Development of a Low Power Micro-Ion Engine Using Microwave Discharge

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Abstract

In this study, we propose a novel micro-ion engine system. Single plasma source is used for both ion beam source and neutralizing electron source. By changing the electrical connection, either operation can be switched. This micro-ion engine system gives translation motion and attitude control to microspacecraft. The major objective of this study is verification of our concept. Small plasma source of 20 mm diameter was developed. Plasma was sustained by microwave power. Using this plasma source, ion beam extraction and electron emission was successively demonstrated.

Introduction

In recent years, microspacecraft have attracted a lot of attentions and many institutes have successfully conducted the fight demonstration of their miniaturized spacecraft of the size 1 kg to 100 kg. In the current stage, their major objectives of the mission are the verification of the successful flight and operation of microspacecraft. As the next stage of the microspacecraft, they will perform more advanced missions which need a propulsion system. Micro propulsion device has been increasingly reauired.[1)] For instance, micro propulsion systems make microspacecraft perform un-loading of the momentum wheel, drag compensation of the atmosphere in very low earth orbits, and formation flight by multiple microspacecraft.

Electric propulsion system can drastically reduce the propellant of propulsion system, and can be suitable for the microspacecraft where the volume and mass are limited. Ione engines are the electric propulsion systems which have high thruster performance, and they have the most flight experiences in the electric propulsions. However, the complicated structures have made the miniaturization difficult. In particular, a discharge cathode and neutralizer are one of the components difficult to be further miniaturized. In an ion engine, generally, they are well miniaturized, and further miniaturization would be difficult.

Here, we propose a novel micro-ion engine system. It consists of multiple identical plasma sources. The plasma was sustained by microwave power, and discharge cathode is not necessary. Each plasma source can be operated as either an ion beam source or a neutralizing electron source. Selection of these operations is conducted by electrical switching of a grid system. We can freely select ion beam extraction or electron emission from one plasma source. Figure 1 shows this conceptual diagram. Here we refer these two operation modes as *ion engine mode* and *neutralizer mode* respectively. These plasma sources

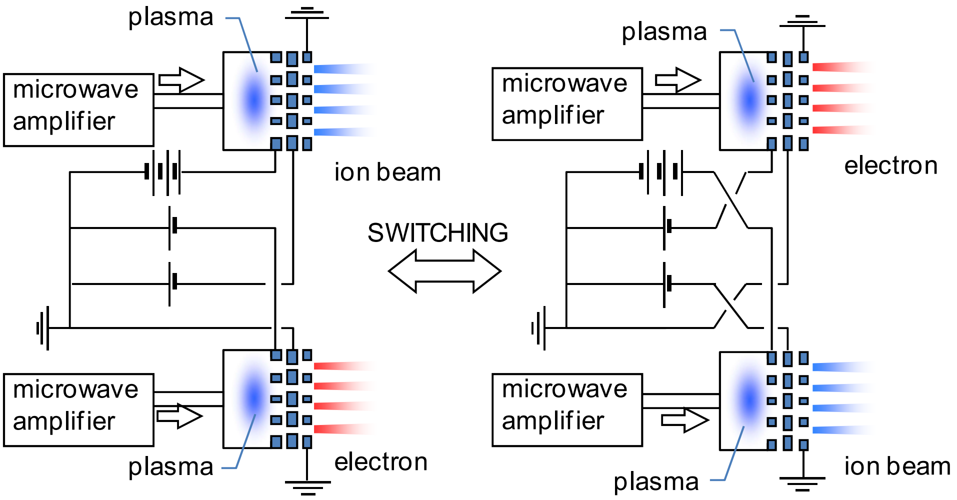

Fig. 1 Conceptual diagram of switching operation of micro-ion engines.

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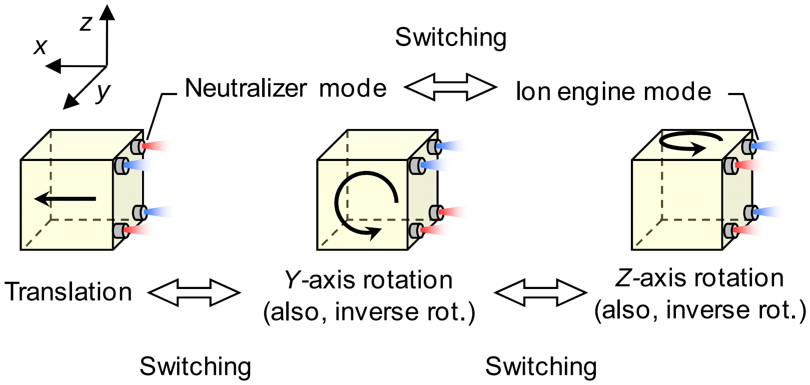


Fig. 2 Conceptual diagram of various motions conducted by operation modes changes of distributed micro-ion engines.

are installed at several points on the spacecraft. Of these sources, only plasma sources with ion engine mode generate thrust. By selecting the combination of the plasma source of ion engine mode, we can give various motions to the spacecraft. Figure 2 shows an example of the constellation of plasma sources and associated motions enabled by the operation combination. This micro-ion engine system gives spacecraft not only translation motion but also attitude control. In microspacecraft mass and volume allowed for each component is strictly limited, and multiple function device is very attractive. In short, our novel concept proposed here is "micro-ion engine system consisted of distributed plasma sources which can be operated both *ion engine mode* and *neutralizer mode*".

In order to realize our novel micro-ion engine system, we have two major challenges in this study: 1) verification of the switching operation of *ion engine mode* and *neutralizer mode* and 2) low power operation of the plasma source. First, the switching of ion engine mode and neutralizer mode is a key technology of our micro-ion engine system. However, such operation has never conducted. Secondly, our distributed micro-ion engine system requires multiple plasma sources, but the usable power in microspacecraft is small.

Microwave ion engine and its miniaturization

Ion engines using microwave discharge have been developed in Institute of Space and Astronautical Science / Japan Aerospace Exploration Agency.[2)] The ion engines with 10 cm diameter, called as μ10, were employed to the deep space explorer HAYABUSA, and now they are working for the return of HYABUSA to the earth.

Since a few years ago, several researchers have studied a micro-ion engine using microwave discharge.[3,4)] They utilized a plasma source identical with a neutralizer of the ion engine μ10, which is also powered by microwave discharge of about 10 W. They successfully developed micro-ion engines of 10 W class by 2 cm diameter plasma source.

Here we are roughly estimating the specification required to our micro-ion engine system. Our target is 50 – 100 kg microspacecraft with 50 – 100 W electrical power. For propulsion device, we are assuming 10 kg mass and 30 W power. Input power allowed for each plasma source would be less than 2 W, in consideration of multiple plasma sources (~4), transmission loss of microwave (~20%) and efficiency of a microwave amplifier (~40%). Residual power of 4 W is used for ion beam extraction and 1 W for gas feeding system. Therefore the properties of micro-ion engine studied here are input power of less than 2 W and ion beam of 1 – 2 mA and 1.5 kV. This class of ion engine would have 1 cm class discharge chamber. Then we call the micro-ion engine system "μ1", which uses microwave power and has the discharge chamber of about 1 cm .

Experimental set-up and method

Vacuum facilities

Experiments were carried out in a 1.0-m-diam, 1.4-m-long space chamber. The chamber is evacuated by a rotary pump of 1300 L/min and a turbo molecular pump of 800 L/s for N_2. The base pressures during the experiment were $4 – 8 \times 10^{-3}$ Pa at 1.0 sccm Xenon flow. The chamber was made of stainless steel and connected to the ground. The inner wall of the chamber played a role of ion beam target.

Thruster

The plasma source developed here has a 20 mm of diameter and 7.0 mm of height. The bottom of the discharge chamber consists of two ring-shaped magnets. The other side of the chamber is a grid system. It has a two-grid-system consisted of screen and acceleration grids made of stainless steel. They are made from commercially available perforated metals. The grid geometry is shown in Table 1. The main objective of this study is the verification of our proposal, and the grid geometry has not been optimized to our micro-ion engine.

The magnets are axially magnetized samarium-cobalt magnets. The magnetic field has more than

0.15 T which is field strength corresponding to the electron cyclotron resonance frequency of 4.25 GHz. Operating gas was fed through 8 holes opened on a back yoke and between the two magnets. The magnetic field configuration and thruster geometry was shown in Fig. 3. In this study, we compared the four kinds of magnetic configurations as shown in Fig. 3. Based on the kinds of outer magnets and inner magnets, we call the configurations Magnet: 1-1, 2-2, 4-1, and 4-2.

Microwave used here is 4.25 GHz and the input power was ranged from 0 – 20 W. Before the experiment, the relation between reading of the power source and actual input power to the discharge chamber was measured using a power meter. Hence, term referred as “microwave power” in this study means the actual power injected to the discharge chamber (reflected power was not subtracted).

The discharge chamber and a DC block were covered with a shield-case made of aluminum plate (downstream surface) and metal mesh (other surfaces). Working gas was fed through a gas isolator, which was outside of the shield-case.

Table 1 Grid geometry

Grid	Thick (mm)	Diam. (mm)	Gap (mm)	Ap. ratio (%)
Screen	0.5	1.5	0.3	48
Accel.	0.5	1.0		21

Switching of ion engine mode and neutralizer mode

Switching of ion engine mode and neutralizer mode was carried out by changing the electrical connection outside of the chamber. Figure 4 shows the electrical connection of both modes. All the

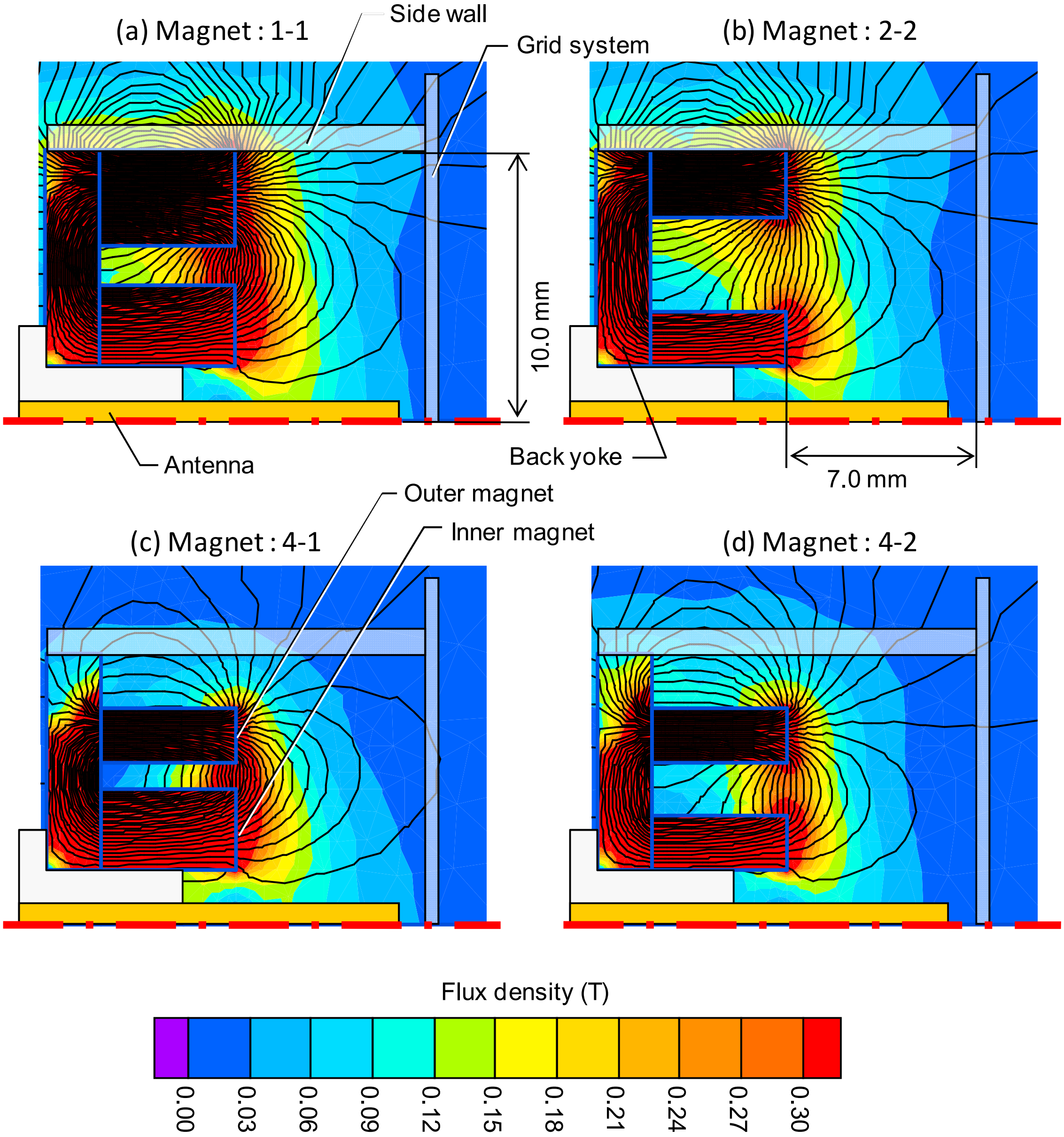
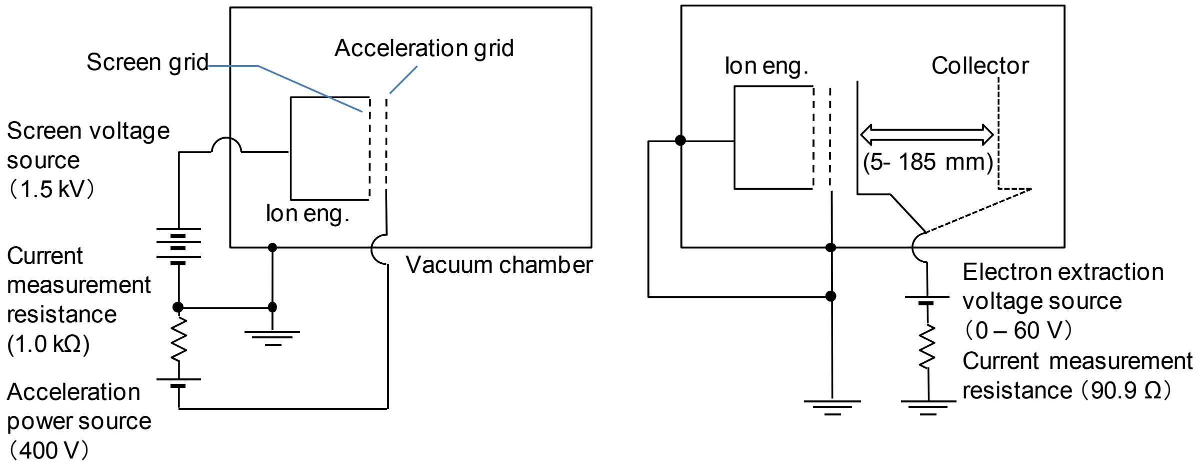


Fig. 3 Magnetic field configurations used in this study.



(a) ion engine mode
(ion beam extraction)

(b) neutralizer mode
(electron emission)

Fig. 4 Electrical circuit diagrams of ion engine mode and neutralizer mode.

experiment of both modes was conducted in series without exposing the chamber to the atmosphere.

In ion engine mode, grid systems are applied voltage as well as a usual ion engine. Screen grid potential was 1.5 kV and acceleration grid potential was -400 or -500 V. A neutralizer was not used. Chamber wall was sustained to ground potential, through which ion beam current pass.

In neutralizer mode, both grids are connected ground potential. Electron collector plate was placed in front of the plasma source. The position of the collector was changed from 5 to 185 mm toward the downstream. The collector was biased to 0 – 60 V from the ground potential. This voltage was called contact voltage here. Contact voltage of this range is almost similar as the neutralizer of μ10 ion engines on HAYABUSA. In the neutralizer development, it was shown that too high contact voltage lead to drastic erosion on the neutralizer. In this study, hence, the contact voltage was changed in that range.

Results and discussion

Ion engine mode

Figure 5 shows the relation between the input microwave power and measured ion beam current. The ion beam current was calculated by the screen current subtracted acceleration current. The microwave power was swept in 10 – 20 s with recording the screen current, acceleration current, and so on. Sampling rate of the recorder was 5 ms and 2000 – 4000 data were obtained in one seeping operation. The power was divided 50 – 100 parts in the sweeping range. The data sorted in the corresponding power was averaged in each part. Mass flow rate was changed from 0.2 to 1.2 sccm.

The minimum power to sustain the plasma and ion beam extraction was 0.3 to 1.2 W in the case of Magnet: 4-2, corresponding to mass flow rate of 1.2 to 0.3 sccm. Basically ion beam current was monotonically increased with the input power and mass flow rate. Decreasing the input power, plasma was finally extinguished and ion beam extraction stopped. We define this power as minimum power to sustain the plasma.

Surface area of magnetic field strength of 0.15 T is almost same in Magnet: 1-1 and 2-2 and larger than Magnet: 4-1 and 4-2. On the other hand, the exposed area to the plasma is the smallest in the case of Magnets: 4-2. In the view point of plasma heating, large area of 0.15 T field has advantage. In the point of plasma loss, small exposed are has advantage. In Magnet:1-1 and 2-2, the current was higher than other small field shapes, but the minimum power to sustain plasma was more than about 2 W. Magnet: 4-2 showed operation even in small power range.

Rapid increase of the ion beam current around 4 W in the case of Magnet: 1-1 and 2-2 was caused by mode change of the microwave plasma. Sometimes these kinds of changes are observed. The emissive region and color of plasma were changed with the mode change, although detailed difference was unknown.

Neutralizer mode

We successfully operated the plasma source as electron emission source by changing the electrical connection of the system. Figure 6 shows the relation between the input microwave power and measured electron emission current. The data was obtained as well as the ion beam measurement.

Seeing rough trend, electron emission current showed higher current than ion beam in high power region of over 4 W, but lower current in low power region of less than 4 W. This difference would be mode-hop around that power, as well as ion beam extraction. Because our interesting is very low power region, farther improvement is necessary.

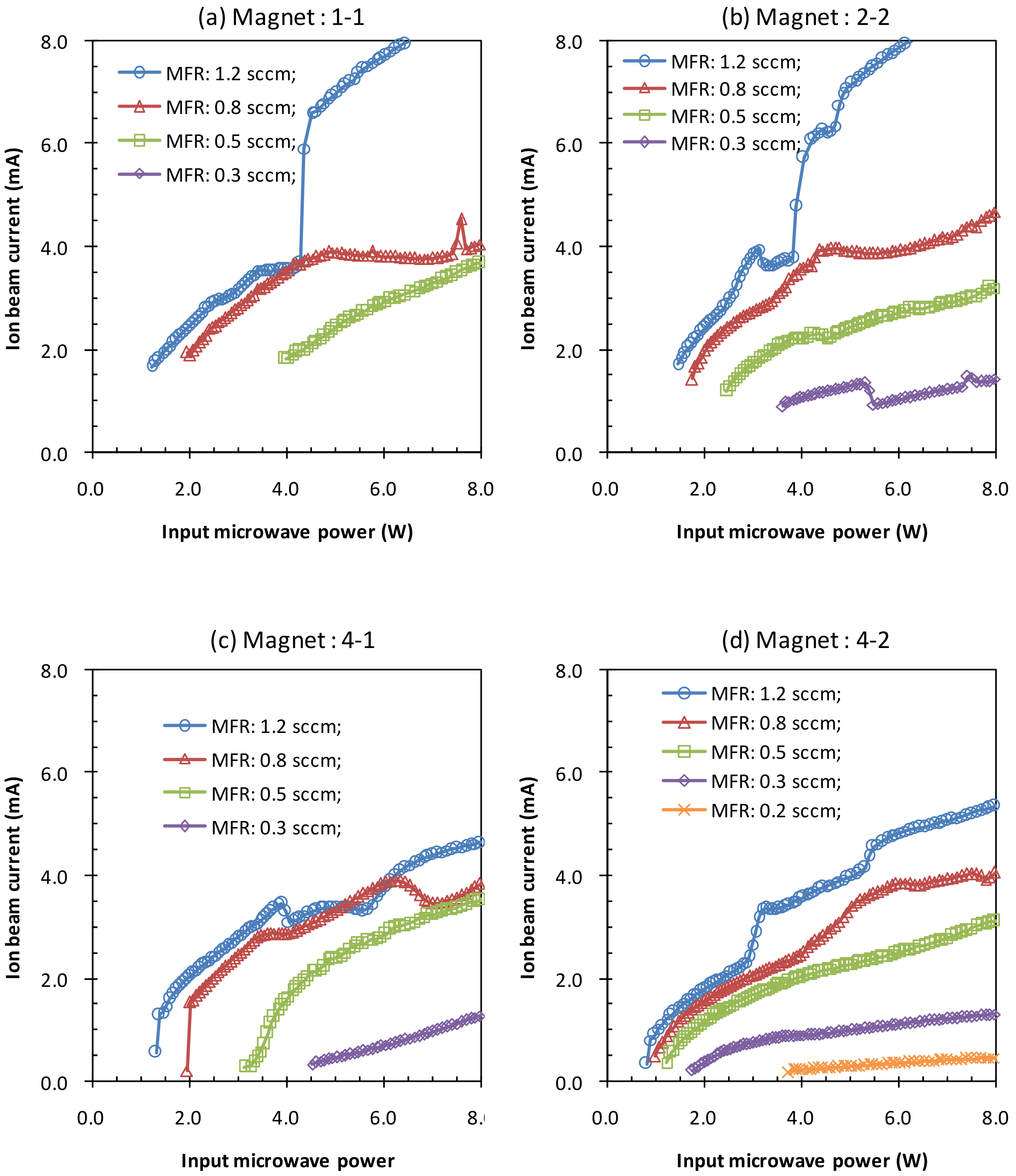


Fig. 5 Dependence of ion beam current on the input microwave power with different magnetic field configuration; (a) Magnet:1-1, (b) Magnet: 2-2, (c) Magnet: 4-1, and (d) Magnet: 4-2.

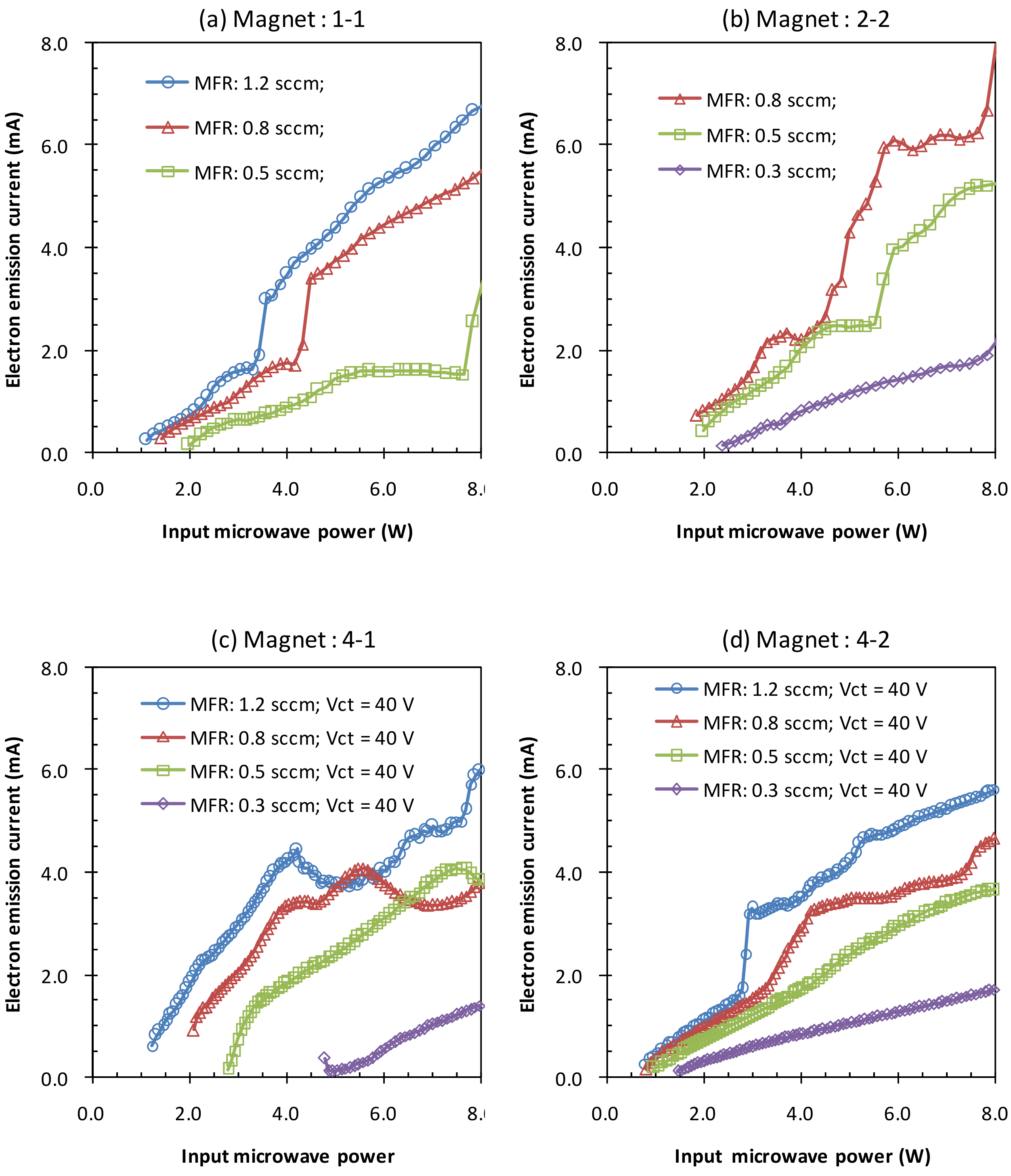


Fig. 6 Dependence of electron emission current on the input microwave power with different magnetic field configuration; (a) Magnet:1-1, (b) Magnet: 2-2, (c) Magnet: 4-1, and (d) Magnet: 4-2. Contact voltage and collector position are (a) 40 V and 5 mm, (b) 40 V and 5 mm, (c) 40 V and 30 mm, and (d) 40 V and 30 mm.

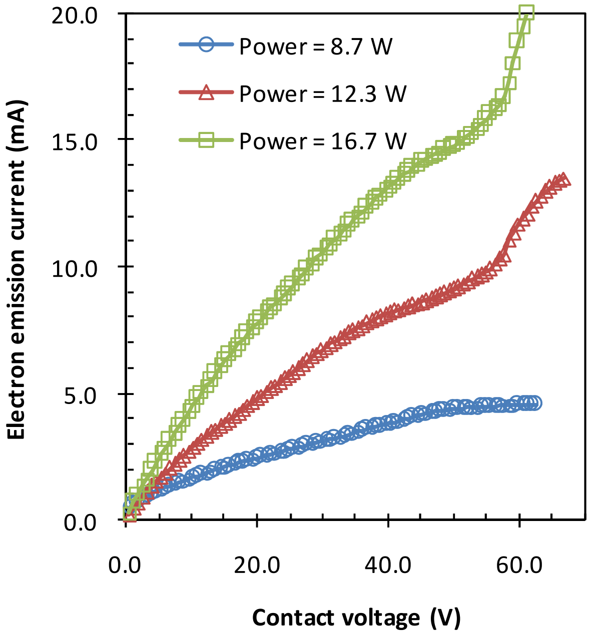


Fig. 7 Contact voltage and emission current at Magnet: 2-2, mass flow rate of 0.5 sccm, and contact collector position of 185 mm.

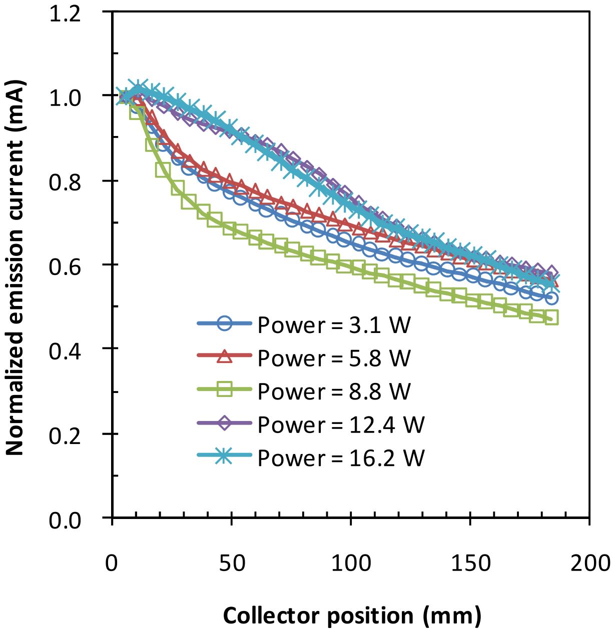


Fig. 8 Collector position and normalized emission current at Magnet: 2-2, mass flow rate of 0.5 sccm, and contact voltage of 40 V

The electron emission current was changed by the contact voltage and collector position. Figures 7 and 8 show the dependence on the contact voltage and collector position at Magnet: 2-2 and 0.5 sccm. Emission current was monotonically increased with the contact voltage. Rapid increase of the current can be shown around 60 V. In some studies of neutralizer, this kind of rapid increase was reported as “knee point”. Usually they are explained by the change to plume mode. Collector position has important meaning in our ion engine. Generally a neutralizer is located to ion beam to give good performance. However, our concept of distributed ion engines are located far apart each other. Our experiment showed the difference of 200 mm caused the decrease of 40 % of emission ability.

Mass flow rate

In all the experiment, mass flow rate of the operating gas was as high as 0.3 to 1.2 sccm to extract current in our interesting range. This high mass flow rate leads to very low specific impulse and does not suited with the micro-ion engine, µ1. One of the reasons is too high aperture ratio of acceleration grid. The major objective of this work is the verification of our concept, and not performance optimization. To reduce the mass flow rate, acceleration grid with smaller hole-diameter must be employed.

Conclusion

In this study, we propose a novel micro-ion engine system, µ1. Single plasma source is used for both ion beam source and neutralizing electron source. By changing the electrical connection, either operation can be switched. This micro-ion engine system can give various kinds of motion to microspacecraft, and reduce the other component. The major objective of this study is verification of the switching operation. Small plasma source of 20 mm diameter was developed. Plasma was sustained by microwave power. Using this engine, ion beam extraction and electron emission was successively demonstrated from one plasma source. Also, it was shown that minimum power for the operation was reduced to less than 2 W.

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