Performance Evaluation of a Miniature Ion Thruster µ1 with a Unipolar and Bipolar Operation

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Abstract: This study shows the system performances of 10-W-class miniature ion thrusters designed for 50 kg small spacecraft. The remarkable feature is that the ion thruster system includes a miniature neutralizer and it has two operational modes with respect to the neutralization. One is a conventional method installing a miniature neutralizer and we call this as a unipolar ion thruster, contrasted with the following bipolar thruster. The other is to use multiple plasma sources and function of an each plasma source is selectable between an ion beam source and neutralizer. The thruster with this operation is referred as to a bipolar operation. In this study, we measured the performance of these thrusters and evaluated the system performance: thrust, total power consumption, and specific impulse. This evaluation includes power and propellant consumptions at the neutralizers and energy conversion losses of the all power processing units. The resulted typical thruster performance is 297 µN thrust with 1100 s specific impulse by 15.1 W total power consumption.

I. Introduction

RESEARCH and development of small spacecraft have extensively grown up in the world and a number of small spacecraft have been successfully launched and operated.1-8) Moreover, an increasing number of planned small spacecraft missions are in need of propulsive capability. Propulsion devices supply the spacecraft with attitude control, station keeping, and orbit transfer. Furthermore, it enables future spacecraft missions such as drag free control from atmospheric or solar pressure, precise constellation flight for interferometer missions, and deorbiting maneuver of end-of-life spacecraft into the atmosphere. The arrival of propulsion devices suitable for small spacecraft, namely micro-propulsion, is awaited.9)

Ion thrusters10) are promising propulsion devices not only for standard-sized spacecraft but also for small spacecraft. Their characteristics of high specific impulse (3000 s), high thrust efficiency (50 %), usage of inert propellant (xenon), and continuously controllable thrust meet the requirements for small spacecraft missions. Several studies on miniature ion thrusters have been conducted to date for several different types of the plasma generators, namely direct current electron discharges,11,12) radio frequency discharges,13) and microwave discharges.14-17)

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In spite of these benefits, however, miniature ion thrusters have not been employed on small spacecraft yet. This is impeded by two reasons. One reason is a severe limitation of the electrical power available on small spacecraft. In general, electrical power available in small spacecraft is roughly proportional to its size and the coefficient is about 1 W/kg. For example, available power in 50 kg small spacecraft was estimated at only 50 W. The miniature ion thrusters developed to date require total power in the range of 30 W at least. The other reason is difficulty of developing a miniature neutralizer suitable for a miniature ion thruster. Neutralizers emit electrons to keep the neutrality of the spacecraft against the ion beam exhaust. The neutralizer dose not generate thrust and they are usually designed to be much smaller than the thruster itself. This implies that further miniaturization, including power and propellant saving, of the neutralizer is more difficult than ion beam source itself.

In order to solve the first problem, the authors developed a miniature ECR(Electron Cyclotron Resonance) discharge ion beam source driven by 1.0 W microwave power and 6.0 W ion acceleration power.[18,19] This ion source has the 250 W/A ion production cost and 37 % mass utilization efficiency for 1.0 W microwave input power and 14.6 µg/s xenon mass flow. Usage of this ion source would realize an ion thruster system of the total power consumption of 10 – 30 W, if it is coupled with the adequate neutralizer having small size, low power, and low propellant consumption

To the second neutralizer problem, the authors have approached by two methods. One is to develop a small neutralizer by converting the low power ion beam source as an electron source[20]. The suitable size and position of the orifice were revealed to extract electrons from that discharge chamber and a miniature neutralizer was developed.[21,22] This neutralizer was driven by the same microwave power and half of the gas flow as the above-mentioned ion source. An ion thruster using the set of this ion beam source and neutralizer is named as µ1 ("mu-one"). This is the smallest ion thruster in the "µ" series of ion thrusters developed in ISAS of JAXA.[23-25] Especially, we refer this ion thruster as to "unipolar µ1 ion thruster" and its operation as to "unipolar operation" as contrasted to with the following operation.

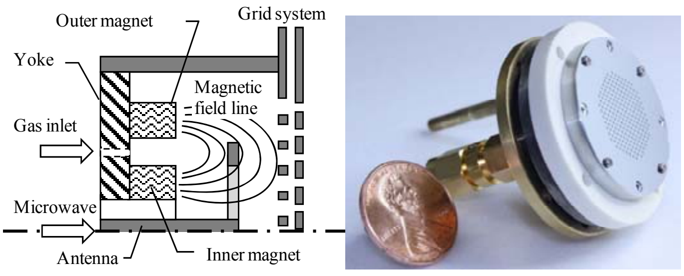
As the other approach, we proposed a bipolar operation[26]. This operation concept is based on the usage of an unoperated ion thruster as a neutralizer for another operated ion thruster. Multiple ion thrusters are installed on spacecraft and each thruster is used as either an ion beam source or a neutralizing electron source. The operational mode is selected by outside electrical connections. The advantage of this operation is to eliminate a device dedicated for a neutralizer, in short, weight reduction of the system. To realize this unique operation, we need special designed grid system. We are referring this operation as a bipolar operation and this is another operation source mode of the miniature ion thruster µ1. We refer the ion thrust using this operation as to "bipolar µ1 ion thruster" and its operation as to "bipolar operation."

The objective of this study is to evaluate the system performances of µ1 ion thrusters for both of unipolar and bipolar operation. Here system performance means the thrust, power consumption, and specific impulse. The remarkable point is that power and propellant consumption by the neutralizer was included in those evaluations. To date, there has been few studies of miniature ion thrusters evaluating those total performances and these information are useful and inevitable for actual mission design of small spacecraft.

II. Experimental setup

A. Microwave discharge chamber

The µ1 ion thruster has a discharge chamber of cylindrical shape with 20-mm-inner diameter. The schematic illustration and picture of the discharge chamber is shown in Fig. 1. Microwave power of 4.20 GHz is introduced into the chamber to generate plasma. Introduced microwave were matched to the plasma impedance and any matching device was not installed. The microwave power line is isolated from the ground potential by a DC-block. Two ring-shaped permanent magnets are installed on the bottom of the chamber. The magnets form a maximum magnetic field of 0.30 T on the magnet surface and minimum field of 0.05 T at the furthest point from the magnet. The electron cyclotron resonance for 4.20 GHz microwave occurs at the magnetic field strength



(a) (b)

Fig. 1 Schematic illustration and picture of a miniature ion beam source

of 0.15 T. The magnetic field represents a magnetic bottle which inhibits electron loss. Working gas (xenon) was fed through holes in the yoke plate and between the two magnets. A gas isolator was installed between the thruster and the gas feeding system. Mass flow rate was controlled using a mass flow controller for xenon with a maximum flow rate of 98 μg/s for xenon and accuracy of ±1% with respect to the maximum flow rate.

Table 1 grid geometries

Grid or orifice		Thickness, mm	Diameter, mm	Gap, mm	Number of holes
Unipolar ion grid	Screen	0.20	0.80	0.25	211
	Accel.	0.30	0.40		
Electron emission orifice		0.80	1.80	NA	6
Bipolar ion grid	Screen A	0.20	0.72	0.25	169
	Screen B		2.20		6
	Accel. A	0.40	0.40		169
	Accel. B		1.80		6

B. Unipolar μ1 ion thruster

An ion beam source of the unipolar μ1 ion thruster has a two-grid ion accelerator system. The grid system is placed across the downstream end of the microwave discharge chamber. The grids are made of molybdenum by chemically etching 211 apertures within a 16 mm diameter region. Detailed grid geometries are shown in Table 1. This grid system is referred herein as "unipolar ion grid" to distinguish it from the after-mentioned "bipolar ion grid". Voltages of screen and accelerator grids were set at 1500V and -350 V respectively.

A neutralizer of the unipolar μ1 ion thruster is developed by replacing the unipolar grid system to an orifice plate with six apertures of 1.8 mm diameter. The orifice is made of aluminum and its thickness is 0.8 mm. This orifice plate is referred herein as "electron emission orifice". Electrons are emitted from the neutralizer by applying negative bias voltage of 0-100 V to the neutralizer. This bias negative voltage is called as contact voltage.

C. Bipolar μ1 ion thruster

The bipolar μ1 ion thruster has a special grid system to achieve both of the ion beam extraction and electron emission. The grid system has two different size apertures, that is, 169 small apertures for ion beam extraction and six large apertures for electron emission. This grid is referred herein as to "bipolar ion grid". When the thruster is operated as ion beam source, voltages of 1500V and -350 V are applied at the screen and accelerator grids respectively. When it is operated as a neutralizer, both grids are set at the contact voltage, depending on the required electron current.

In this study, we utilized one unipolar μ1 thruster and two bipolar μ1 ion thrusters. The unipolar ion thruster consists of an ion beam source and a neutralizer. We refer this thruster as to simply "μ1". The two bipolar thrusters have an identical design. We refer one thruster as "μ1A" and the other as "μ1B". Both of the μ1A and μ1B can be operated as an ion beam source or a neutralizer and there is no device dedicated for neutralization.. Each operation is referred as to "ion source mode" and "neutralizer mode".

D. Vacuum facilities

All the experiments were carried out in a 1.0-m-diameter, 1.4-m-long vacuum chamber. The chamber is evacuated by a rotary pump of 1300 L/min and a turbo molecular pump of 800 L/s for N2. The operating pressures during the experiment were between 4–8×10^{-3} Pa at 50 μg/s xenon flow. The chamber is made of stainless steel and is used as the ground reference for all tests.

III. Experimental method and performance evaluation

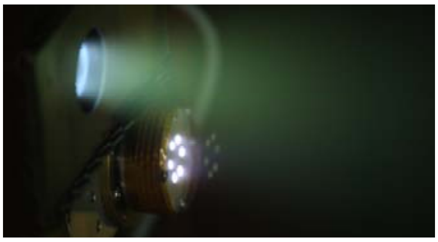
A. Neutralization

In this study, all of the ion thrusters were operated under neutralization. Here neutralization means that ion beam current is equal to the electron current. To check this neutralization, ion thruster system was isolated from the ground line and those are connected only by a 1.0 kΩ resistance. Fig. 2 shows the electrical connections for both of the unipolar operation and bipolar operation. For the both configurations, the discrepancy of ion current and electron current appears as a current passing through the 1.0 kΩ resistance. This current is called as ground return current. Contact voltage of the neutralizer was automatically controlled to minimize the magnitude of the ground return current by feedback circuit. Residual error of the ground return current was typically around 0.01 mA.

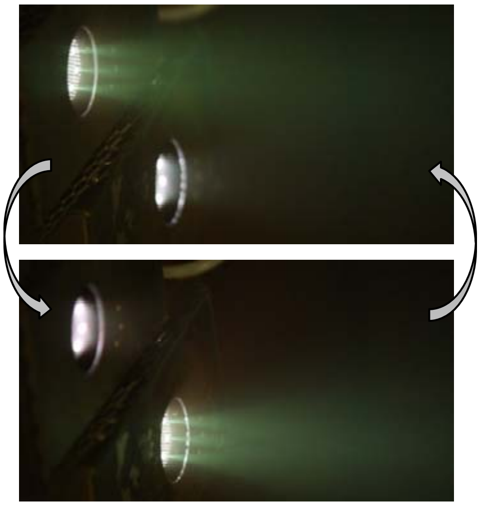
It should be cared that the terminology of neutralization, in this study, does not mean that emitted electrons go to and mix up with ion beam. The above-mentioned neutralization just means the same amount of ion and electron current are emitted. Fig. 3 shows the operational views of the unipolar thruster and bipolar thruster.

B. Measurement of ion beam current and contact voltage

Input microwave powers to both of the ion thruster and the neutralizer were kept at the same power. Those microwave powers were swept continuously between 0 and 4 W and their dependences on the other parameters were measured. First, the microwave powers were set around 0.5 W, then they were increased gradually up to 4.0 W, and finally decreased again to around 0.5 W. The sweeping speed

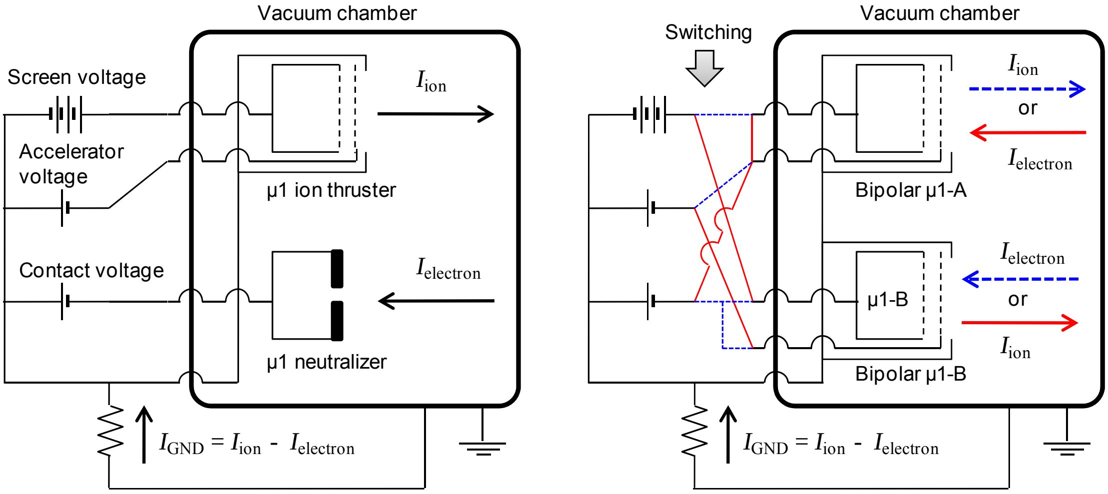


(a) unipolar μ1 ion engine



(b) bipolar μ1 ion engine

Fig. 3 Operational view of the ion thrusters; (a) unipolar operation and (b) bipolar operation.



(a) Unipolar operation

(b) Bipolar operation

Fig. 2 Electrical connections of the ion thrusters; (a) unipolar operation and (b) bipolar operation.

was 0.1 W/s. During sweeping, the screen current, accelerator current, input microwave power, and contact voltage were recorded with a 500-Hz sampling rate. The sweeping power range was divided into one hundred intervals, and data of 4,000–8,000 points were averaged over each interval. During power sweeping, the mass flow rate was fixed. The ion beam current was calculated by subtracting the accelerator current from the screen current. The accelerator current was less than 2.0% with respect to the beam current in the power over 1.0 W and less than 10 % in a power region below 1.0 W.

Table 2 Assumptions of the power sources

Type of output	Typical output	Energy efficiency η
Beam voltage	1.5 kV, 5 mA	0.75
Accelerator voltage	-350 V, 0.1 mA	0.30
Contact voltage	-40 V, 5 mA	0.30
Microwave	4.20 GHz, 3 W	0.45

C. Performance evaluation

Thrust: *T*, total power consumption: *P*, thrust to power ratio: *T/P*, and specific impulse: I_{sp} are calculated by the following equations.

$$T = \gamma_{\mathrm{T}} I_{\mathrm{b}} \sqrt{2MV_{\mathrm{b}}/e} \tag{1}$$

$$P = \frac{P_{\mathrm{i\mu}} + P_{\mathrm{n\mu}}}{\eta_{\mu}} + \frac{V_{\mathrm{b}}(I_{\mathrm{b}} + I_{\mathrm{a}})}{\eta_{\mathrm{b}}} + \frac{V_{\mathrm{a}} I_{\mathrm{a}}}{\eta_{\mathrm{a}}} + \frac{V_{\mathrm{c}} I_{\mathrm{b}}}{\eta_{\mathrm{n}}} \tag{2}$$

$$\mathrm{T/P} = \frac{T}{P} \tag{3}$$

$$I_{\mathrm{sp}} = \frac{T}{(\dot{m}_{\mathrm{i}} + \dot{m}_{\mathrm{n}})g} \tag{4}$$

where e is the element charge, M is the xenon ion mass, g is the gravitational acceleration, $\gamma_{\mathrm{T}}$is the thrust coefficient, I_{b} and I_{a} are the beam current and accelerator current, V_{b}, V_{a}, and V_{c} are the beam voltage (screen voltage), accelerator voltage, and contact voltage, $P_{\mathrm{i\mu}}$ and $P_{\mathrm{n\mu}}$are the input microwave powers to the ion source and the neutralizer, η_{μ}, η_{b}, η_{a}, and η_{n} are the energy conversion efficiencies of power sources, respectively microwave power, screen voltage, accelerator voltage, and contact voltage, $\dot{m}_{\mathrm{i}}$ and $\dot{m}_{\mathrm{n}}$ are the mass flow rate for the ion source and neutralizer.

In the above calculation, thrust coefficient and energy conversion efficiencies were assumed and the others were values measured in this study or physical constants. We used the thrust coefficient of 0.90 based on the assumption of ion beam divergence of 20 degrees and the ratios of doubly charged ion of 0.02. Assumed energy conversion efficiencies of the power sources are listed in Table 2. We have not developed the power processing units for our miniature ion thruster system. The listed values are the specifications of commercially available on-board power sources (DC) and solid state power amplifier under development.

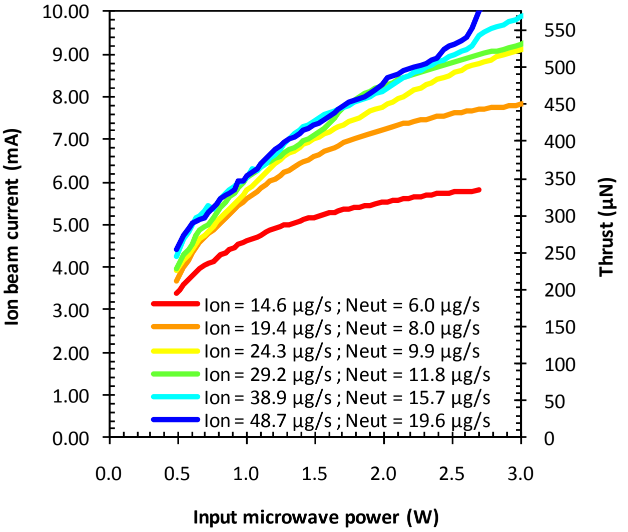


Fig. 4 Ion beam current and thrust of the unipolar ion thruster. In the legend, "ion" and "Neut" mean mass flow rate rates of the ion beam source and the neutralizer respectively. Mass flow rate of the neutralizer was set at 40% of the ion beam source.

IV. Results of the unipolar operation

A. Ion beam current of the unipolar mode

The unipolar ion thruster μ1 generated the ion beam current from 3 to 10 mA depending on the microwave power of 0.5 to 3.0 W. The current dependence on the microwave power and mass flow rate is shown in Fig. 4. For example, the thruster gives ion beam current of 6.58 mA (thrust of 379 μN) at the microwave power of 1.49 W and propellant flow of 19.6 µg/s. This means ion production cost of 226 W/A and propellant utilization efficiency of 46% (including only ion source). Increasing the microwave power resulted in higher beam current and thrust. The ion production cost is the lowest at the minimum microwave power. Increasing the propellant flow rate results in the higher thrust. In this case, however, the current increase shows saturation at over 29.2 µg/s. Here mass flow rate of the neutralizer was set at 40% of the mass flow of the ion beam source. Ion beam current was also measured at different flow rate for the neutralizer (30% and 50%), and it was confirmed that the beam current was not affected by the neutralizer mass flow rate.

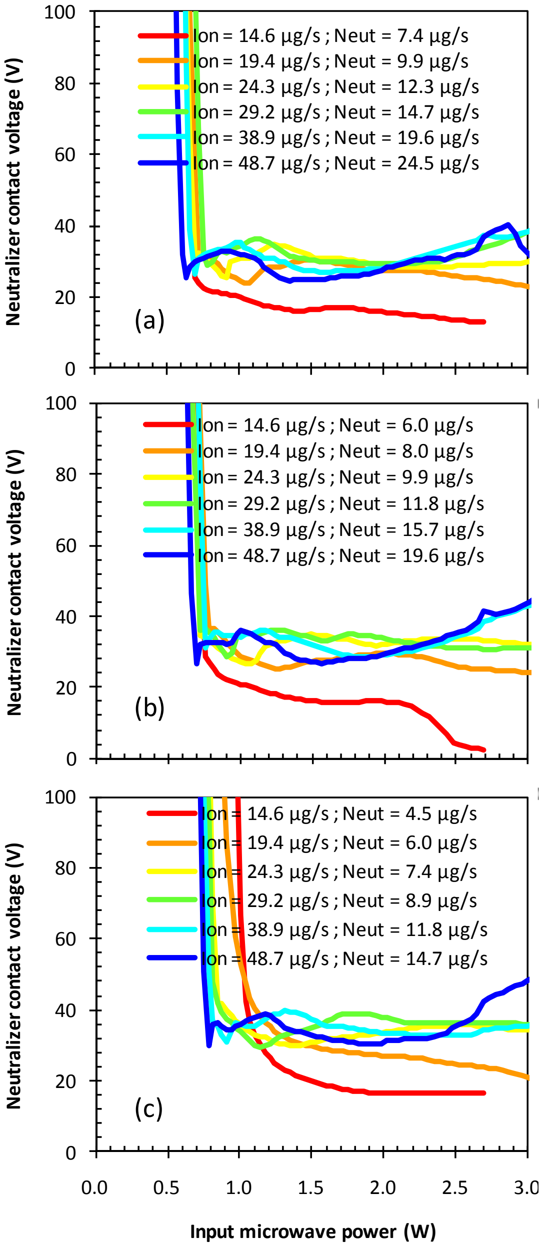


Fig. 5 Contact voltage of the unipolar ion thruster. In the legend, "ion" and "Neut" mean mass flow rate rates of the ion beam source and the neutralizer respectively. Ratio of the neutralizer mass flow rate was set at (a) 50%, (b) 40%, and (c) 30% of the ion beam source. Input microwave powers to the ion source and neutralizer were the same.

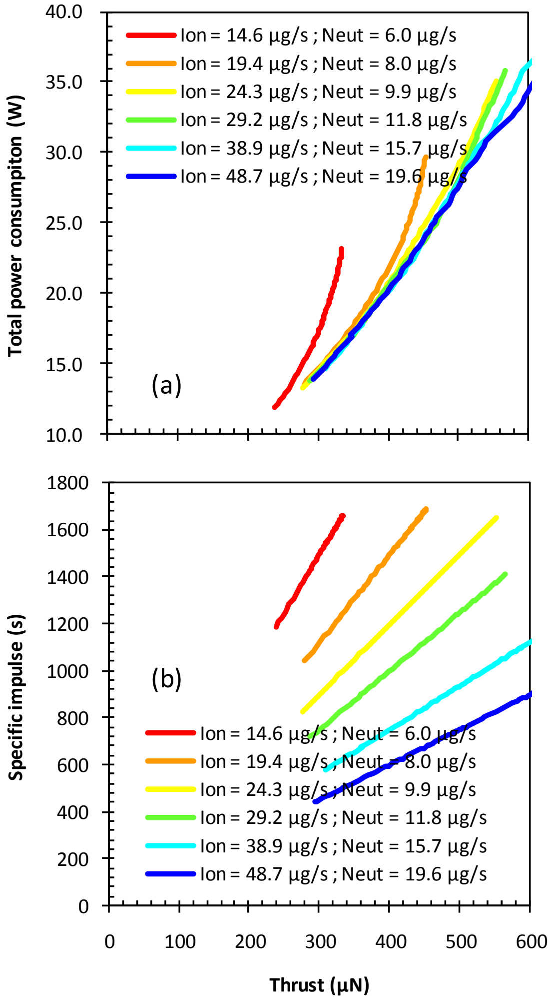


Fig. 6 Thrust vs. total power consumption and specific impulse of the unipolar ion thruster, where the neutralizer power and propellant consumption and energy conversion loss at power sources are included in the calculation. Mass flow rate of the neutralizer was set at 40% of the ion beam source.

B. Contact voltage of the unipolar mode

The neutralizer of μ1 thruster had typical contact voltage between 20–40 V to accomplish the neutralization. The contact voltage is determined by the required electron current and the state of the plasma (by microwave power and mass flow rate) and the beam current itself is changed by the microwave power and mass flow rate. As a result, the contact voltage dependence on the microwave power and mass flow rate was not monotonic. It was shown in Fig. 5, where the mass flow rate of the neutralizer was changed at 30, 40, and 50% of the ion beam current. A common characteristic is the existence of the threshold microwave power for the contact voltage. In all of the case, the contact voltage showed the step increase at a certain point by reducing the microwave power. Below the threshold power, the contact voltage was from 200 to over 400 V. This threshold power increases by decreasing the neutralizer mass flow rate. In the view point of thruster performance, higher mass flow rate of the neutralizer monotonically decreases the specific impulse. However, this result shows too low mass flow rate results in too high contact voltage or operation stop.

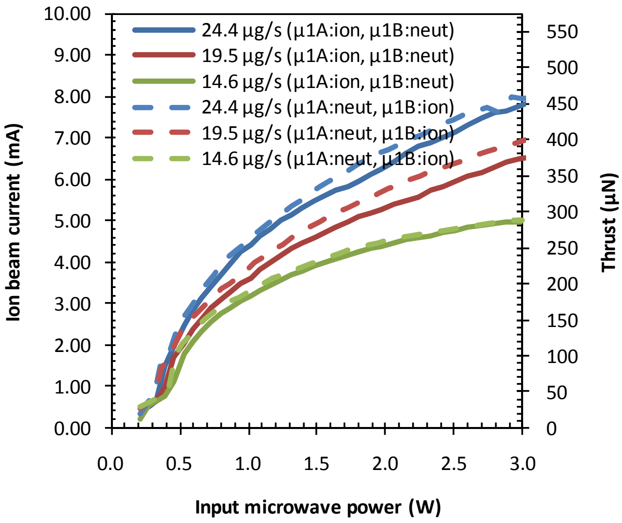


Fig. 7 Ion beam current and thrust of the bipolar ion thruster. In the legend, "ion" and "Neut" mean ion source mode and neutralizer mode respectively. Mass flow rate of the neutralizer was set at 40% of the ion beam source.

C. Thruster performance of the unipolar mode

Using the experimental data of the unipolar ion thruster with the neutralizer mass flow rate of 40%, total power consumption and specific impulse are calculated. The result is summarized in Fig. 6 against the thrust, where power and propellant consumption by the neutralizer and energy conversion loss at power sources are included in the calculation. The total power consumption ranged from 10 to 30 W generating the thrust from 200 to 500 μN and with the specific impulse over 1000 s. For example, an ion thruster generating 379 μN thrust with 1410 s specific impulse was obtained by the total power consumption of 19.9 W. In lower power operation, 297 μN thrust with 1100 s specific impulse was by 15.1 W total power.

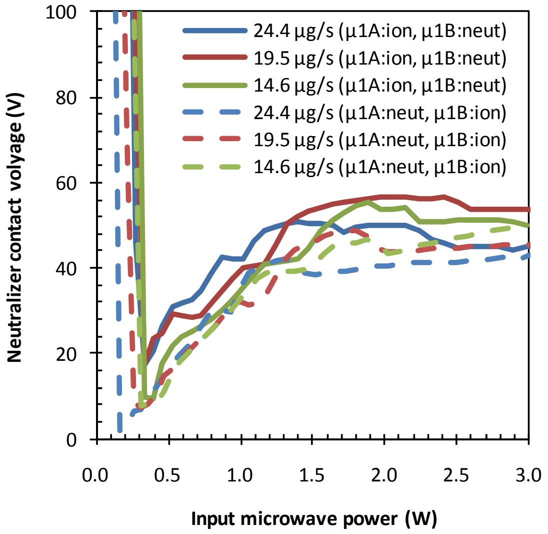


Fig. 8 Contact voltage of the bipolar ion thrusters. In the legend, "ion" and "Neut" mean ion source mode and neutralizer mode respectively. Both thrusters are operated at the same mass flow rate.

V. Results of the bipolar operation

A. Ion beam current and contact voltage of the bipolar mode

Two bipolar ion thrusters, μ1A and μ1B, were placed 100 mm away from each other in parallel to the beam direction. Two sets of ion thruster operations were performed; one is that μ1A is ion source mode and μ1B is neutralizer mode and the other is μ1A is neutralizer mode and μ1B is ion source mode. For both operations, ion beam current are contact voltage were measured as well as the unipolar operation. In the all of the experiment, μ1A and μ1B thrusters consumed the same microwave power and mass flow each other.

Ion beam current of the bipolar ion thrusters were lower by 20-30 % than the unipolar operation. The current dependence on the microwave power and mass flow rate is shown in Fig. 7. In this figure, solid and dashed curves represents the operational mode of the each thruster. For example, the μ1A thruster shows ion beam currents of 4.73 mA at the microwave power of 1.55 W and propellant flow of 19.6 μg/s. The current dependence on the power and mass flow is qualitatively same as the unipolar mode, but the magnitude of the current was lower than the unipolar mode. This would be mainly caused by the geometrical difference of the grid system.

There is a little difference of the currents between μ1A and μ1B at the same mass flow rate. Those two thrusters have the identical design and manufacturing processes, and the beam current should be equal. The authors are considering this difference is caused by slight error of the machining and misalignment of the assembling.

B. Contact voltage of the bipolar mode

The magnitude of the contact voltage of the bipolar thrusters were similar as the unipolar thrusters. Its dependence on the microwave power and mass flow rate is shown in Fig. 8. Too low microwave power leads to a steep increase of the contact voltage as well as the unipolar thruster. The threshold value for this jump is lower than the unipolar thruster. The operation of the neutralizer-mode-bipolar thruster differs from the neutralizer of the unipolar thruster mainly by the required electron current and mass flow rate. Because the bipolar thrusters supplies lower beam current than the unipolar thruster, the electron current required to the neutralizer mode is lower. Mass flow rate of the neutralizer mode is the same as the ion source mode. On the other hand, the neutralizer of the unipolar mode is operated by the 30-50% of the mass flow rate of the ion source. However, this difference would not affect the contact voltage directly, because higher mass flow rate of the bipolar thruster is canceled out by the higher gas conductance of the bipolar grid. Actually, the bipolar grid has the almost twice gas conductance than the electron emission orifice.

C. Thruster performance of the bipolar mode

The thruster performance of the bipolar thrusters are summarized in Fig. 9. The total power consumption ranged from 10 to 30 W generating the thrust from 150 to 400 μN and with the specific impulse between 500–1000 s. For example, an ion thruster generating 300 μN thrust with 780 s specific impulse was realized by the total power consumption of 20 W. Because of the lower beam current, the total performance of the bipolar thruster is lower than the unipolar thruster. The features of the bipolar thruster are the simplicity of the system and resulted light weight. Then this advantage does not appear in the performance shown in Fig. 9. Unipolar mode or bipolar mode, whichever is more superior depends on the mission requirement, that is trade-off between power and weight. In general, the unipolar thruster has higher performance (lower power) heavier weight than the bipolar thruster.

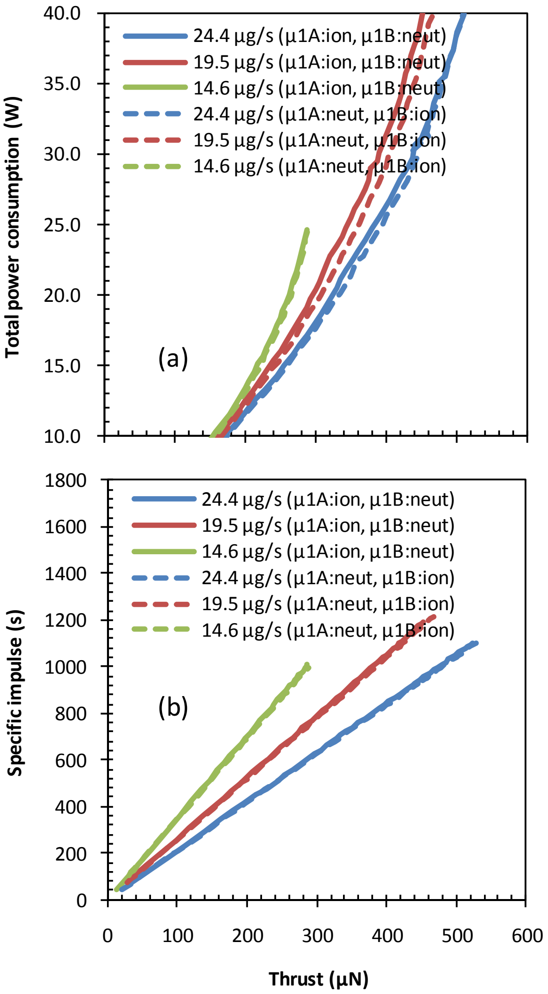


Fig. 9 Thrust vs. total power consumption and specific impulse of the bipolar ion thruster, where the neutralizer power and propellant consumption and energy conversion loss at power sources are included in the calculation. Mass flow rate of the neutralizer was set at 40% of the ion beam source.

VI. Conclusion

The authors have developed miniature ion thrusters suitable for small spacecraft of the 50 kg class. These ion thrusters include a miniature neutralizing system. Two ion thruster systems were proposed with respect to this neutralization methods: unipolar ion thruster and bipolar ion thruster. The unipolar ion thruster has the conventional set of an ion beam source and a neutralizer. The bipolar ion thruster is the combination of the plasma sources which can be used either for ion beam source or for neutralizer. Plasma sources operated as ion beam source or neutralizer are arbitrarily selected depending on the requirement. Generally, the unipolar thruster has higher performance and the bipolar thruster has simpler system and lighter weight.

In this study, system performances of miniature ion thrusters were evaluated for both of unipolar and bipolar operation. Here system performance means the thrust, power consumption, and specific impulse. One feature is that power and propellant consumption at the neutralizer was included in those evaluations. In the experiment, ion beam current, contact voltage, and consuming powers were measured. In the all of the measurements, ion thruster was operated under a neutralization state. As a result, the unipolar miniature ion thruster generated 379 μN thrust with 1410 s specific impulse by 19.9 W total power consumption or 297 μN thrust with 1100 s specific impulse by 15.1 W total power. In the case of the bipolar operation, its thrust and specific impulse were lower by 10–20% than the unipolar mode of the same total power consumption. For both cases, these miniature ion thrusters showed the system performance compatible with the 50 kg spacecraft.

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