Development of a miniature microwave discharge neutralizer for miniature ion engines

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Abstract: For the improvement of the performance of a miniature microwave discharge neutralizer, the dependencies of the performance of a neutralizer on the microwave frequency, magnetic field strength, antenna length among other factors were investigated. Extracted electron current depend on magnetic field strength and microwave frequency, and the optimal magnetic field depends on the operational condition. Overall, extracted electron current was achieved 19 mA at xenon mass flow rate of 5 μg/s, incident microwave power of 2 W and collector applied voltage of 30 V. The demonstrated performance is enough for practical use as a 30 W class microwave discharge ion engine for 50 kg class satellites.

I. Introduction

There have been many missions using ion engine as a main propulsion, such as Deep Space I,[1] HAYABUSA,[2] and others,[3] and these missions showed usefulness of the ion engine. The ion engine is one of the breakthroughs in Space applications.

The adoption of small satellites, with their flexibility, short development time and low cost, has also been a breakthrough in space applications. Until recently, however, size restrictions have limited the capacity of the available propulsion systems and this degrades the ability of the small satellites. Hence, the demand of mN class miniature propulsion systems drives the development of miniature propulsion system. So, there have been many studies in Europe, the United States, Japan, among other countries. [4-12] One of the candidates of small propulsion system is miniature ion engine, since it offers high specific impulse, 3000 sec and high thrust efficiency, 60-70%.

There are many types of ion sources, conventional electron bombardment type ion source, RF discharge ion source, microwave discharge ion source. We focus on microwave discharge ion source, since it has a potential to have a long lifetime to be simpler system than conventional electron bombardment-type ion source system.

Therefore, we have been developed a miniature microwave discharge ion engine, an ion thruster head and a neutralizer. Ion beam was extracted from the ion thruster head and electron beam was extracted from the neutralizer for neutralize ion beam extracted from ion thruster head. Since the ion engine consists of ion thruster head, in which ion beam was extracted and neutralizer, in which electron beam was extracted.

The thruster performance, propellant utilization efficiency, ion beam production cost, estimated thrust, estimated specific impulse and estimated thrust efficiency are 0.91, 610 W/A, 0.79 mN, 4,100 sec and 0.57, respectively, at $\dot{m}$ =0.018 mg/s, and P_i = 8 W. The above results demonstrate the possibility of practical application of the miniature microwave discharge ion engine. [12)]

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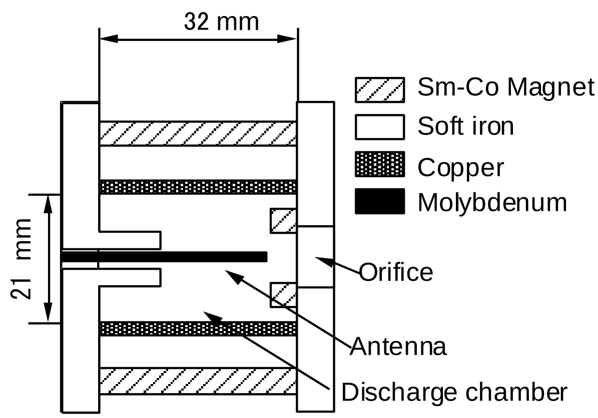

Figure 1. Cross section of a miniature microwave discharge neutralizer.

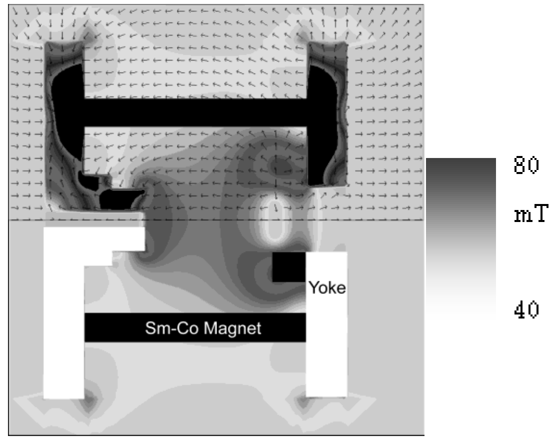

Figure 2. Magnetic field distribution of a miniature microwave discharge neutralizer.

There are candidates as a neutralizer of the ion thruster head; a field emission cathode, [13] a filament cathode, IC cathode, [9] a microwave discharge cathode[14] and a hollow cathode. The microwave discharge cathode has advantages; it has a longer lifetime than the filament cathode and the hollow cathode, since it would be free from contamination and degradation of its electron emission capacity. In addition, an ion engine system can be simple because microwave source can be shared with thruster head. A miniature microwave discharge neutralizer is under development, although it has thus far shown poor performance, with an electron current of 15 mA, an incident microwave power of 4 W and a xenon mass flow rate of 0.005 mg/s. For practical application, we have to improve its performance, the extracted current of 12 mA can be achieved at incident microwave power of 2 W.

Therefore, we investigate the dependency of the extracted current on the microwave emitting antenna length, the orifice diameter, the magnetic field strength for improvement of the neutralizer performance. The target is that extracted electron current achieve 12 mA /s, at mass flow rate of 5 μg/s and incident microwave power of 2 W.

II. Experimental setup

The cross section of the miniature microwave discharge neutralizer developed at Kyushu University is shown in Fig. 1. The inner diameter of the discharge chamber is 21 mm and the length is 32 mm. The ion source consists of an antenna and a magnetic circuit, which consists of several samarium cobalt (Sm-Co) permanent magnets and iron yokes. The magnetic field strength inside the discharge chamber can be changed by changing the number of the permanent magnets (4 mm×4 mm×32 mm), which set around the discharge chamber. The magnetic field distribution with six Sm-Co magnets at outside of the discharge chamber and three magnets (4 mm×4 mm×4 mm) on the front yoke is shown in Fig. 2. A magnetic mirrors are located at the tip of a central yoke and three permanent magnets on the front yoke. Electrons are trapped in the region between magnetic mirrors and go back and force between two magnetic mirrors for effective ionization.

Two microwave power amplifiers were used for this experiment. One can be used at 900 MHz, 1200 MHz and 1600 MHz. and the other, at 2450 MHz. Microwave power is fed through a coaxial line into the antenna. A linear antenna is used, the length of the antenna can be changed. It is made of Molybdenum. The diameter of the antenna is 1 mm. Electrons are collected by a collector. It is at 10 mm downstream of the neutralizer and is applied +30 V at the collector against the neutralizer. The collector voltage can be changed.

High-purity (99.9995%) xenon gas was used as the propellant. A thermal mass flow controller was used. The flow rate error is less than 5% for most of the conditions. A 0.6 m diameter by 1 m long vacuum chamber was used in the experiments. The pumping system comprised a turbo molecular pump with overall pumping speed of 520 l/s for air.

For measurement of the loss at the antenna, the ion saturation current into the antenna was measured. To apply DC voltage to the antenna, bias-T was used to separate DC current from RF current. The insertion loss of bias-T is 0.4 dB and the maximum bias voltage and the maximum microwave power are 50 V and 25 W, respectively. We applied -50 V at the antenna for the measurement of the ion saturation current into the antenna. We confirmed that the ion currents are saturated at -50 V.

III. Results and discussion

A. Dependency on antenna length

Figure 3 shows the dependence of the extracted electron current on the antenna length. The electron current increase with the antenna length below 29 nm, and then decease with the antenna length. The maximum current is 19.2 mA at the antenna lengths of 27 mm and 29 mm. beyond 31 mm, the current suddenly decreases from 19.2 to 16.6 mA, and then slightly decreases with the increase in the antenna length. At 31 mm, the axial position of the tip of the antenna is the same as the tip of the permanent magnets on the front yoke. So strong electric field produced by the microwaves will not applied ionization zone, which is in the region between the central yoke and front yoke magnets. And the antenna length is shorter than 25 mm, it is almost the same position of the front yoke side ECR layer. Therefore, the effective microwaves-plasma coupling would be not expected if the antenna length is below 25 mm.

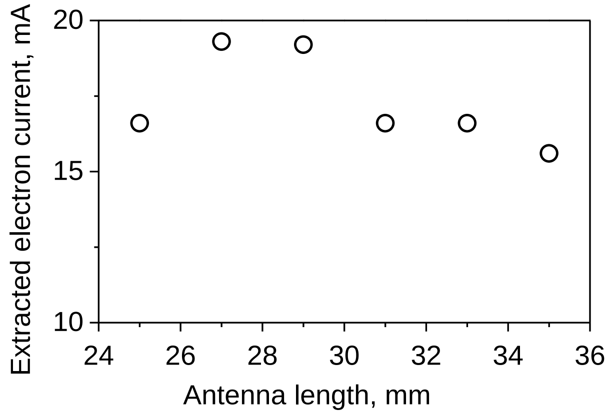

Figure 3. Extracted electron current vs. Antenna length.

B. Dependency on magnetic field strength

Figure 4 shows the extracted electron current vs. incident microwave power for four magnetic field strength, number of magnets of 8, 9, 10 and 11.The microwave frequency is fixed at 1600 MHz and mass flow rate of 5 μg/s. The extracted electron current is maximum with 19.2 mA at the number of magnet of 9, which is beyond our target, 12 mA. This tendency would be due to the trade-off between effective coupling with the microwaves using electron cyclotron resonance and suppression of the diffusion of electrons by magnetic field. The electron cyclotron resonance layer (at B=57 mT, corresponding to the microwave frequency of 1600 MHz) is shown in Fig.5. With increase in the number of magnets expand ECR layer, therefore, electrons gain energy from the microwaves more effectively. And with the Number of magnets of 9, there is an adequate area of ECR layer. With increase in the strength of the magnetic field strength, the diffusion coefficient electrons across the magnetic field line is decreased, it prevent electron extraction from the neutralizer. And in this condition, the optimum number of magnets is nine.

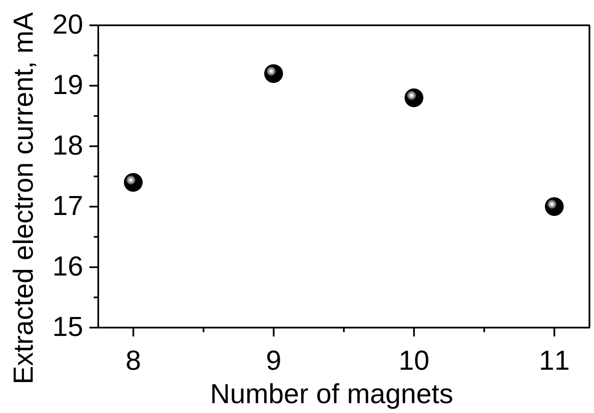

Figure 4. Extracted electron current vs. number of magnets.

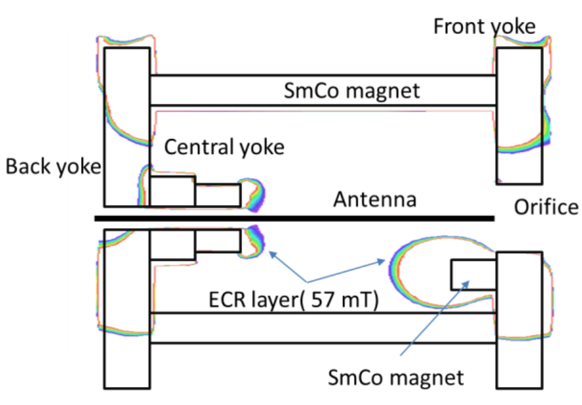

Figure 5. ECR layer with nine magnets, the antenna length is 35 mm.

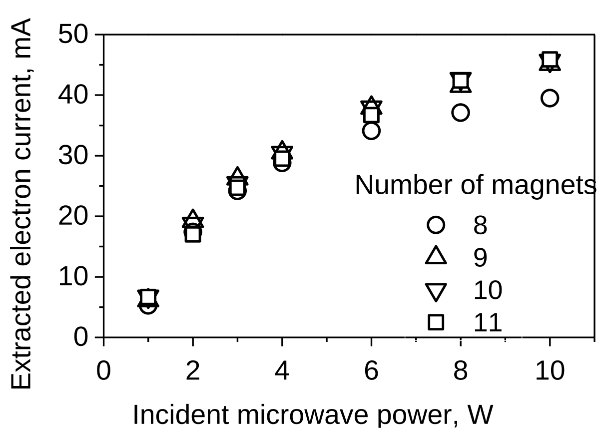

Figure 6. Extracted electron current vs. incident microwave power.

The optimum number of magnets is changed and it depends on operational condition. Figure 6 shows the extracted electron current and the incident microwave power for four number of magnets. The optimum number of magnets is nine below incident microwave of 4 W, and it becomes ten at P_{in} =6 W and at P_{in} >8 W, It is eleven.at that condition, the microwave frequency of 1600 MHz and mass flow rate of 5 μg/s. With the increase in the incident microwave power, the electron temperature inside the discharge chamber would increase, electrons can be extracted against the strong magnetic field.

C. Dependency on microwave frequency

To investigate the dependency of the extracted electron current on the microwave frequency, the extracted electron currents were measured for four frequencies, 900 MHz, 1200 MHz, 1600 MHz and 2450 MHz. As previous sections, we had optimized the antenna length and the number of permanent magnets for each frequency. That is, the optimum antenna length with 900MHz, 1200 MHz, 1600 MHz and 2450 MHz is 29 mm, 29 mm, 29 mm and 31 mm, respectively. The optimum number of magnets with 00MHz, 1200 MHz, 1600 MHz and 2450 MHz is 4, 6, 9 and 15, respectively.

Figure 7 shows the relation between the microwave frequency and the extracted electron current at incident microwave power of 2 W and mass flow rate of 5 μg/s. the extracted electron current increase with the increase with the microwave frequency below 1600 MHz, and decrease beyond 1600 MHz; the current becomes maximum at 1600 MHz and it is 19.2 mA. The minimum current is 7.7 mA at microwave frequency of 2450 MHz. However, if the incident microwave power is larger than 10 W, the extracted electron current increases with the increase in the microwave frequency and the best frequency is 2450 MHz among all, as shown in Fig. 8.

The reasons of these results are as follows. Under the low incident microwave power condition, the average electron energy is low, this results in too strong magnetic field suppress the extraction of the electron. Therefore, the performance of 2450 MHz is worst of all. On the other hand, if the electron average energy is enough high, that is Pin≥10 W, confirmation by the strong magnetic field suppress the loss on walls(discharge chamber wall, antenna, yoke, magnets), therefore, 2450 MHz is best of all. The same effect should be seen when the mass flow rate is increased. Indeed, when the mass flow rate of 10 μg/s and the incident microwave power of 6 W, the extracted current with 1200 MHz, 1600 MHz and 2450 MHz is 34.8, 47.5 and 49.6 mA, respectively. For the 10 mA class neutralizer, the best frequency is 1600 MHz, and for a high current required neutralizer, the frequency should be 2450 MHz or more.

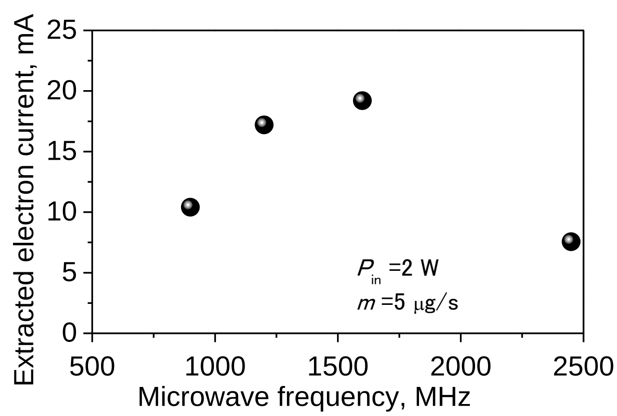

Figure 7. Dependency of Extracted electron current on microwave frequency.

The optimum parameters for our target neutralizer are as follows, the antenna length is 29 mm, the number of magnets is 9, and the microwave frequency is 1600

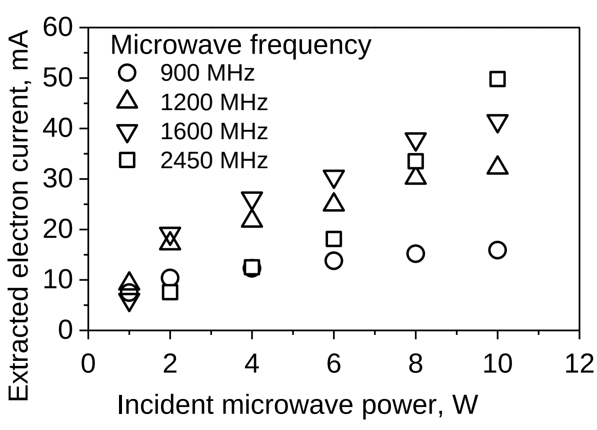

Figure 8. Extracted electron current vs. incident microwave power for four microwave frequencies.

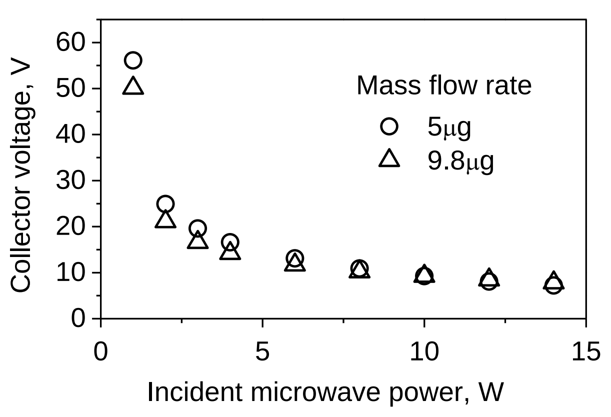

Figure 9. Dependency of collector voltage on incident microwave power.

MHz. Under the condition, with 12 mA extracted current, we observed the collector voltage vs. incident microwave power, as shown in Fig.9. At 1 W, the collector voltage is 56 V, it is not adequate, since it is beyond the sputtering threshold of Mo. The collector voltage, however, decreases to 25 V incident microwave power of 2 W. There is little difference whether the mass flow rate of 5 μg/s or 9.8 μg/s.

D. Dependency on mass flow rate

For the high current neutralizer, we investigates the relation between the extracted electron current and the mass flow rate. Figure 10 shows the relation between the extracted electron current and the incident microwave power for four mass flow rate, 5.0, 9.8, 20, 29 μg/s. The microwave frequency is set at 2450 MHz.

When incident microwave power is less than 4 W, the differences are little, but the currents with mass flow rates of 20 and 29μg/s jump from 4 W to 6 W; the extracted currents of 20 and 29 μg/s is 66.5 mA and 82.2 mA, respectively. At this time, the mode would change to so-called plume mode.

The difference between 20 and 29μg/s can be seen at P_{in} < 10 W, but P_{in} >10 W, there is little difference between 20 and 29μg/s, 139 mA and 141 mA at P_{in} =14 W. The maximum extracted current of this neutralizer is about 140 mA and this limit would not change by the increase in mass flow rate or incident microwave power. For higher current, we have to re-design the neutralizer,

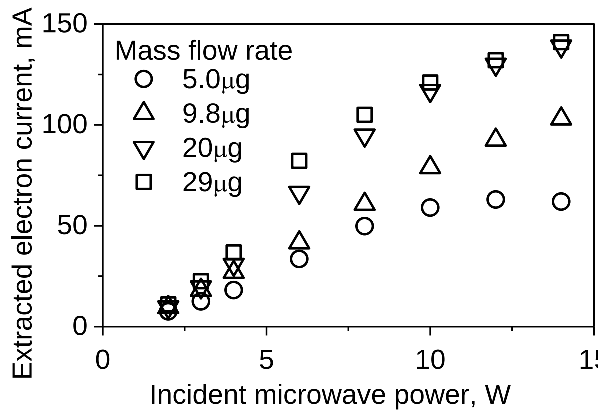

Figure 10. Relation between extracted electron current and incident microwave power for three mass flow rate.

IV. Conclusion

For the development of a microwave discharge neutralizer, the dependency of the extracted electron current on various parameter was investigated for extracting electron current of 12 mA at the incident microwave power of 2 W, mass flow rate of 5 μg/s and the collector voltage of 30 V. The extracted electron current depends on the antenna length, the magnetic field strength and the microwave frequency. These parameters are optimized and the extracted current is 19.2 mA at mass flow rate of 5 μg/s, incident microwave power of 2 W collector voltage of 30 V The optimum microwave frequency for our goal is 1600 MHz, the antenna length is 29 mm and the number of magnets is nine. At this condition, the collector voltage is 12 V if the extracted current is fixed at 12 mA, this result shows the neutralizer can be used for practical application.

With microwave discharge ion thruster head developed at Kyushu University, the performance of the ion engine, thrust, specific impulse and the thrust efficiency, are 0.79 mN, 3100 sec and 0.44 at total consumption power of 10 W and mass flow rate of 23 μg/s. This ion engine will expand the ability of small satellites.

Acknowledgments

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The following pages are intended to provide examples of the different reference types. You are not required to indicate the type of reference; different types are shown here for illustrative purposes only.

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