Performance Dependence on Microwave Frequency and Discharge Chamber Geometry of the Water Ion Thruster

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Abstract: The water ion thruster is a gridded ion thruster for CubeSat. Water has some advantage as a propellant for CubeSat, but the performance drops when applying water to the miniature ion thruster which normally uses xenon. In this work, the frequency of the microwave and the shape of the discharge chamber are changed experimentally to improve the performance, and the effect of these changes is discussed.

Nomenclature

B = magnetic field
C_i = ion production cost
I_s = screen current
P_{IN} = input of microwave power
P_{REF} = reflection of microwave power
e = elementary charge
m_e = mass of the electron
Γ = reflection coefficient
Γ^2 = power loss ratio
ω_m = frequency of microwave

I. Introduction

The water ion thruster is a gridded ion thruster for CubeSat[1]. Water is fed to the discharge chamber of the ion source as a vapor, and the plasma is generated by electron cyclotron resonance (ECR) heating. It has two grids, a screen grid, and an acceleration grid, and these extract the ion beam. The neutralizer has also the discharge chamber, in which the plasma is generated, and the negative bias voltage applied to the neutralizer to emit electrons to neutralize the ion beam.

Many propulsion systems for CubeSat have been proposed[2], while water has some advantages as a propellant for CubeSat[3], such as safety, storability, and availability in deep space. Most of the propellants used for chemical propulsion in standard-size satellites are toxic and costly. Therefore, these do not suit the concept of CubeSat: short-term and low-cost development. A common propellant used for electric propulsion is xenon, but it is costly and also has the problem of storability. It requires being stored in high pressure, and this structure makes difficult to install the system into CubeSat. Availability in deep space is one special feature of water. Water in moon or asteroids can be used as a propellant, and we can refuel the propellant in space. It should be a strong advantage to conduct deep space exploration. That's why some propulsion system using water have been proposed[4-6].

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On the other hand, water has several issues as a propellant for an ion thruster. Oxidization is one serious problem when using water. Especially when using a propellant for electric propulsion, the oxidization at the electrodes should occur. Furthermore, a hollow cathode, commonly used as a cathode of a hall thruster and gridded ion thruster, is easy to be oxidized and impossible to be used with water. Our water ion thruster overcome the problem with using the microwave discharge plasma both the ion source and the neutralizer and eliminating the hollow cathode.

The performance dropping compared with using xenon is also a problem. Water is lighter than xenon and it causes that the thrust-to-power ratio decreasing. It directly causes dropping of the thrust and extending the mission duration because of the strict limitation of the power consumption on CubeSat. The lower ionization cross section and dissociation of water molecules are other reasons of the performance dropping[7]. These two require more microwave power to keep the same plasma density and also decrease the thrust-to-power ratio as a result.

This work focuses on the performance improvement, especially on the extraction of the ion beam from the ion source. The frequency of the microwave and the shape of the discharge chamber are changed experimentally to improve the performance, and we discuss the effect of these changes.

II. Experimental setup

A. Design of the Discharge Chamber of the Ion Source.

The discharge chamber of the ion source consists of the yoke, ring-shaped magnet, antenna, wall, and screen grid as shown in Fig. 1. The plasma is generated using ECR heating by the magnetic field generated by the ring-shaped magnet and the microwave from the antenna. The diameter of the ion source is 20 mm.

The ECR region, where the ions are mainly generated, is determined from the distribution of the magnetic field and the frequency of the microwave. The intensity of the magnetic field of the ECR region is shown below:

$$B = \frac{m_{\mathrm{e}}\omega_{\mathrm{m}}}{e} \qquad (1)$$

In the experiment, we changed the frequency to control the ECR region, and also changes the distance between the screen grid and the magnet to reveal which effect is significant to increase the ion beam extraction.

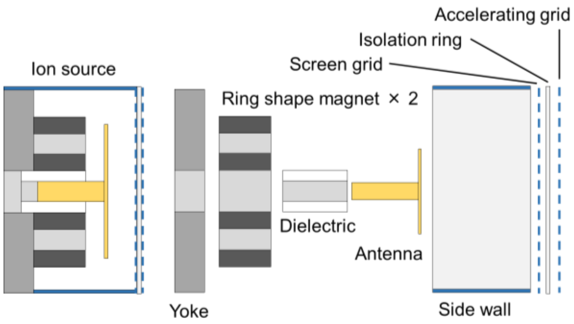


Figure 1 Design of the discharge chamber of the ion source.

B. Effect of the Change of the Frequency

Figure 2 shows the magnetic field in the discharge chamber of the ion source and the ECR region of some frequency. The thruster, which is currently optimized for using xenon, uses 4.25 GHz for generating the plasma. The region can be controlled by changing this frequency. It typically moves to the axial direction, and this will cause the extraction of the ion beam because of some effect from this moving.

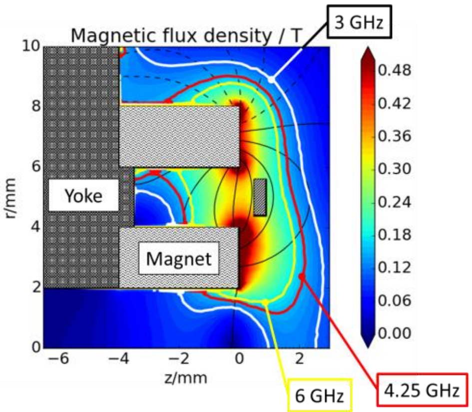


Figure 2 Magnetic field and ECR regions of each frequency.

Firstly, the loss of the ions to the screen grid, the ring-shaped magnet, and the antenna changes because of changing the distance between the ECR region and these parts. As a result, when the microwave power input is equal, the density of the plasma may be affected by this loss, and the ion beam current may change.

Secondly, the distance between the plasma and the screen grid may affect the extraction of the ion beam. When the plasma density is same, the closer to the grid the plasma is, the larger the ion beam may be extracted.

Thirdly, the mirror ratio changes when changing the region where the plasma mainly exists. The ECR region, where the ions are mainly generated, should have a strong relation to the region where the plasma exists, so the mirror ratio changes with changing the frequency. The intensity of the magnetic field at ECR region decrease with the frequency becomes lower. Therefore, the lower frequency should achieve higher mirror ratio and the plasma density may increase.

C. Effect of the Distance between the Screen Grid and the Magnet

The distance between the screen grid and the magnet changes with shortening or extending the height of the side wall. The positional relationship between the antenna and the magnet does not change, so this shortening or extending of the height does not affect the ECR region directly. On the other hand, the loss of the ions to the wall and the distance between the plasma and the screen grid should change, and we can observe the first and second effects mentioned in the precious section independently of the frequency.

Another important effect of changing the distance is the resonance of the microwave. The microwave is radiated from the antenna and reflected at the screen grid, and the standing wave is built. The amplitude of the standing wave changes by the shape of the discharge chamber. This standing wave affects the absorption and the reflection of the microwave and the plasma density be affected as a result. When discussing this effect, it should be considered that the wavelength of the microwave, 5-10 cm, is much longer than the scale of the discharge chamber and the plasma, 1-20 mm. It means most of the theory of the wave in a vacuum and in plasma is not applied directly because these set the condition that the scale is large enough compared with the wavelength.

D. Experimental Condition

Experimental conditions are shown in Table 1. The plasma was generated with higher input power of the microwave than that needed keeping it. The ion source was operated without the neutralizer and the common ground of the ion source was connected that of the vacuum chamber. Water is fed to the discharge chamber as a vapor and the mass flow rate was controlled by bang-bang control system[1]. The microwave frequency was changed stepwise by programmable signal generators and its power is controlled by the amplifier.

Table 1 Experimental conditions.

Distance between the screen grid and the magnet, mm	2.5, 3.0, 4.0, 5.0
Microwave frequency, GHz	3.0 - 6.0
Microwave power input, W	1.0, 1.5, 2.0, 2.5
Mass flow rate, µg/s	4×10^1
Screen grid voltage, V	800
Acceleration grid voltage, V	-100
Chamber pressure, Pa	$< 5 \times 10^{-2}$

III. Result and Discussion

The result is shown as the ion production cost and the power loss ratio of the microwave. The definitions of them are

$$C_\mathrm{i} = \frac{P_\mathrm{IN} - P_\mathrm{REF}}{I_\mathrm{S}}, \tag{2}$$

and

$$\Gamma^2 = \frac{P_\mathrm{REF}}{P_\mathrm{IN}}. \tag{3}$$

The ion production cost is appropriate to directly evaluate the effect on the ion beam extraction. The power loss ratio is important to consider the resonance of the microwave in the discharge chamber.

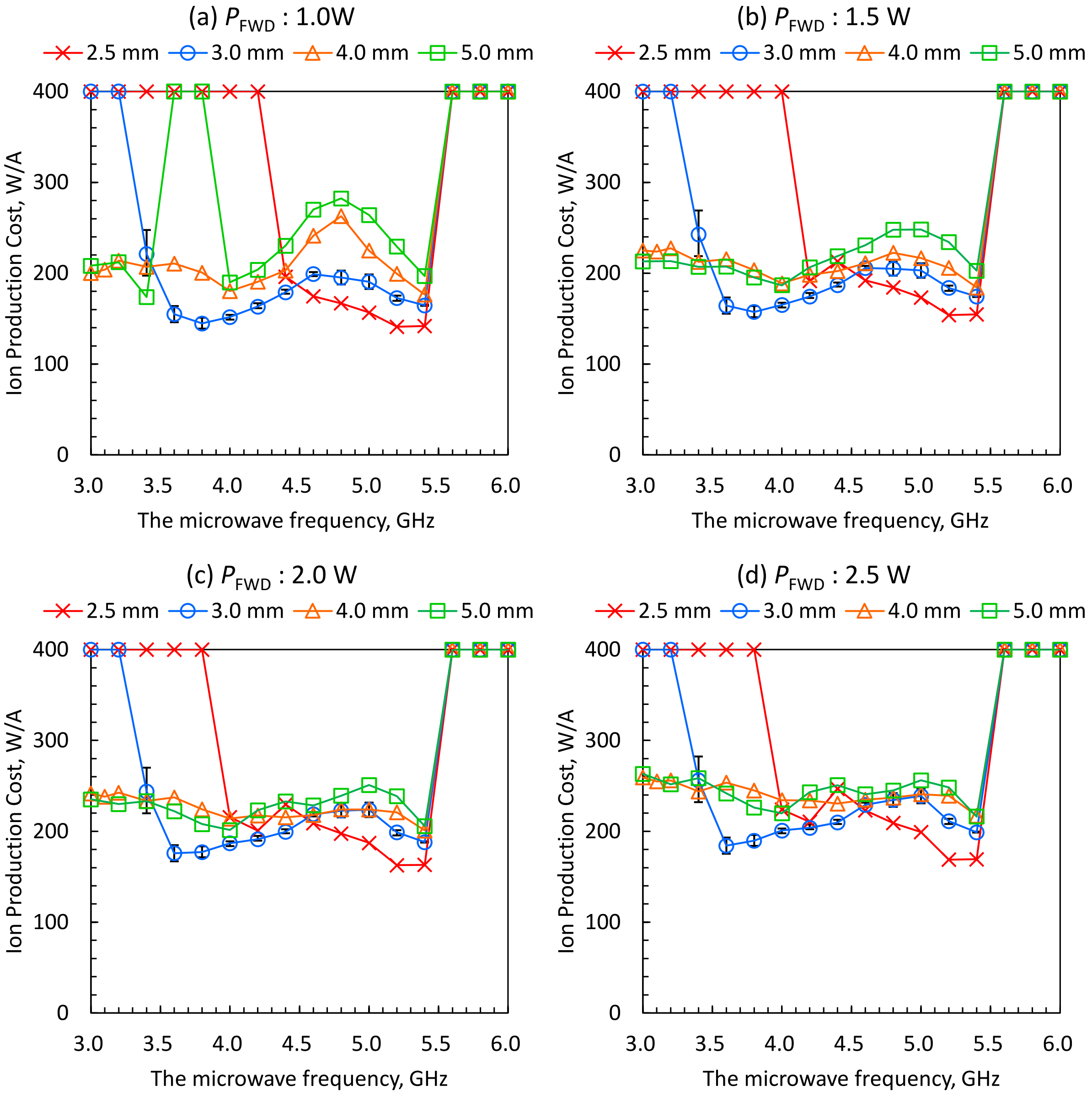
A. Ion Production Cost

The ion production cost of each condition is shown in Fig. 3. Each graph shows the results of each microwave power input. The points where the plasma was not kept is shown as the point that the ionization cost is 400 W/A. The lowest ion production cost is 1.4×10^2 W/A at the microwave power is 1.0 W and the distance between the screen grid and the magnet is 2.5 mm. It achieved 30 % reduction from that already reported[1].

The plasma could not be kept with the frequency of over 5.6 GHz at every condition. This is the effect of the loss of the ions to the magnet and the antenna. The results did not depend on the distance between the screen grid and the magnet, and it suggested that this phenomenon was the effect related to the antenna and the magnet, whose positional relationships did not change. The distance between the ECR region at 5.6 GHz and the antenna is 0.4 mm, and that between the ECR region and the magnet is 1.3 mm. It is one criterion to keep the plasma. The mirror ratio also has the effect to increase the ion production cost, but it should be a gradual change.

At low frequency, the plasma with 2.5 mm and 3.0 mm condition could not be kept. The frequency at which the plasma was not kept is lower than 3.8 GHz with the distance of 2.5 mm and lower than 3.4 GHz with the distance of 3.0 mm. This may be caused by the effect of the loss to the screen grid. The distance between the ECR region and the screen grid where the plasma could not be kept is shorter than 0.5 mm for the result with the distance of 2.5 mm, and is shorter than 0.85 mm for the result with the distance of 3.0 mm. The difference between the two results cannot be explained only this discussion, and there should be other effects depends on the distance.

The effect of the distance between screen grid and the plasma can be seen especially in the result with the microwave power input of 1.0 W. At the range of the frequency of 4.6-5.2 GHz, where the effect of the loss to the wall is not so strong, the ion production cost increased with extending the distance. This increase is not apparent with higher microwave power input, but it is because the plasma density increased.


(a) P_{FWD} : 1.0W

(b) P_{FWD} : 1.5 W

(c) P_{FWD} : 2.0 W

(d) P_{FWD} : 2.5 W

Figure 3 Microwave frequency versus ion production cost. The distance in the legends: 2.5 mm, 3 mm, 4 mm, and 5 mm, are the distance between the screen grid and the magnet. The points where the plasma was not kept are shown as the point that the ionization cost is 400 W/A. The error bars are only shown in 3 mm, whose experiments were conducted twice. The others were conducted once. (a) The microwave power input of 1.0 W, (b) The microwave power input of 1.5 W, (c) The microwave power input of 2.0 W, (d) The microwave Power input of 2.5 W.

B. Power Loss Ratio

The power loss ratio at the microwave frequency of 1.5 W is shown in Fig. 4 (a). The power loss ratio changes with the microwave frequency and the trend of the peak frequency is different from each condition of the distance between the screen grid and the magnet.

The power loss ratio with the distance of 4 mm is shown in Fig. 4 (b). The higher the microwave power input was, the lower the power loss ratio was. It simply means that the high-density plasma can absorb the microwave power efficiently. On the other hand, the peak frequency of the power ratio does not change with the power. It means the plasma density has little effect on the peak frequency.

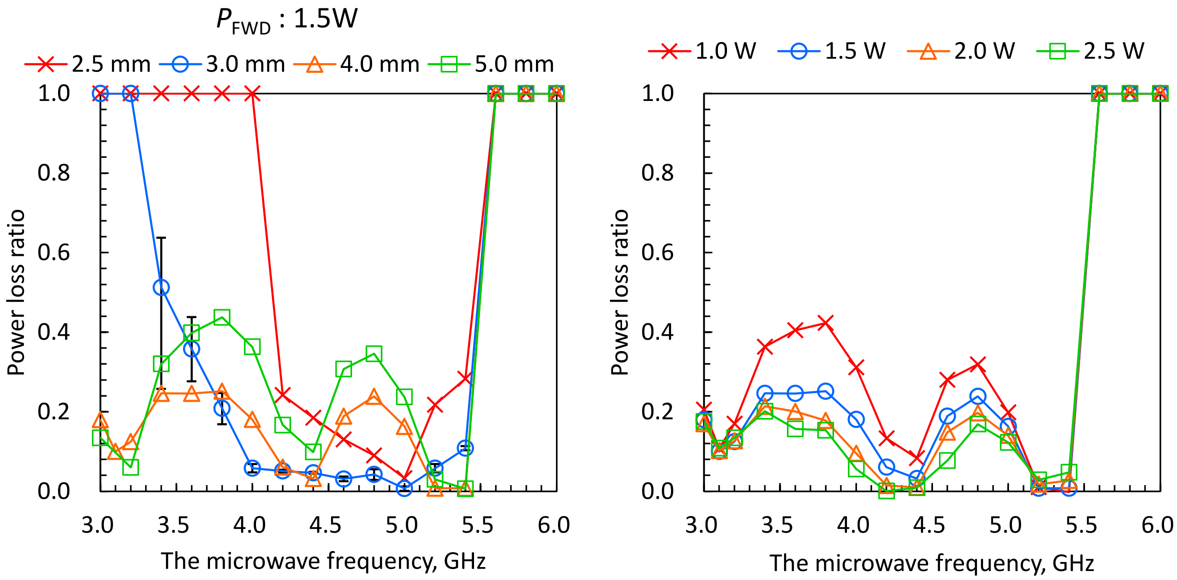


Figure 4 Power loss ratio versus the microwave frequency. (a) Result when the microwave power input of 1.5 W. The distance in the legends are the distance between the screen grid and the magnet. The error bars are only shown in 3 mm, whose experiments were conducted twice. The others were conducted once. (b) Result when the distance between the screen grid and the magnet of 4.0 mm. The power in the legends are the microwave power input. Every experiment was conducted once, therefore, no error bar is shown.

IV. Conclusion

The experiment which changes the microwave frequency for generating the plasma and the distance between the screen grid and the antenna was conducted to improve the performance and to reveal the effect of these changes. The lowest ion production cost is 1.4×10^2 W/A at the microwave power is 1.0 W and the distance between the screen grid and the magnet is 2.5 mm. It achieved 30 % reduction than that of the previous research.

The effect of the loss to the wall and the distance between the plasma and the screen grid were observed, and these show some criteria required to the design. It is also revealed that the power loss ratio is strongly related to the plasma density, as expected. On the other hand, the plasma density has little effect on the peak frequency of the power loss ratio. These knowledge are useful to re-design and optimize the ion source or the neutralizer, and the optimization would increase the performance more.

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