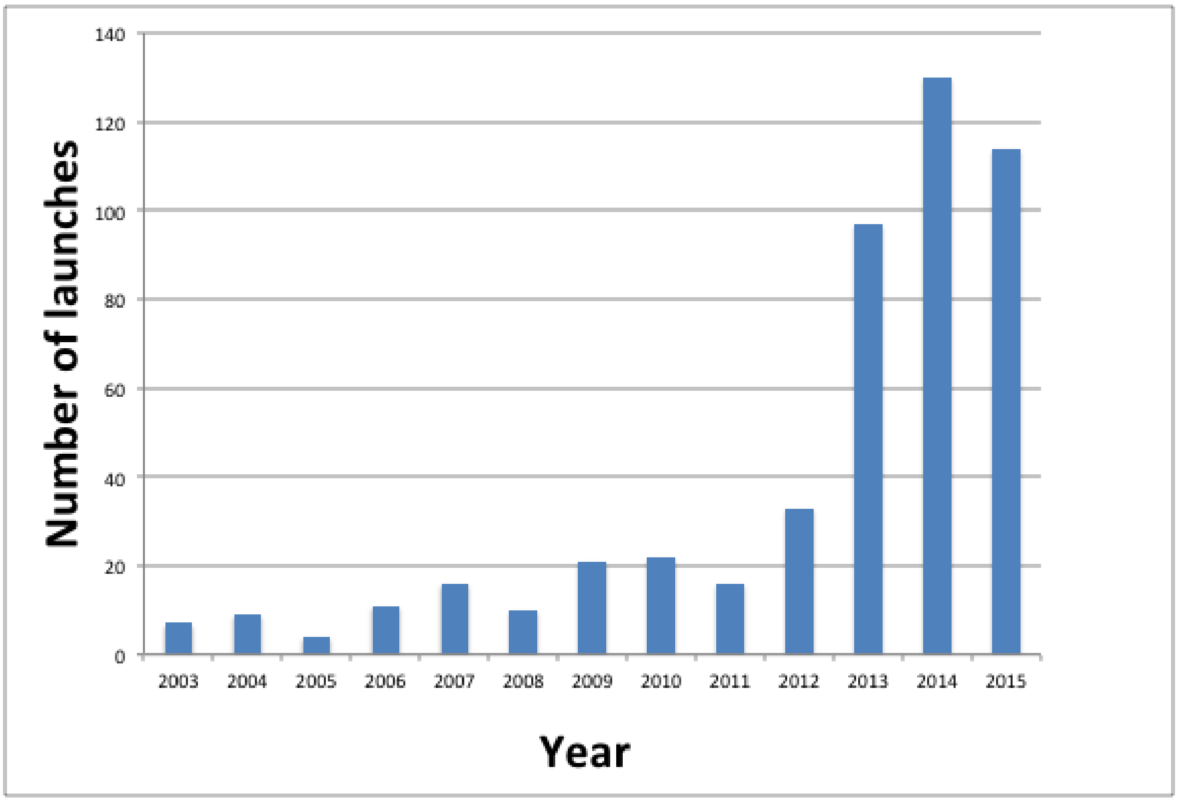

Fig. 1-1 The number of launches of the 50 kg or less class satellites per year

1.2 Types of propulsions

There are several type of thrusters used in space. The most famous one is the chemical rocket. There are also electrical rockets which we call electric propulsion. Chemical propulsion systems and electric propulsion systems have opposite features in terms of thrust and specific impulse. Chemical rockets get thrust by exhausting high energy and pressure gas by the reaction between fuel and oxygen. It has a feature of high thrust and low specific impulse. Specific impulse is a word used to express the efficiency of fuel. On the other hand, electric propulsions have features of low thrust and high specific impulse. The graph comparing the thrust and specific impulse for some thrusters is shown in fig 1-2[6]. These two features give us habitat segregation in missions. Chemical rockets are mainly used when you want high energy within specific time. Electrical propulsion systems are used in missions lasting for very long time period requiring low energy. Electrical propulsion system is being used in more than 200 satellites until now. Electrical propulsion systems gain thrusts mainly by exhausting high energy ions.

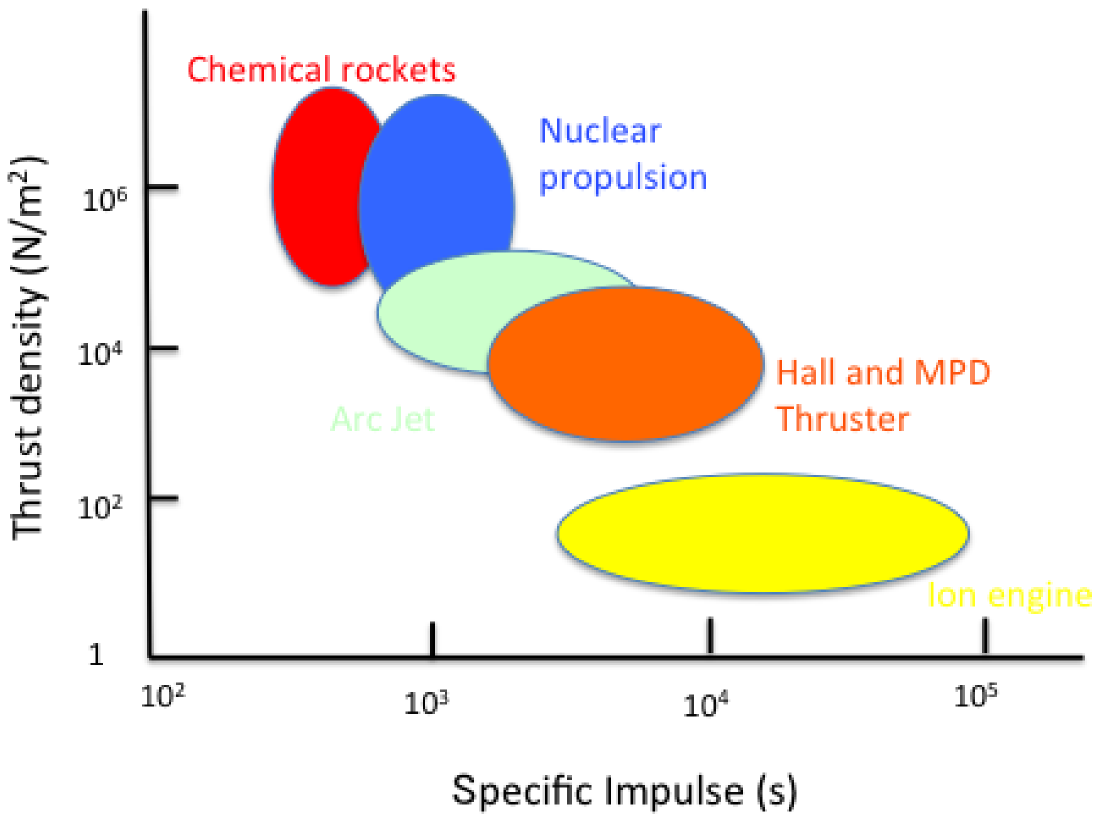

Fig 1-2 Graph of thrust against specific impulse

1.3 Required performance

In missions which satellites stay at the height of about 200 km, satellites might move through air drag, in this case thrusters are needed to cancel out the resistance and also in cases such that the satellites need to change its own position as expressed in section 1.1. To solve the tasks given, a miniature microwave discharge plasma thruster for micro satellites is under development.

Now we will assume a mission held at super low altitude to get high resonance. First we assume the power generated by the solar panels. Generated power is estimated by the assumption that the area of the solar panel is 0.4 m×0.5 m and the conversion efficiency of the solar panel is 40%. Secondly, we estimate the drag force we must cancel out. The drag is calculated by following equation.

$$\mathrm{F} = \frac{1}{2}\rho v^2 C_d S \tag{1-1}$$

In this equation, ρ, v, C_d and S represent the density of the air, the velocity of the satellite, drag coefficient and the area of the projected area against the direction of movement. These parameters are assumed that ρ is 3.5×10^{-9} kg/m^3 and v is the velocity of the satellite at the altitude of 200 km (7.8 km/s). C_d is changeable by the parameter of the atmosphere and shape of the satellites. In the case of Super Low Altitude Test Satellite (SLATS), C_d is 0.2~0.5 when the attack angle is 0~15 deg[8)]. We calculate C_d assuming that attack angle is 0~15. By adopting the parameter, the drag is estimated to be 0.2~0.5 mN. This time, we set the objective thrust as 0.5 mN. The power used for thrust system should be 20~30% for widely application, so the objective power consumption of the thruster system is under 20 W[9)]. Specific impulse is also important parameters for thruster system. Specific impulse is defined in the following equation and it represents the duration of the unit thrust by using unit propellant mass2

$$I_{sp} = \frac{F}{\dot{m}g} \cong \frac{v_i}{g} \tag{1-2}$$

In this equation, F, $\dot{m}$ and g represent the thrust and mass flow rate and gravitational acceleration. The nearly equal is valid only when 100% of the propellant gas is utilized. The unit of specific impulse (I_{sp}) is s.

From these parameters, the optimum specific impulse is estimated as 1000 sec. From the above, the required performance is are 0.5 mN and 1000 sec, respectively, with a total power consumption of 20 W in the thruster system. In addition, the simplicity of the thrust system is also important. Simple structure provides high robustness, compactness, light weight and low cost. These are very important point for microsatellite. Therefore, the objective performance should be achieved with the simple thrust system.

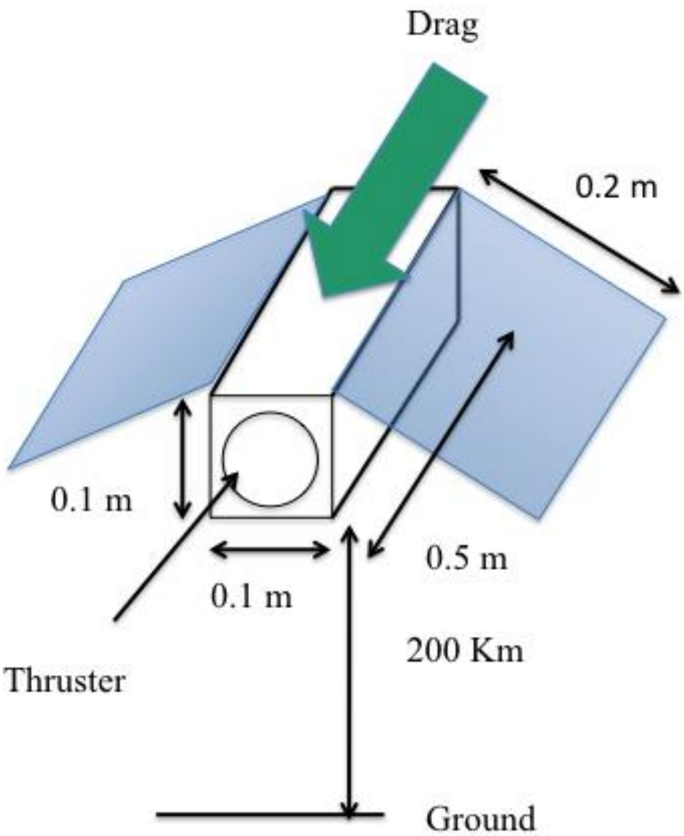

Fig 1-3 Image of the satellite

Table. 1-1 The Properties of the assumed satellite

Altitude	200 km
Size	0.1 m×0.1 m×0.5 m
Mass	50 kg
Power generation	100 W
Mission period	1 years

1.4 Purpose

The purpose of our research is to develop a thruster for the use in super low altitude micro satellite. In order to adapt to the micro satellites, the whole system including the tanks for the propellant needs to be compact in size. In this study we tried to adopt water propellant to the thruster. Propellant being in liquid state is an advantage since size of the tank is an important factor. We will talk about choosing propellants and the size of the tank more in detail afterwards. The concept of the developing thruster will be also shown in chapter 2. Developing thruster uses microwave discharge to generate plasma and it doesn’t have grid to accelerate the ions as ion thrusters. Ion thrusters use grids to accelerate ions by their potential difference. Removing the grids form the thruster will give us simple structure with lower conservation energy.

Chapter 2
Miniature Microwave Discharge Plasma Thruster

2.1 Mechanism of ion acceleration

The schematic of ion acceleration is shown in figure 2-1. The plasma is generated by microwave discharge. Electrons are trapped by a magnetic field, in the area between magnetic mirrors. This magnetic configuration is called the magnetic tube and this configuration is used in some microwave discharge neutralizer and ion thruster[10]. Electrons gain energy from the microwaves, they collide with propellant particles, and the propellant atoms are ionized. Once plasma is generated, ions are accelerated by the potential difference between the plasma inside the thruster and the space by keeping the potential of the discharge chamber and space potential same. High energetic electrons can also go out to downstream with ions against the potential hill. These electrons and ions are neutralized outside the thruster; it does not need a neutralizer. Therefore, this thruster is very simple and small, with low power requirements.

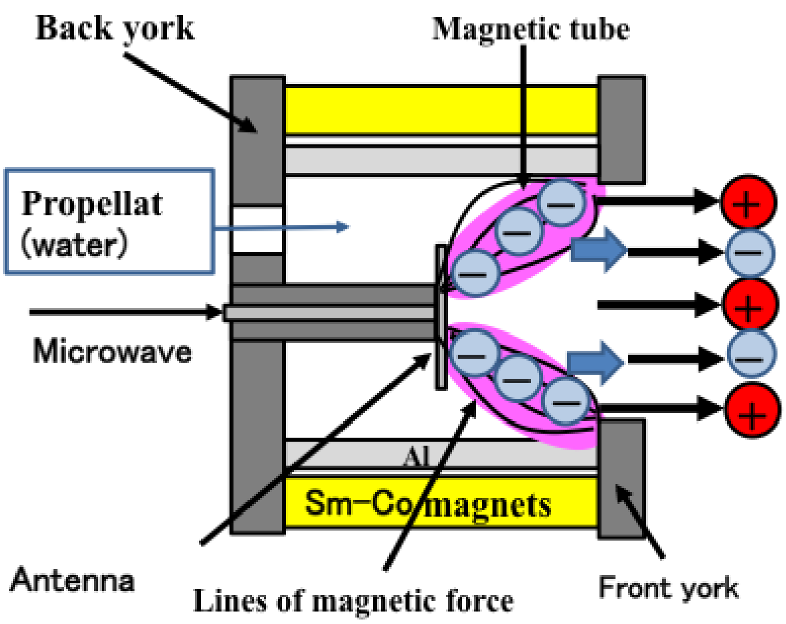

Fig 2-1 Schematic of the thruster

2.2 Selection of the Propellant

The most common propellant used for electric propulsion is Xenon. Xenon requires low ionization energy to be ionized. However in this study, we mainly used water and argon. Water is a liquid propellant at standard condition, so the volume of the tank can be kept smaller than gas propellant.

In order to show that the size of tank changes, we calculated the size needed. We assume the tank is sphere shape.

The equation shown below is used to calculate the thickness of the tank needed.

$$t = \frac{Pr\beta}{2\sigma} \tag{2-1}$$

As we assumed in section 1-3, we calculate with the amount of propellant lasting for 1 year kept in the tank made of plastic. The thickness of the tank becomes 24.7 μm. So the weight of the tank becomes 536 mg in case of using polyethylene as a tank. In the case of Xenon, thickness is 670 μm and it is usually kept in a titanium tank. So the mass of 229.5 g which is much higher than water tank. Xenon is kept in supercritical state so a pretty thick tank is required to keep it safe. In both cases we used 2 as safe value β.

Also we had a choice of other liquid such as alcohol or hydrogen peroxide. We chose water since it is cheap without causing contaminations as alcohols and less oxidization as hydrogen peroxide.[11)] Argon is used as propellant on account of high specific impulse and low cost. Specific impulse is in inverse proportion to the mas of the propellant, so specific impulse become longer by adopting Argon. The price of Argon is about 1/1000 of the one of Xenon, because 1% of atmosphere is Argon. The price of water is 1/5 of Argon. Cost and size occupation is the important for widely application of thrust system in the future. The table comparing the propellants is shown in table 2-1. The important part of the table is mainly the big difference in the cost of each propellant.

Table 2-1 The comparison of the propellants

	Unit Price (JPY/Kg)	Ionization energy (KJ/mol)	Volume at standard condition (dm^3)
Xenon	500,000	1170.4	24
Argon	500	1520.6	24
Water	100	1214.6	0.18

2.3 Expectation of the Performance[12)]

It is very important that the thruster is available to achieve the required performance. Required performances will be calculated by the following equations.

The potential difference between the plasma inside the thruster and the space is estimated as 20 V, because the sheath potential is 20 V by the previous research done using the developing thruster in Kyushu University. In that case, the velocity of the extracted ion v_i is calculated by following equation from the ion's equation of motion. This time we assume, we obtain only water ions H_2O^+.

$$v_i = \sqrt{\frac{2\varphi e}{m_i}} \tag{2-1}$$

In this equation, φ, e and m_i represents the potential difference, elemental charge and ion mass respectively. From this equation, the ion velocity is 14.6 km/s.

$$I_{sp} = \frac{F}{\dot{m}g} \cong \frac{v_i}{g} \tag{2-2}$$

By the equation above the specific impulse becomes around 1489 sec and estimating the propellant utilization as 70 %, we obtain 1000 sec of specific impulse. I_b means the ion beam current. In this case, we need to obtain 0.5 mN and we calculate the ion beam current required to get enough thrust.

$$F = \dot{m}v = \frac{m_i}{e} I_b v_i \tag{2-3}$$

Therefore, this thruster concept can meet the objective performance. And the ion beam current needed is 183 mA.

2.4 Microwave Discharge

We used the method of microwave discharge to generate plasma. The utility of microwave discharge is shown in the mission of HAYABUSA[13]. Microwave discharge have the merits for thruster shown in the below.

1) Long lifetime and simplification by no need of the electrodes
2) Needlessness of the beforehand heating
3) Low power consumption by using existing electron

In this thruster, Electron Cyclotron Resonance (ECR) is used to give energy to the electrons to accelerate. The accelerated electros hit the neutral particles. By hitting high energy electrons to neutral particles, plasma will be generated. In this thruster, the magnetic tube is formed between the central yoke and front yoke as. Electrons make a round trip between the central yoke and front yoke along the magnetic lines of force and reflected at the both ends by the sheath potential. Magnetic mirrors in the both ends also contribute the reflection of the electron. Electrons gain energy from microwave by approaching the strong electric field area near the antenna many times. Plasma can be generated effectively on account of this effect. In the magnetic tube, guiding center also do ∇B drift because the magnetic field strength is large and it generate the ∇B along the magnetic tube.

Chapter 3
Experimental Facility and Setup

3.1Experimental facility

3.1.1Vacuum chamber

There is a vacuum chambers in the laboratory. The small vacuum chamber shown in fig 3-1 and the large vacuum chamber. The inner diameter and the length of the small vacuum chamber are 0.6 m and 1.0 m, respectively. The pumping system consists of a rotary pump (pumping speed 1.5×10^{-2} m^3/sec) and turbo molecular pumps (pumping speed 5.2×10^{-1} m^3/sec). The chamber baseline pressure is below 5.7×10^{-4} Pa. The back pressure is 2.7×10^{-2} Pa at the argon mass flow rate of 82 μg/sec. This vacuum chamber is connected to GND through whole experiments and this is the baseline voltage.

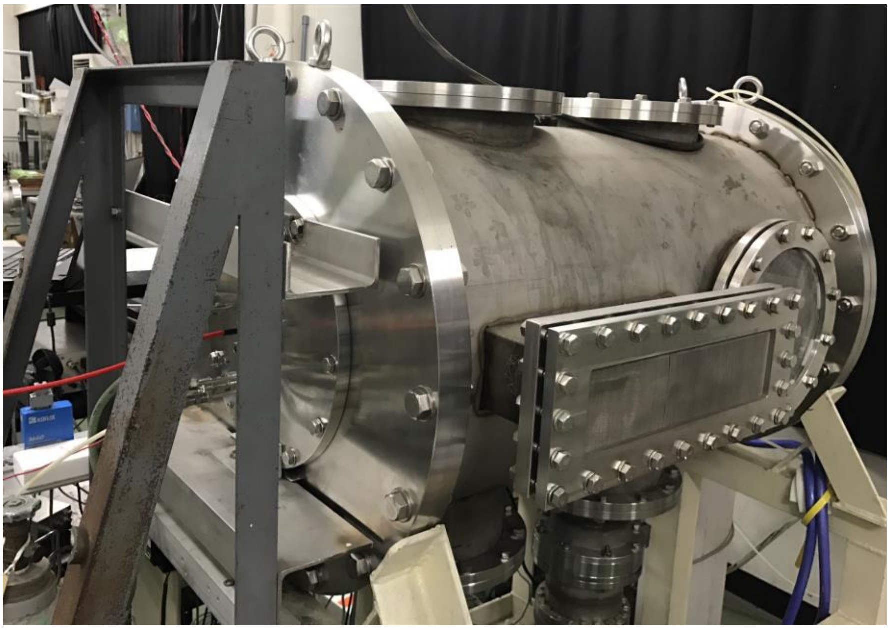

Fig. 3-1 Small vacuum chamber

3.1.2 Devices being used

In this study we use several devices to do experiments. WE 7000 in Fig 3-2 is used to collect the data being used in the experiment such as Forward and Reflection power gaining data from the amplifier. And ion beam current obtained form ion collector. Microwave amplifier in fig 3-5 is used to amplify incident microwave power from the microwave generator n fig 3-4. This microwave is used generate plasma for the thruster. Bipolar DC supply is used to apply wide range of voltage to the ion collector.

Fig 3-2 WE7000

Fig 3-3 Bipolar power supply

Fig 3-4 Microwave generator

Fig 3-5 Microwave amplifier

Table 3-1 Models of the apparatus used in experiments

Object	Company	Name of the apparatus	Model
Save the data	Yokogawa	Measuring station	WE7000 series
Oscillate the power	nF	Bipolar DC Supply	BP 4610
Generate microwave	Anritsu	Digital Modulation Signal Generator	MG3660A
Amplify microwave	R & K	High frequency power amplifier	CA801M162-4747R

3.2 Miniature Microwave Discharge Thruster

In this study, we use a microwave discharge thruster as shown in figure 3-2. The size is 50 mm×50 mm×27 mm. Fig. 3-3 shows the parts assembly of the thruster with 12 mm and discharge chamber length. Sm-Co magnets surround the discharge chamber and are located between yokes made of soft iron. The magnet size is 4 mm×4 mm×12 mm. The inner diameter and the height of the discharge chamber are 21 mm and 12 mm respectively. There are a spacer (diameter 21 mm) and an orifice plate(12 mm for the one shown in the photo) in front of the front yoke. The thickness of the spacer and orifice are 4 mm and 2 mm respectively. The antenna is made of molybdenum. The antenna, which is star shaped, has a thickness of 1 mm and a circular diameter of 9 mm. This star shaped antenna showed best performance in the previous study.[14)] We studied about several types of antenna which are star, circle and cross. For argon star shape showed the best performance.

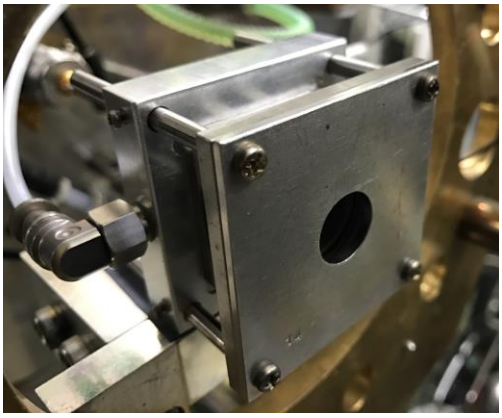

Fig 3-2 Microwave discharge plasma thrusters of 12 mm diameter thruster

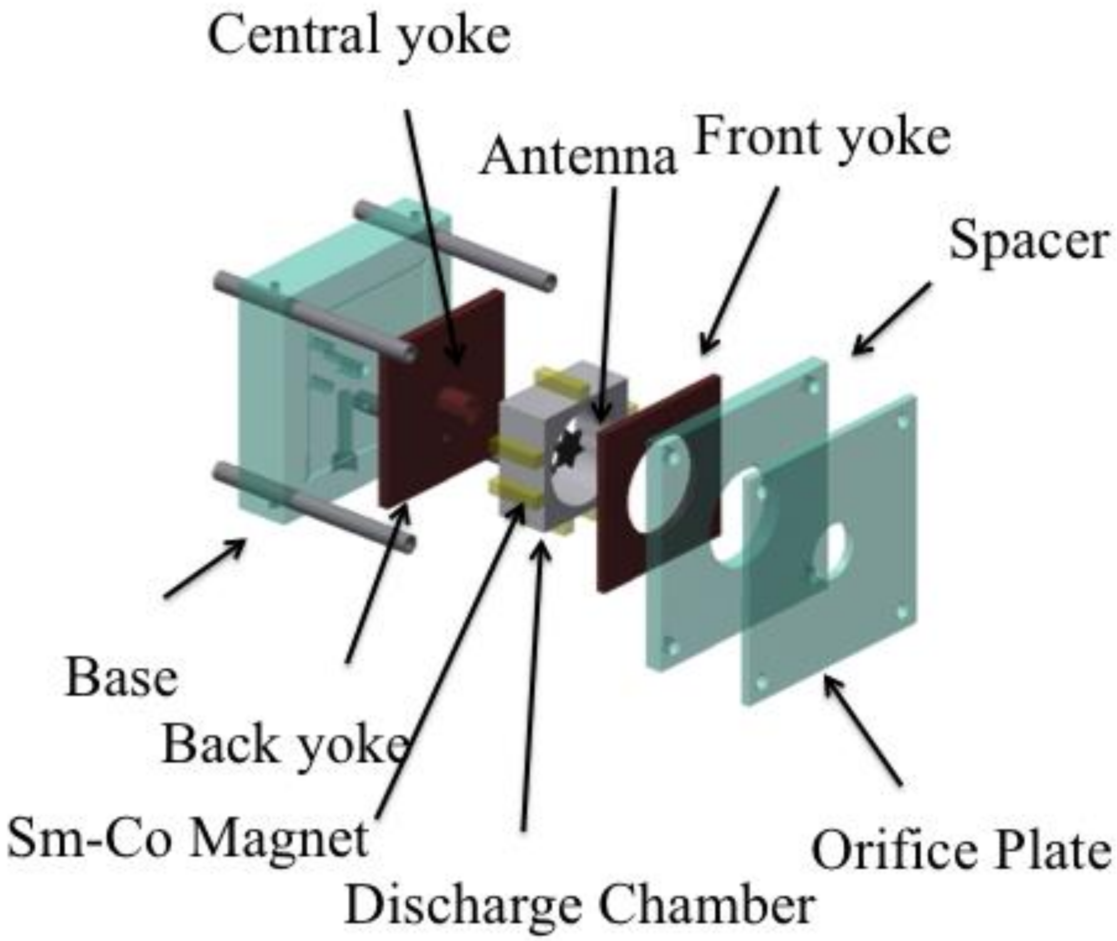

Fig 3-3 Parts assembly of the thruster

3.3 Ion Bean Measurement

Ion beam current was measured to estimate the thrust performance. Fig. 3-4 shows the schematics of the ion beam current measurement. Ion collector is used to collect the ions and measure ion beam. We only need ion to measure but our thruster also emits electrons so we have to repel them. In order to repel the electrons, minus voltage is applied to the ion collector. Fig. 3-5 shows the ion collector used in this study. It has cylindrical shape to be able to measure wide range of plasma from the thruster. At first we tried using plate collector but there are some scattered ions caused by charge exchange[15)]. Fig 3-6 shows the scattered ion beam not being collected by a plate collector.

Cylindrical collector has an aperture ratio of 48% to prevent the confinement of neutral particles. We applied voltage with 1000 Hz of frequency with the range of 10V ~ -100 V to the collector. This range is to give saturation to the current. At first when we tried to measure ion beam current by simple negative voltage, we couldn’t see saturation in ion beam current, meaning we can’t measure collect ion beam current value. So we did the experiment with other ranges but between the range of 10 V ~ -100 V. We need to swing the voltage to positive voltage to catch the electrons. The photo of the circuit used in this experiment is shown in figure 3-7. It uses instrumentation and isolation amplifier. And we use Bipolar power supply with the circuit explained. Since the ion beam current didn’t saturate enough so we used fitting with the measured point using the equation 3-1.

$$I = I_i + I_e \, exp\left\{-\frac{(\varphi_p - V)}{T_e}\right\} \tag{3-1}$$

In this study, optimization of the thruster is a main theme. In order to find the optimization, we changed the size of orifice, magnetic field distribution and the shape of an antenna using 1.6 GHz of microwave frequency for 10 W ~ 30 W of power. We choose to change them because it made a better result in previous reaserch[16)]. We use argon and water propellants with the mass flow rate of 2.8 sccm and 7.52 sccm.

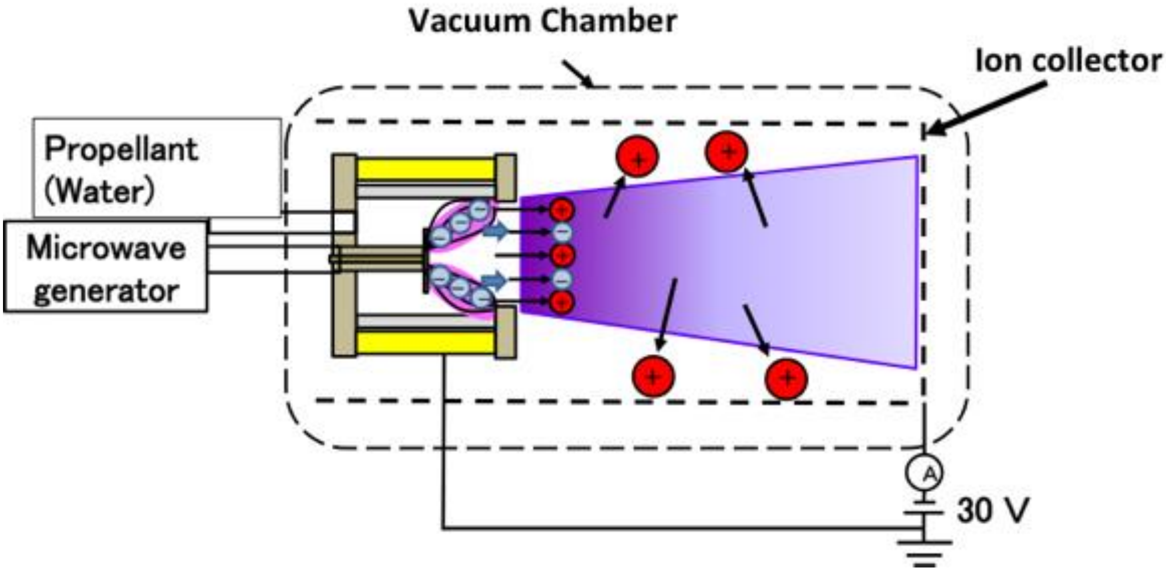

Fig 3-4 Schematic of ion beam current measurement

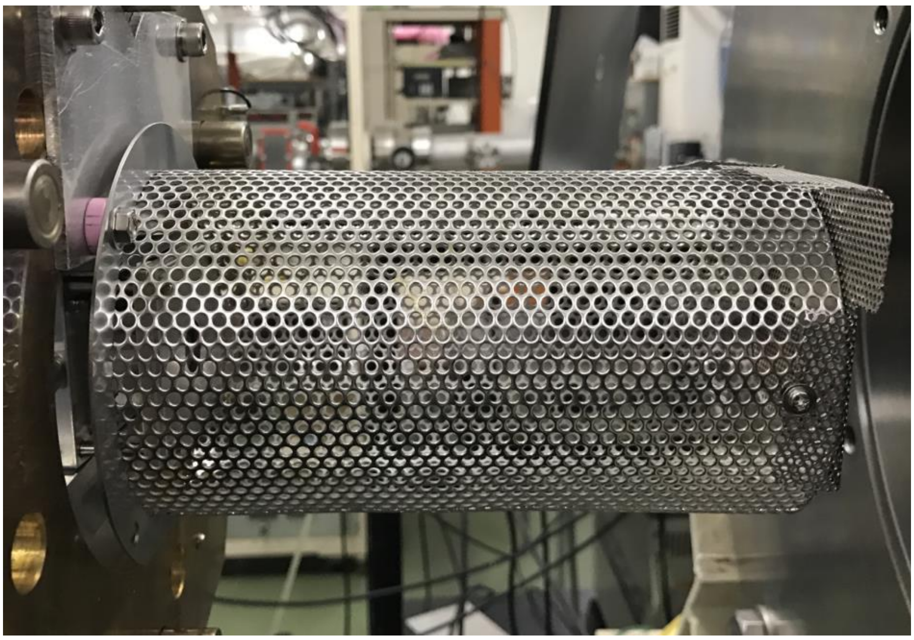

Fig 3-5 Cylindrical shape ion collector

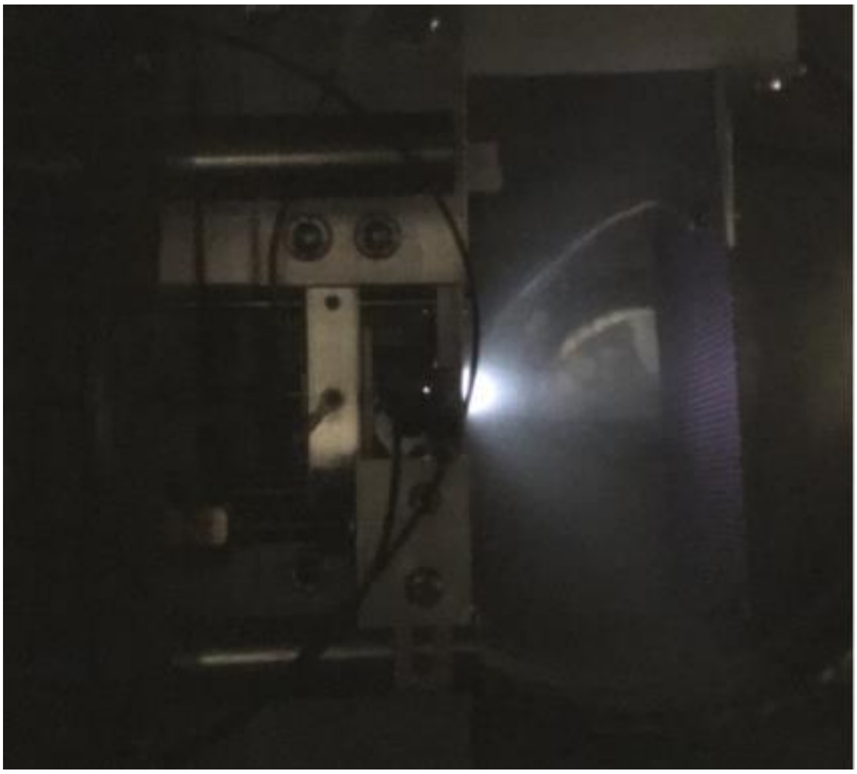

Fig 3-6 Ion beam measurement using plate collector

Fig 3-7 photo of Circuit used to measure ion beam current

3.4 Propellant supplying system[17)]

Figure 3-8 and 3-9 shows the propellant supplying system used in this study. The mass flow rate of the propellant used in the experiment which is water in this case is controlled by needle valve. First, water is storage in the vaporizing tank. Water will be vaporized at the tank and be supplied to the temporary vapor storage tank. The pressure of the temporary vapor storage tank is kept between 1050 and 950. This pressure is controlled by solenoid valve and needle valve set between two tanks. Finally mass flow rate is controlled by needle valve and solenoid valve between temporary vapor storage tank and the thruster. The big tank in fig 3-9 is vaporizing tank and the narrow size one is the temporary vapor storage tank. The two green valves are solenoid valves which are controlled by labview.

Calibration was done by using pressure drop method. First, temporary vapor storage tank was with initial pressure P_0. Valve will be open and time taken for the change in pressure is the parameter due to propellant consumption.

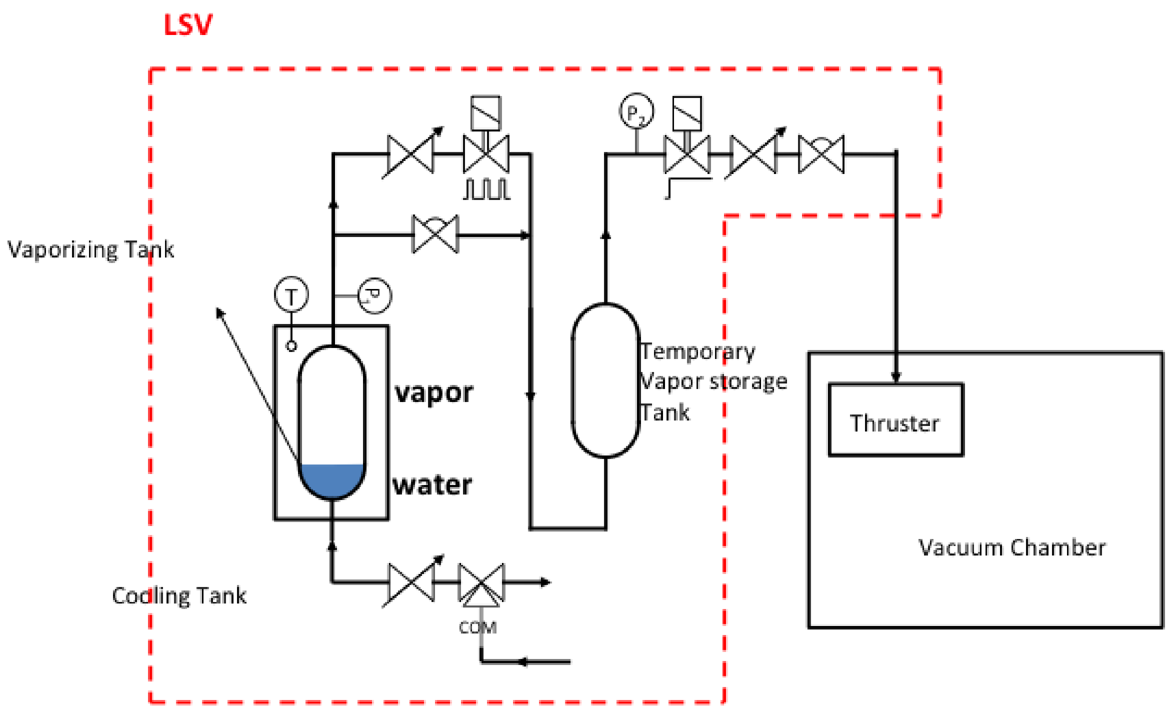

Fig 3-8 Diagram of the propellant supplying system

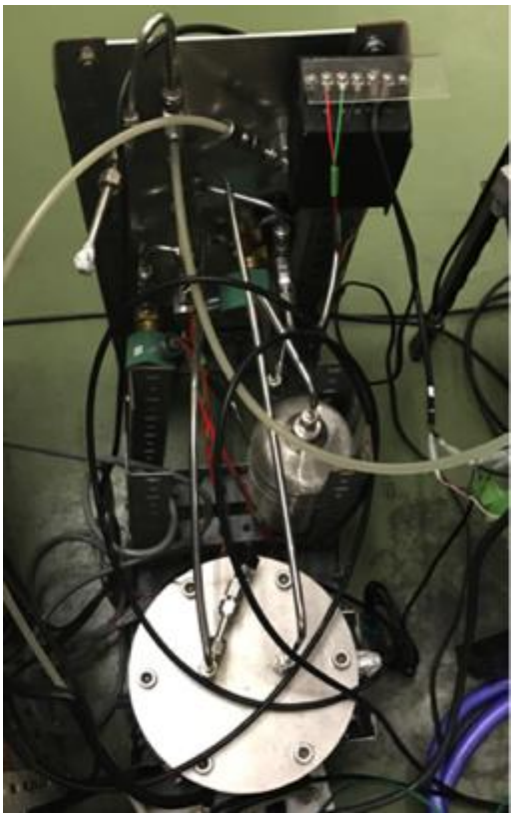

Fig 3-9 Photo of the supplying system

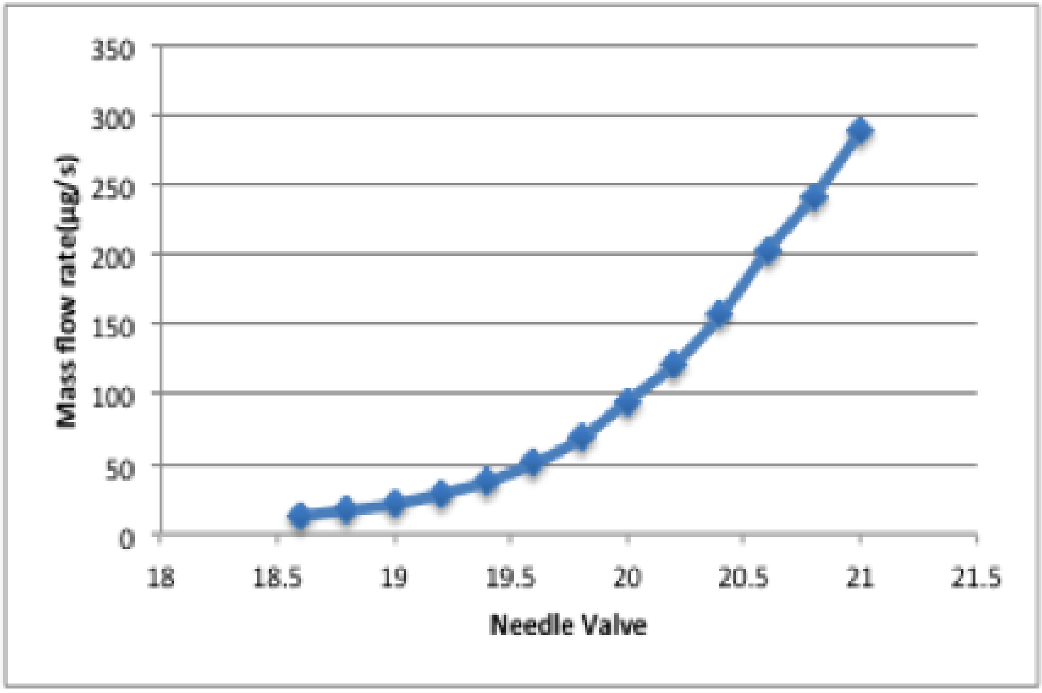

Fig 3-10 calibration graph for the supplying system

Chapter 4
Experimental Result and discussion

4.1 Orifice Dependency

In this study we change the size of the orifice to find the best condition in terms of igniting and the thrust. The orifice used were 5 mm, 6 mm, 8 mm, 10 mm, 12 mm and 14 mm with 7 number of magnets. When the size of the orifice is small, the density of neutral particles will increase so the ignition will occur easily but the amount of exhausting ions will decrease. On the other hand, large size orifices can exhaust more ions but the density of the neutral particles will decrease. In order to see the orifice dependency we use an ion collector. Figure 4-1 and Figure 4-2 show the photo of the ignited microwave discharge thruster using water and argon as a propellant respectively. The frequency of the incident microwave power is 1.6 GHz and power was from 10 W to 30 W by 2 W. We compare water and argon propellant with 2.8 sccm and 7.52 sccm for each propellant. Since the required performance of the thruster is calculated with 20 W. We compared the ion beam current when 20 W of incident microwave power is applied. Figure 4-3, figure 4-4 and figure 4-5 are graphs which show the orifice dependency for the microwave discharge thruster.

When 2.8 sccm of propellant is supplied to the thruster, the highest ion beam current value was 4.90 mA and 15.54 mA when water and argon was supplied respectively. For water the best orifice size was 12 and argon was 14. For the mass flow rate of 7.52 sccm they both got the highest ion beam current when 14 mm of orifice was used. When 14 mm of orifice was used with 2.8 sccm of mass flow rate, water plasma could not be generated but when 7.52 sccm was used it did ignite.

The reason why when water propellant's mass flow rate was 2.8 sccm didn't show good result is because the neutral particle density wasn't kept in the optimized condition for the generation in plasma. In order to generate plasma using microwave discharge, mean free path is an important factor.

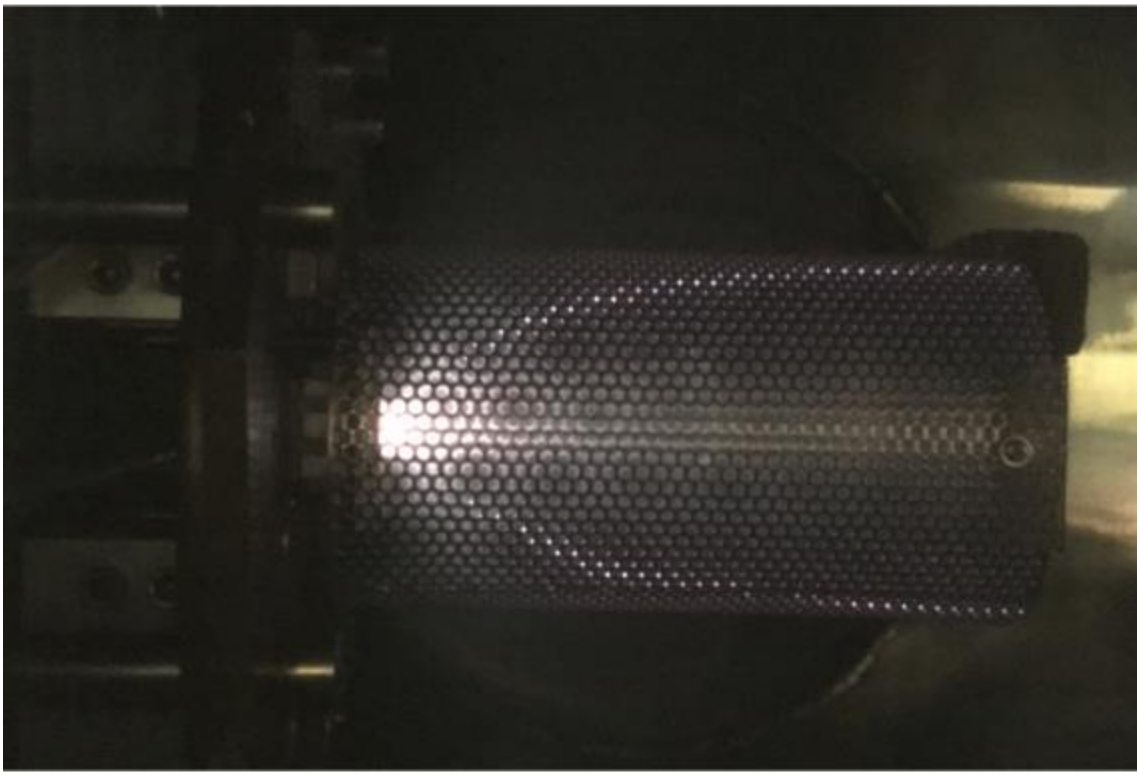

Fig 4-1 Photo of water propellant plasma

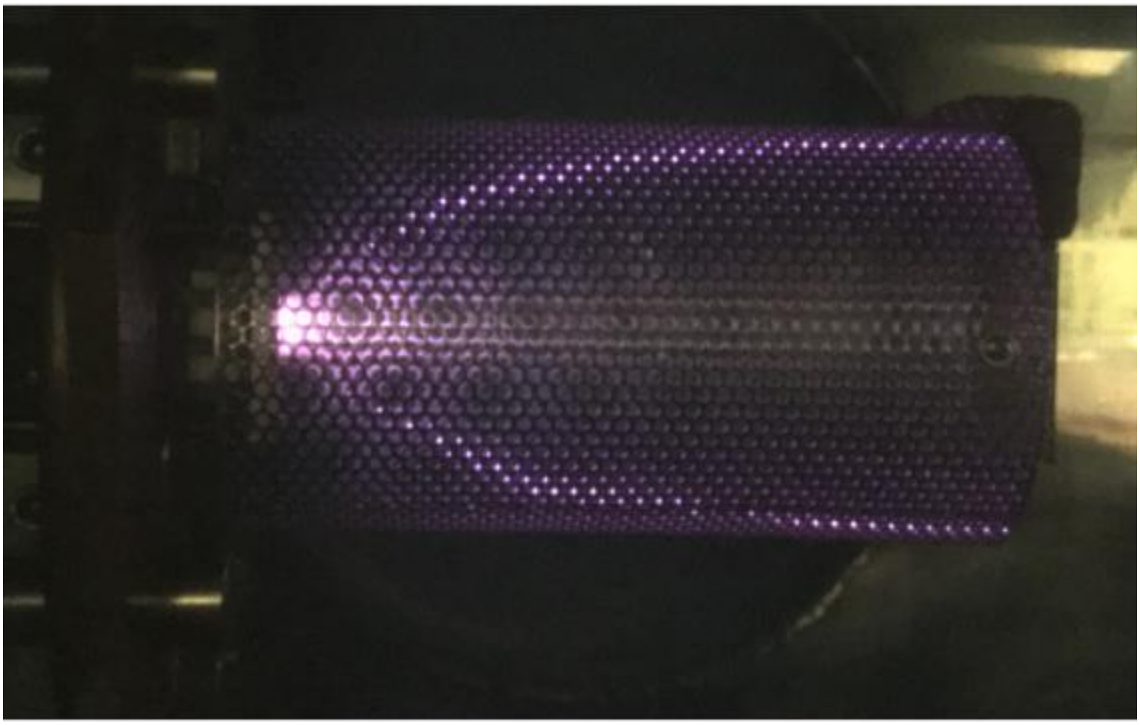

Fig 4-2 Photo of Argon propellant plasma

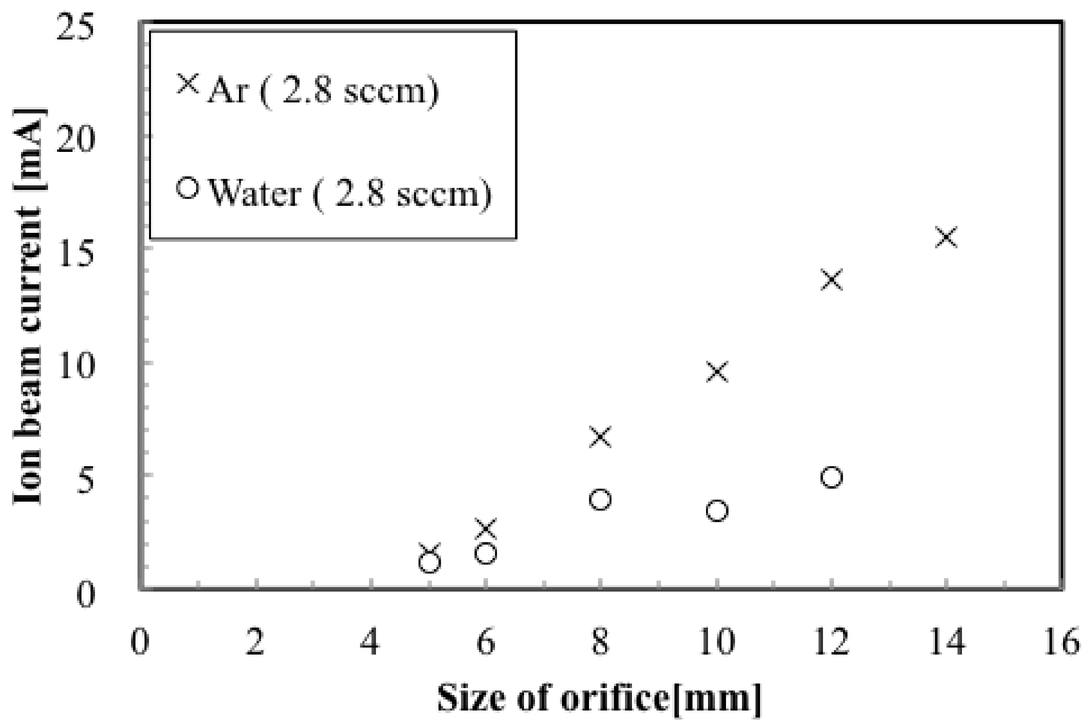

Fig 4-3 Graph of orifice dependency (2.8 sccm)

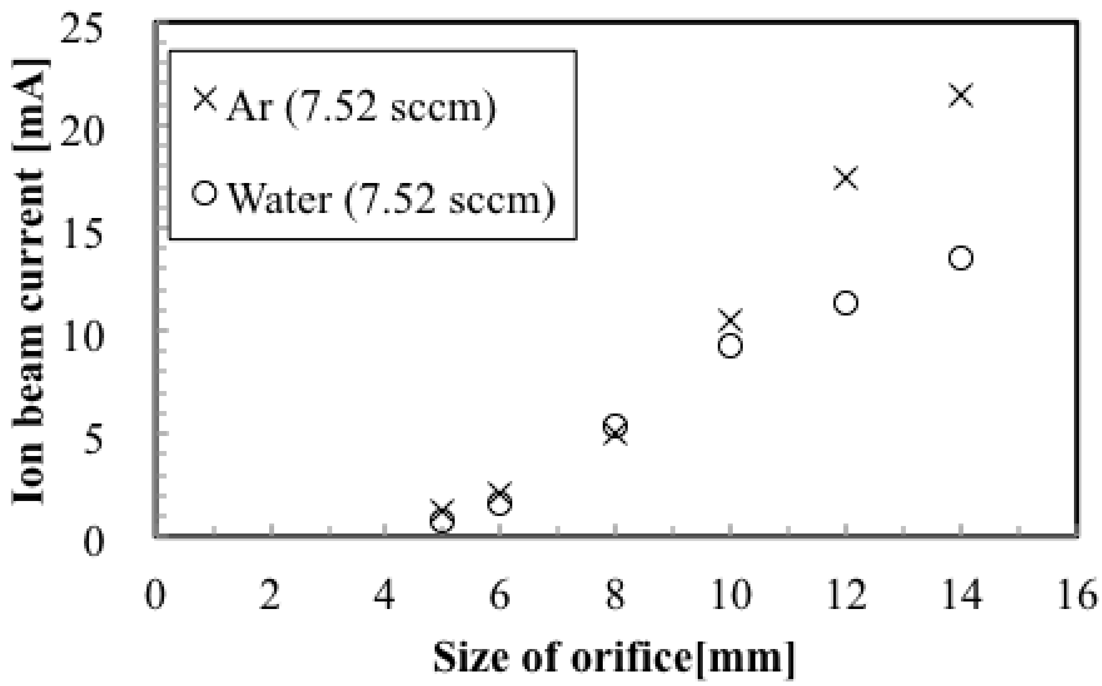

Fig 4-4 Graph of orifice dependency (7.52 sccm)

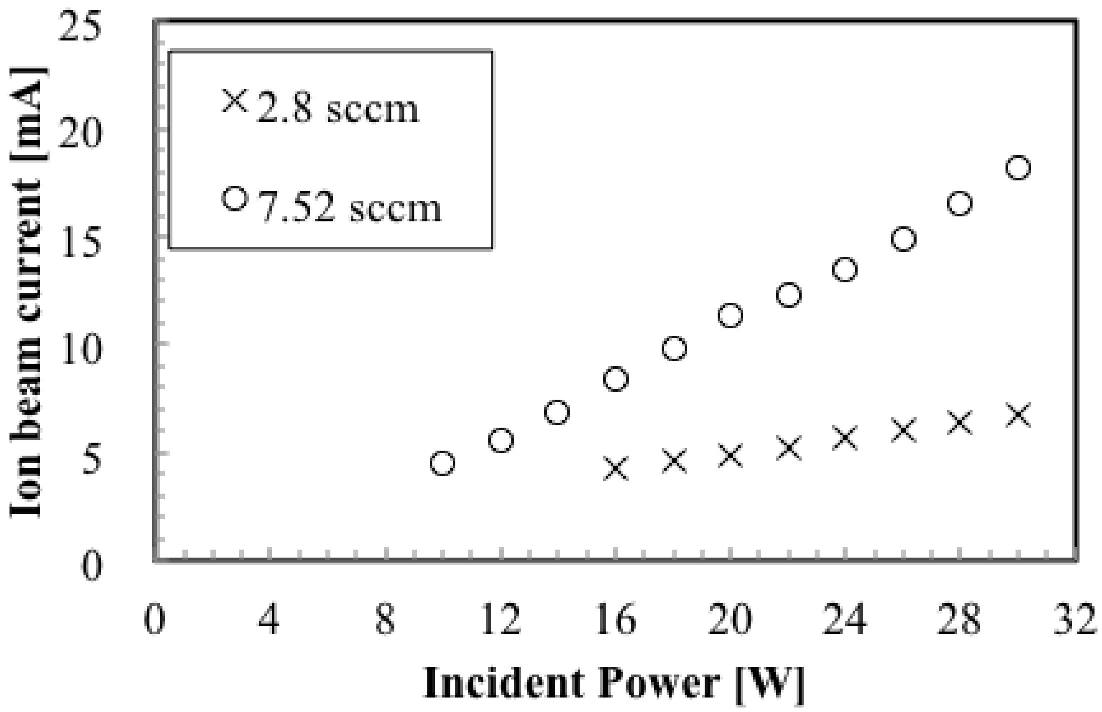

Fig 4-5 Graph of the optimized orifice using water as a propellant

4.2 Magnetic field dependency

The magnetic field distribution inside the discharge chamber can be changed by the number of magnets. Figure 4-6 ~ 4-7 shows the magnetic field distribution for magnets. For microwave discharge, ECR layer is a very important factor. The surface of an antenna needs to touch to accelerate the ions efficiently. 9 magnets was the best performance for the previous research using argon as a propellant. This value was focusing on ion beam current and not in igniting conditions. In this study we will measure the ion beam current for the magnets of 6, 7, 8, 9 and 10. The frequency of the incident microwave power is 1.6 GHz and power was from 10 W to 30 W by 2 W as we used in orifice dependency experiment. Plasma couldn't be generated with 6 magnets either for argon nor water. The best ion beam current obtained for water was, when 7 magnets were used and it went down as we increase the number of magnets. For argon propellant 9 magnets gave us the highest ion beam current value as shown in figure 4-7. But for 7.52 sccm, the best result is obtained from 9 magnets in both of the propellant.

This suggests that electrons didn't accelerate enough so energy was low. When we look at the magnetic field distribution, the ECR layer is inside the antenna so the electrons couldn't get enough energy. For more number of magnets, the tendency was different depending on the mass flow rate for water. For 2.8 sccm water propellant, we can say that plasma is trapped by magnetic field.

So, if we try using 2.8 sccm, 7 magnets give us the best performance but for 7.52 sccm, 9 is the best. Optimization exists for both mass flow rates and type of propellant and they are different. If we look at figure 4-11, when mass flow rate is 7.52 ion beam current value increases but not for 2.8 sccm. When mass flow rate is larger, there are cases which plasma is developed also in front of an antenna is shown in the previous research. So The importance is plasma being trapped inside the discharge chamber rather than antenna touching ECR layer

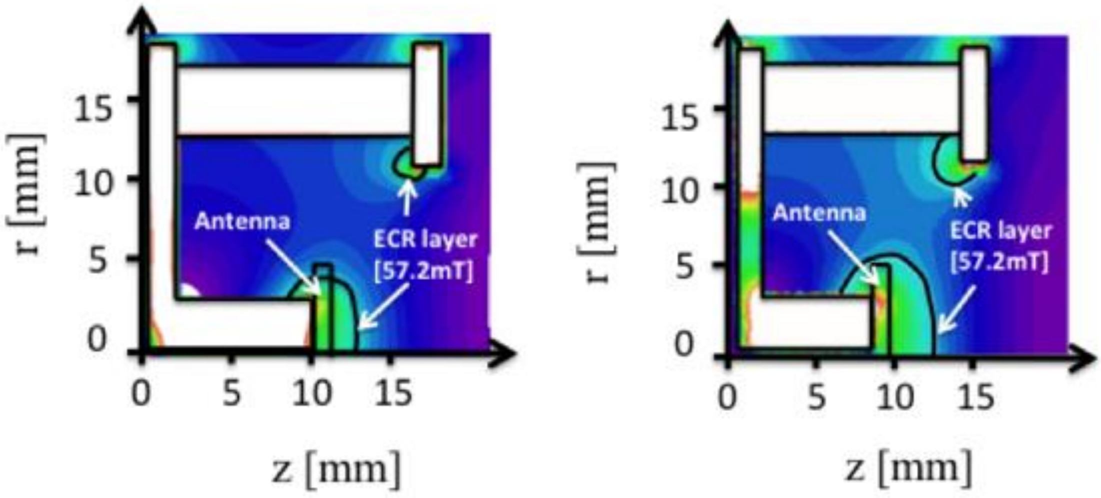

Fig 4-6 magnetic field distribution when 6 magnets (left) and 7 magnets (right)

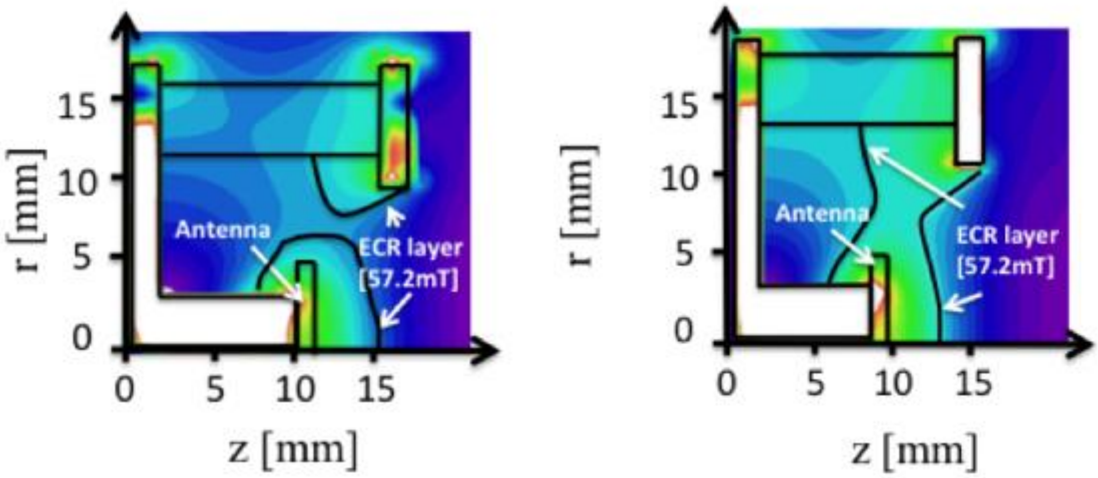

Fig 4-7 magnetic field distribution when 8 magnets (left) and 9 magnets (right)

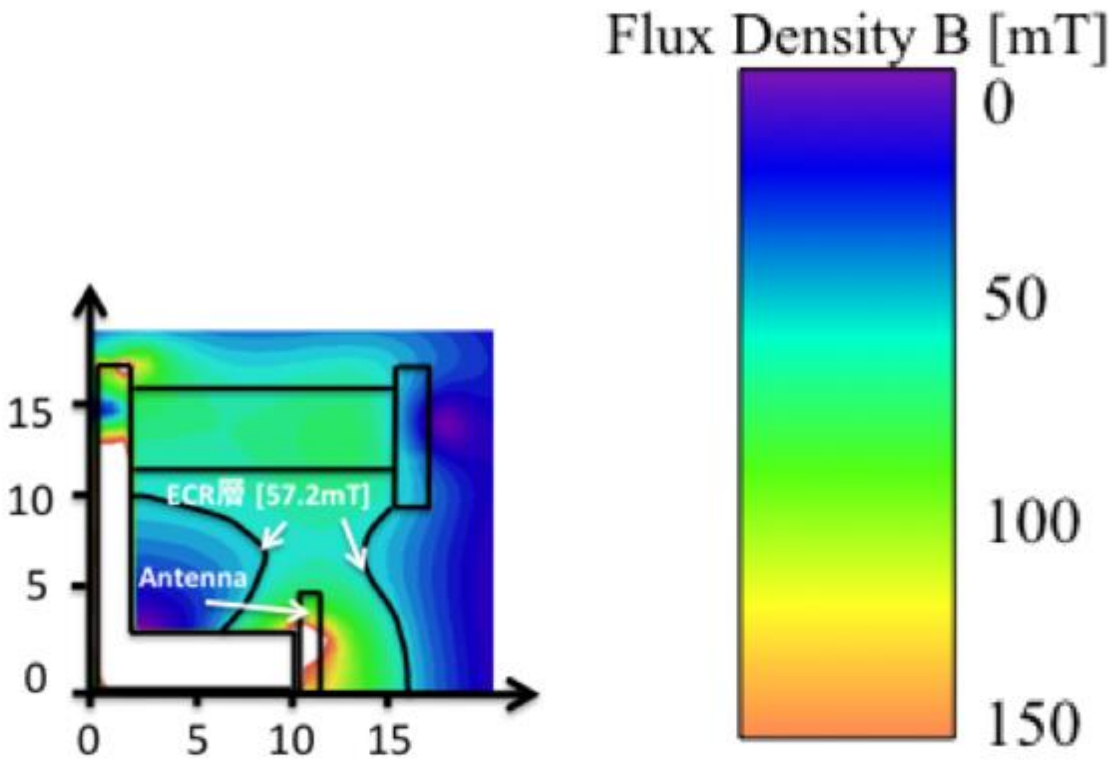

Fig 4-8 magnetic field distribution when 10 magnets (left) and strength (right)

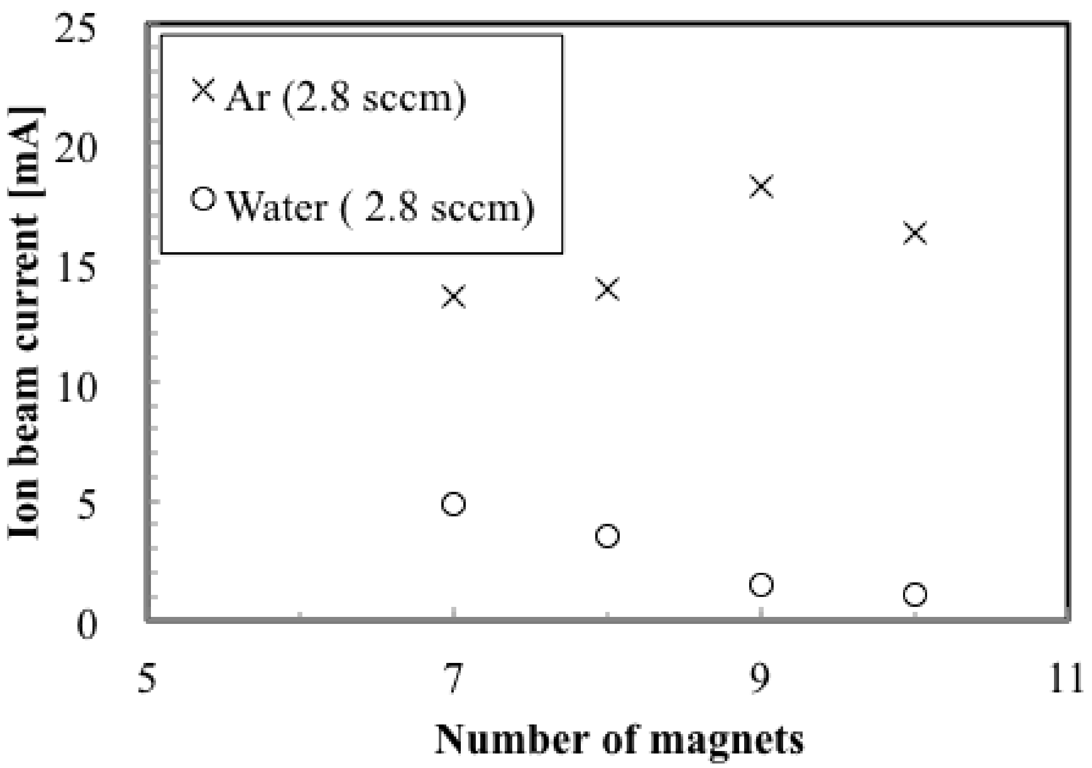

Fig 4-9 Graph of the magnetic field dependency (2.8 sccm)

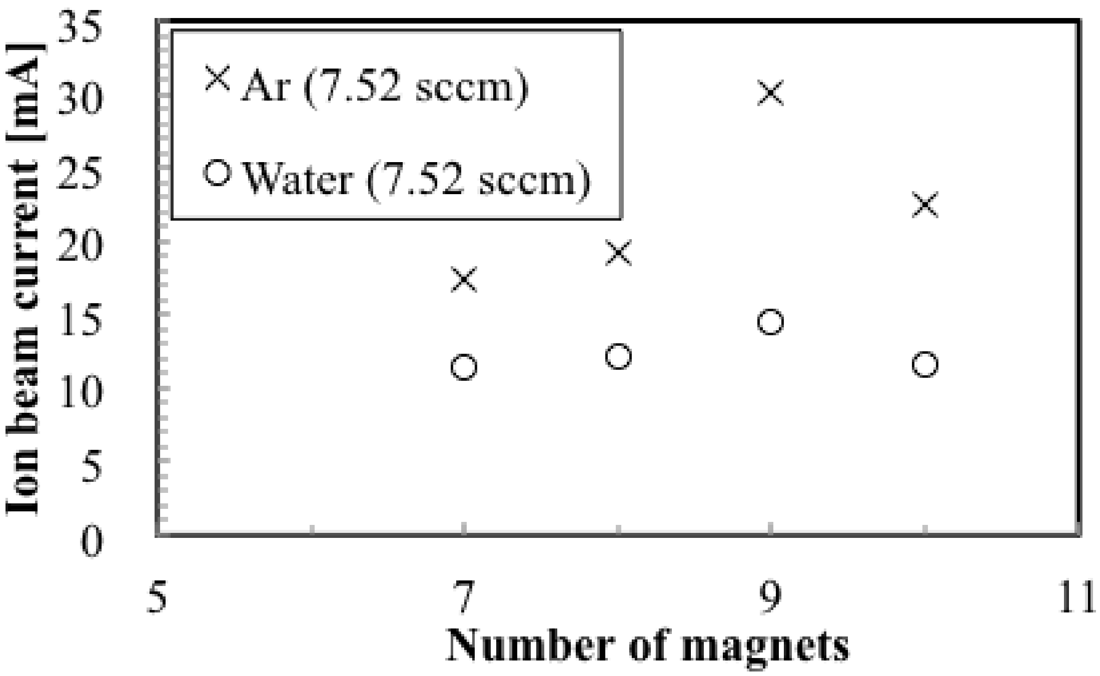

Fig 4-10 graph of magnetic field dependency (7.52 sccm)

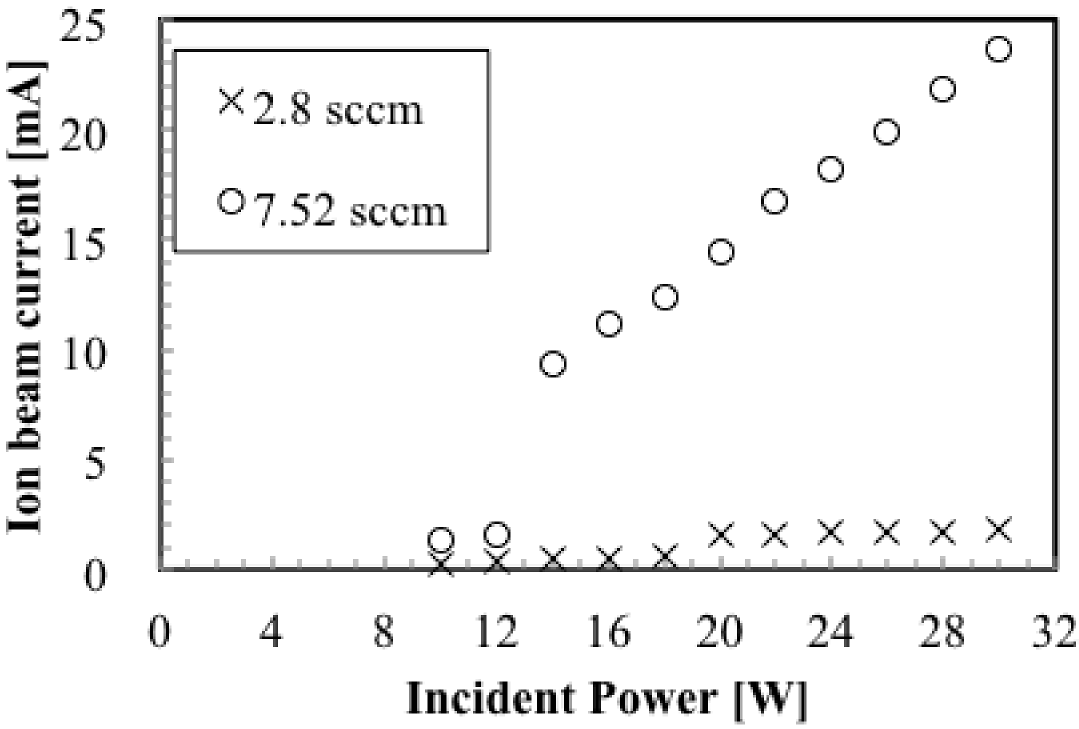

Fig 4-11 graph when optimized thruster for water propellant (7.52 sccm)

4.3 Antenna dependency

Fig 4-9, fig 4-10, fig 4-11 and fig 4-12 show the result of the experiment of the antenna’s shape dependency. The experiment was done under the condition of 1.6 GHz of incident microwave power, 12 mm of orifice and 7 magnets. The experiment was done again using 10 W ~ 30 W of incident microwave power. The experiment using circle antenna showed good result for water propellant but not for argon. For argon it didn’t even ignite plasma. But when we tried using low frequency we could ignite so ignite condition of 7 magnets wasn’t suitable for argon. Focusing to the water propellant, at high incident microwave power the value of ion beam current was higher than other types of antenna. For 20 W of incident microwave power, there wasn’t much difference in the ion beam current when 2.8 sccm of water was used. When we apply higher incident microwave power, we obtain larger difference in the antennas than other power. In previous study it is known that low density propellants, circle shape antenna gave best result but when amount of plasma is high, then the ion beam current becomes less[18].

Fig 4-12 Star shape antenna

Fig 4-13 Circle shape antenna

Fig 4-14 Cross shape antenna

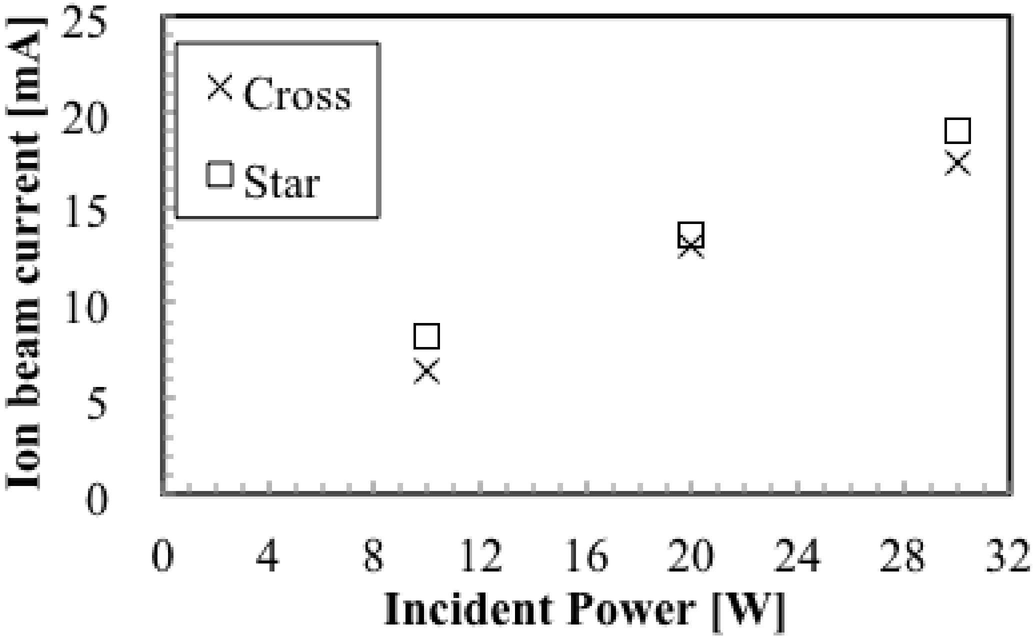

Fig 4-15 Antenna dependency Ar (2.8 sccm)

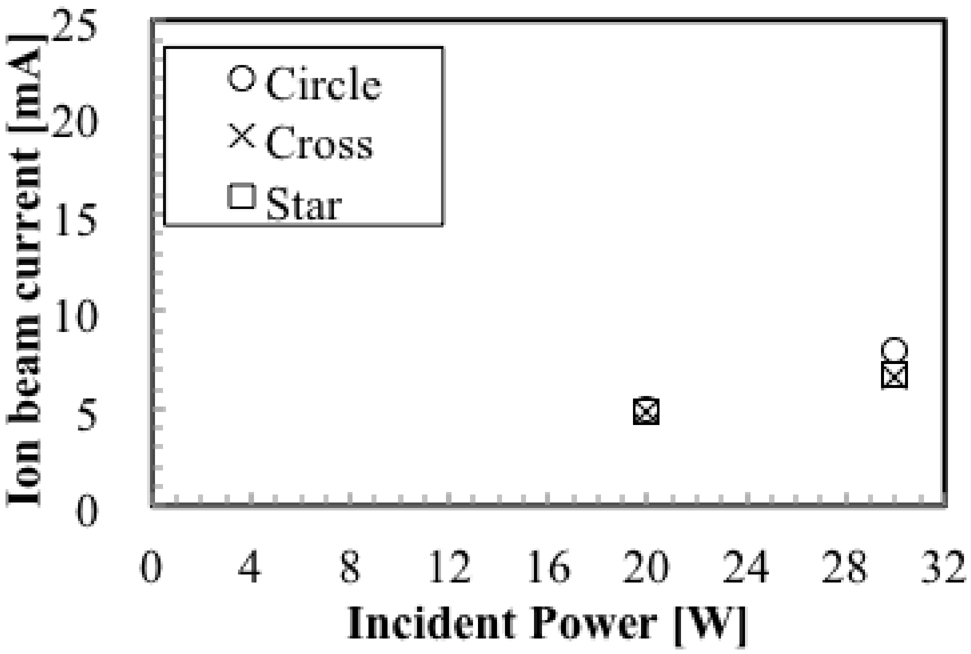

Fig 4-16 Antenna dependency water (2.8 sccm)

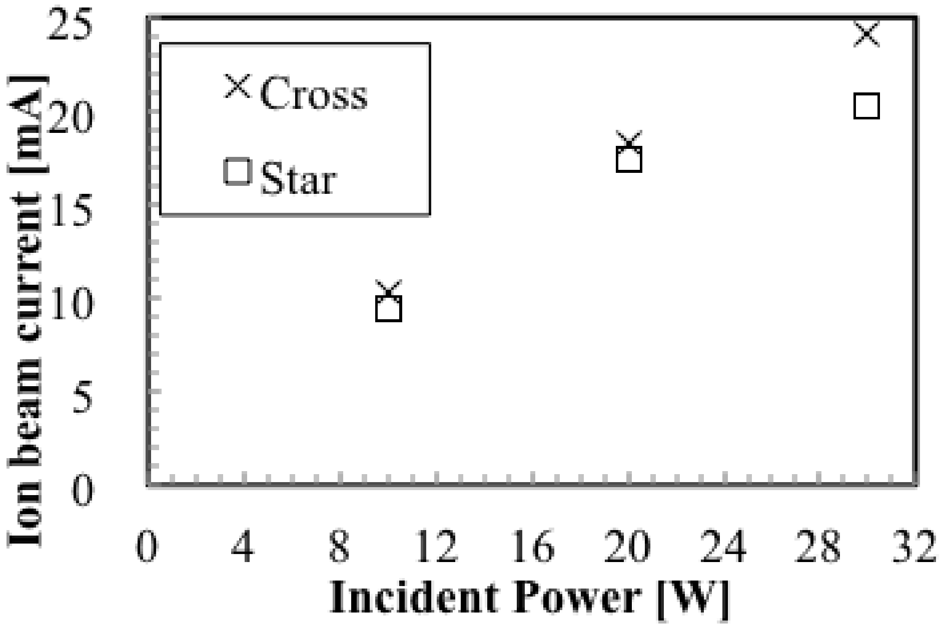

Fig 4-17 Antenna dependency Ar (7.52 sccm)

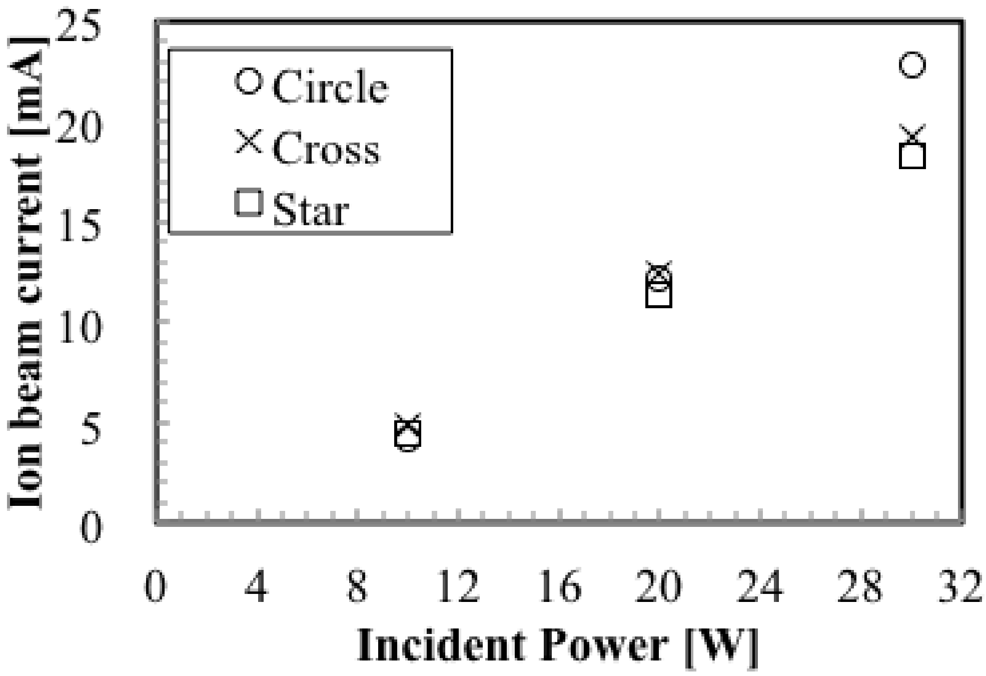

Fig 4-18 Antenna dependency water (7.52 sccm)

4.4 Thrust Performance Estimation

We have been changing the size of orifice, number of magnets and shape of the antenna to optimize liquid propellant microwave discharge plasma thruster. By the above section, we succeeded to ignite plasma using water propellant to microwave discharge thruster. Up to this section, we were measuring the ion beam current by using cylindrical collector. Since the aperture ratio is 48% in case of cylinder collector, we need to recalculate the value of ion beam current.

Table 4-1 shows the thrust and specific impulse calculate using the formulas expressed in the section above and the recalculated ion beam current. The mass flow rate which is almost equal to 2.8 sccm of argon is 7.52 sccm of water but the result obtain is not high enough. The objective value is 500 μN.

Table 4.1 Thrust and specific impulse

	Ar (2.8 sccm)	Ar (7.52 sccm)	Water (2.8 sccm)	Water (7.52 sccm)
Thrust	190 μN	490 μN	28.2 μN	135 μN
Specific impulse	242 s	233 s	57 s	145 s

Summary

In this study we investigated about the optimization of the miniature microwave plasma thruster by changing the size of orifice, number of magnets and shape of an antenna. The final thrust obtained was 135 μN when using 7.52 sccm and 28.2 μN when 2.8 sccm of water propellant. The result of our research is shown below.

1. The best size of orifice was 12. Larger than this orifice we couldn't ignite plasma for 2.8 sccm water. Because the neutral particle density wasn't kept in enough condition for the generation in plasma. In order to generate plasma using microwave discharge, mean free path is an important factor.
2. The number of magnets condition changes by the mass flow rate of water. When high mass flow rate is being used plasma is generated in front of an antenna so the distance from the ECR layer is not an important factor. Plasma will be trapped stronger inside discharge chamber. So the density of plasma will increase and more ions are expected to exhaust.
3. The shape of antenna also affects the plasma generation we suppose. The largest thrust was obtained from circle shape when 30 W but our object is 20 W and at that stage the shape of the didn't affect much.
4. Thrust obtained was lower than the object value. But thinking of the mass of the tank, we could try using much higher mass flow rate.

In this study, we succeeded to show the thrust from the thruster. In the future we need to see the mechanism of the plasma inside the microwave discharge thruster to be able to do changes more specific. The investigation of the plasma generation mechanism of plasma is important for the improvement of the thrust performance. In future, numerical simulation can help us. Also that, the thrust should be measured directly without using ion beam current or other methods by more reliable method for accurate evaluation of the thrust performance such as using thrust balance with high resolution.

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