Operational Characteristics of a Microwave Discharge Neutralizer for the ECR Ion Thruster μ20

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Abstract: Operational characteristics of a microwave discharge neutralizer for a 20-cm diameter electron cyclotron resonance ion thruster have been experimentally investigated. The impact of neutralizer axial and radial position, and microwave power on neutralizer performance is discussed. An optimum position was determined that decreases coupling voltage, required xenon flow rate, direct impingement current by beam ions, and drain currents to the accelerator and decelerator grids.

I. Introduction

In order to advance the technology of electron cyclotron resonance (ECR) microwave discharge ion thrusters known as the "μ(mu)" family, we have been developing a 20-cm diameter thruster μ20 after successful development and flight experiences of an asteroid explorer "Hayabusa" employing four 10-cm diameter thrusters μ10. In contrast to the μ10 whose ion beam current was saturated to 150 mA at higher microwave powers than 30 W, the μ20 can generate 500 mA ion beam current with 100 W microwave power and 1100 – 1300 V acceleration voltage, yielding beam ion production cost (discharge power per unit beam current) of 200 W/A and thrust of 27 mN thanks to enlargement of the discharge chamber and moderate plasma density below cutoff. The μ20 will be applied to deep space missions with larger delta-v and more massive spacecraft than Hayabusa.

Enhancement of ion beam current on μ20 requests us to scale up electron emission current from the microwave discharge neutralizer. The neutralizer designed same to the μ10 was devoted to the test to extract 500 mA electron current with enhanced microwave power and mass flow rate. Large potential gap between beam plasma and the neutralizer will induce the sputtering erosion of the nozzle and the microwave feed probe. The previous paper insisted that a long life of the microwave discharge neutralizer over 10000 hours is achieved at the contact voltage less than 50V[1)], which is also an R&D target of the neutralizer for μ20. Optimization of the magnetic strength and the nozzle configuration reduced the contact voltage[2)].

Life-test of the μ20 ion thruster started without neutralizer and 2300 hours of operation time have accumulated until summer of 2008[3)]. Before dedicating the neutralizer to the test, we have to design the neutralizer installation layout beside the ion source. Most of ion thrusters in the world are equipped with hollow cathode neutralizers just

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beside the ion source oriented parallel to thruster axis. This is because there was no discernible impact of neutralizer axial location on the coupling voltage as reported by Bechtel[4)] and the thruster assembly should be as compact as possible. On the other hand, coupling voltage of microwave discharge neutralizers tends to be higher than that of hollow cathodes and the similar neutralizer layout is not suitable for achieving the acceptable performance. After trials and errors, the μ10 neutralizer was positioned just outer the diverging ion beam edge so that the angle of the neutralizer orifice axis with the axis of the thruster was 45 degree as shown in Fig. 1.

This paper discusses the preliminary results of a test program to optimize the μ20 neutralizer operating conditions such as radial and axial positions, microwave power and xenon flow rate when the neutralizer is mounted on the same radiator panel as ion source. For simplicity, the orientation angle of the neutralizer was fixed perpendicular to the thruster axis in this study and will be determined in the final stage of flight model design.

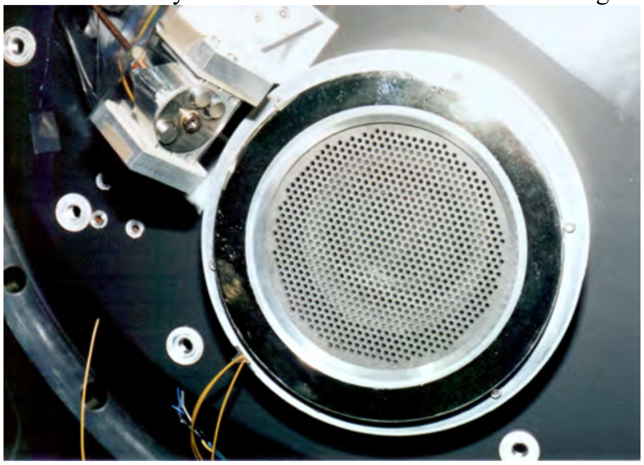

Fig. 1. Slanted mounting of the μ10 neutralizer.

II. Experimental Apparatus

A laboratory model of the μ20 dedicated the life-test was used for this investigation[3)]. The thruster provided a 0.5 amp beam current at a net accelerating potential (screen voltage) of 1300 V and an accelerator potential of -150 V. Table 1 shows the specifications and typical operating conditions of the μ20 thruster. The ion source was mounted on a 500-mm diameter aluminum panel for radiation cooling by using ceramic insulators as depicted in Fig. 2. The radiator and the exterior housing of the ion source for electro-static shield were electrically connected and they were hung on a stainless steel flange of the sub-chamber of the endurance test facility. The chamber wall was grounded. The thruster was operated with standard laboratory power supplies for a screen grid, an accelerator grid, and a neutralizer. The neutralizer potential was also applied to a decelerator grid, which is the same configuration as Hayabusa μ10. The neutralizer and decelerator currents can be separately monitored by shunt resisters (not shown in Fig. 2). The above mentioned power supplies have the common point (P.S. common in Fig. 2) that is connected to the system ground by way of a current meter whose internal resister is 1Ω. Current continuity equation at the P.S. common yields:

$$I_s = I_n + I_d + I_a + I_g$$

Nomenclatures are also described in Fig. 2. In most cases, the neutralizer could emit electrons and form plasma bridge between beam ions and ground return current I_g could be eliminated without depending on the electron emission from the chamber walls. Because drain currents to the accelerator and decelerator are sufficiently small compared to the screen and neutralizer currents, the neutralizer current was controlled so that it equals to the screen current in order to make the experiment easier. In this case, the ground return current compensates the drain currents as indicated by the following equation:

$$I_g = -(I_d + I_a).$$

Microwave powers in the following experimental results were calibrated and defined at the antenna input connectors. Microwaves are generated by microwave power amplifiers individually and supplied to the ion source and the neutralizer through coaxial cables and DC blocks that pass microwaves at insertion losses less than 5%, but their both ends are electrically isolated. The neutralizer is mounted on an adjustable supporting bracket that can change the neutralizer position manually (which requires vacuum break). Fig. 3 shows the locations of neutralizer front tip tested in this work. In all cases, the neutralizer was oriented perpendicular to the thruster axis. The facility, approximately 2 m in diameter and 5 m long, utilizes cryogenic pumps to operate at a nominal pumping speed of approximately 40,000 l/s. Background pressure was lower than 2×10^{-3} Pa at the total xenon flow rate as large as 12 sccm. Neutralizer performances were obtained after at least 2 hours continuous firing for warming up.

Table 1. Specifications of the μ20.

Beam diameter (mm)	200
Microwave frequency (GHz)	4.25
Microwave power (W)	100 (at ion source antenna) 22 (at neutralizer antenna)
Screen voltage (V)	1300
Accelerator voltage (V)	-150
Decelerator and neutralizer voltage (V)	~ -30 (Constant current operation)
Nominal xenon flow rate (standard cubic centimeter per minute: sccm, 1 sccm = 0.9747 mg/s for xenon)	10.2 (Ion source) 1 – 2 (Neutralizer to be defined)
Beam current (mA)	500 (nominal), 250 (min.), 540 (max.)
Thrust (mN)	27 (nominal), 30(maximum)
Specific impulse (s)	2800
Mass utilization efficiency	0.74 (Ion source only)
Screen grid thickness (mm)	0.75
Accel. grid thickness (mm)	1.0
Decel. grid thickness (mm)	1.0
Number of apertures	3087
Screen aperture diam. (mm)	3.05
Accel. aperture diam. (mm)	0.9 – 1.3 (initially as drilled)
Decel. aperture diam. (mm)	2.6
Screen open area fraction	67%
Accel. open area fraction	9% (initially as drilled)
Decel. open area fraction	48%

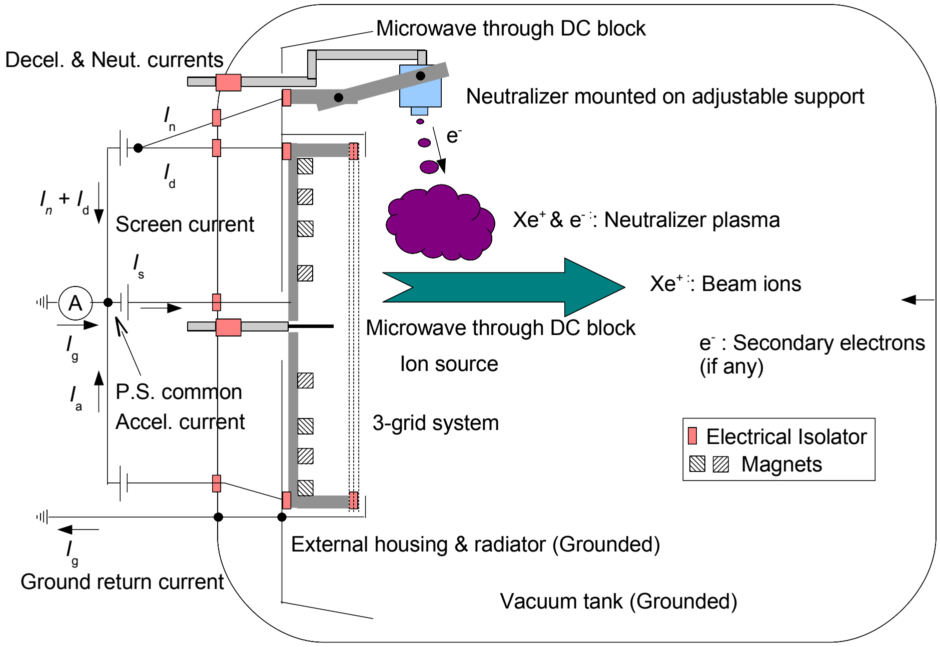

Fig. 2. Electrical schematic of the neutralizer characterization test.

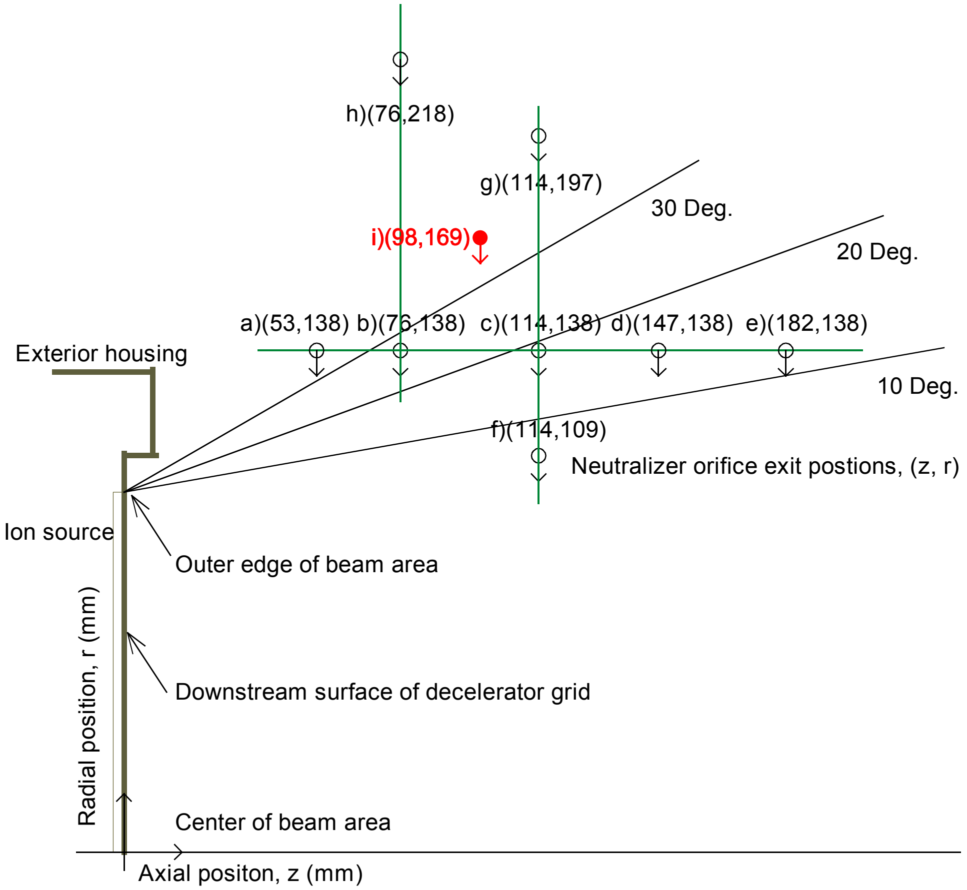

Fig. 3. Neutralizer front tip (orifice exit) locations.

III. Results and Discussion

This section presents results obtained from neutralizer location change trials and detailed operational characteristics.

A. Typical neutralizer performance of the first time mounting on a thruster radiator panel

The position c) in Fig. 3 was selected for our first time trial of neutralizer operation mounted on the radiator panel. The radiator temperature without neutralizer operation was approximately 90 degrees Celsius at the nominal beam current of 500 mA and neutralizer operation increased the radiator temperature by only several degrees. The neutralizer temperature varies from 130 to 180 deg. C. depending on operating conditions. The sum of microwave power and DC power (neutralizer current multiplied by neutralizer voltage) seems to dominate the neutralizer temperature. Fig. 4 shows typical neutralizer performance curves obtained at the c) position. The left graph shows the voltage – current characteristics at constant flow rates. Neutralizer coupling voltage increases rapidly at currents higher than 400 mA. The right graph shows coupling voltage as function of flow rate at constant currents. As can be seen, the voltage monotonously decreases as flow rate increases at currents smaller than 400 mA, while there is an optimum flow rate at higher currents that minimize the voltage. The right graph contains some anomalies in the curve of 500 mA. Sometimes this kind of instabilities were observed which were probably related to the plasma generation between the neutralizer and the ion source exterior housing although the difference was not clearly visible from the plasma luminosity. Authors think that neutralizer plasma coupling stability will be the future work as well as neutralizer durability.

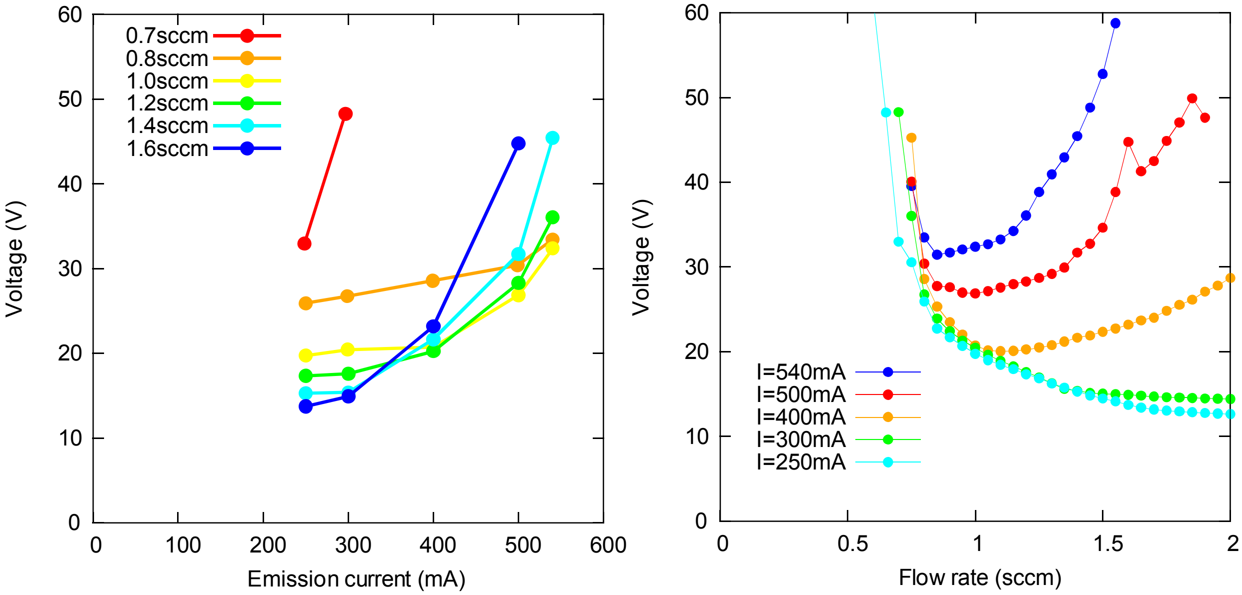

Fig. 4. A typical neutralizer performance curves obtained at the position c).

B. Axial location

Fig. 5 shows the impact of neutralizer axial position on neutralizer performance. These data were obtained along the line a) to e) in Fig. 3. Only operation at the position a) indicated slight electron back-streaming. The screen current increases by 1 mA at the nominal beam current of 500 mA when the accelerator potential was raised by 10 V (-150 V→-140 V) with keeping the screen potential to 1300 V. This point a) is not practical neutralizer position at all because there is no margin to the electron back-streaming from the beginning of thruster life. The drain currents to accelerator and decelerator are higher as the axial position decreases. The same trend was reported on a hollow cathode neutralizer[5)]. The electron back-streaming and the larger drain currents suggest that the neutralizer plasma generated just downstream the ion optics will be denser and negative potential barrier that prevents electron back-streaming will be weaken due to inflow of plasma slow ions. The effect is not so strong but the coupling voltage decreases as the axial position increases. The larger the axial position is, the smaller the optimum flow rate that minimizes the coupling voltage. The lower most of Fig. 5 shows the beam impingement current to the neutralizer when the neutralizer bias voltage was zero and the beam current was 540 mA. The impingement current increases at down stream side because of the increase of beam interception by the neutralizer body.

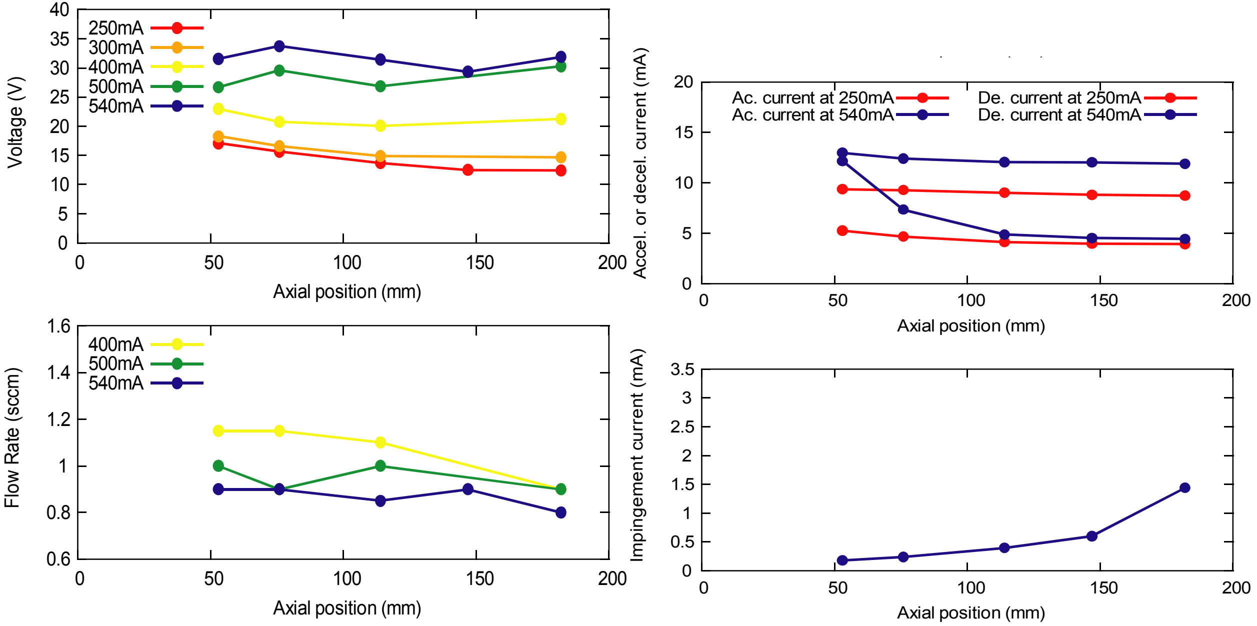

Fig. 5. Impact of neutralizer axial position on performance.

C. Radial location

Fig. 6 shows the impact of neutralizer radial position on neutralizer performance. These data were obtained along the line f), c) and g). The operation at outer region slightly increases the optimum flow rate in most cases but the coupling voltage is almost constant. Accel. and decel. drain currents are also almost constant when radial position changes. Beam interception is so severe at the position f).

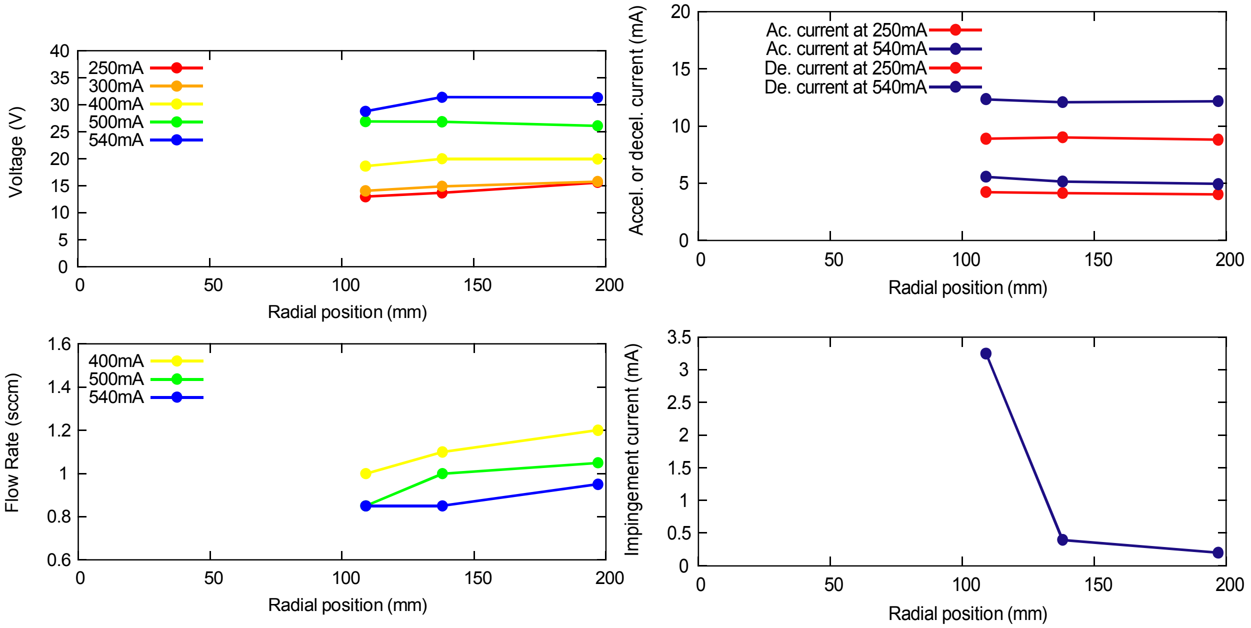

Fig. 6. Impact of neutralizer radial position on performance.

D. Summary on neutralizer location

In order to decrease neutralizer resources (power or flow rate), the neutralizer location should be as close as possible to the diverging beam edge and far away from the ion source to downstream as illustrated in Fig. 7. But there are many other things to be considered for practical thruster design. For example, the neutralizer bracket should be as small as possible for lightweight. Another issue is thermal design of the neutralizer. If lowering the neutralizer temperature is required for longer life of the microwave components used in the neutralizer and the neutralizer cooling depends on the conduction cooling to the radiator panel, the bracket should be shorter. Another cooling philosophy is enhancement of radiation cooling of neutralizer itself by increasing the bracket length or surface area if the neutralizer operating temperature can be set high. The design trade off is not so simple. Fortunately, the position impact on neutralizer performance is not so large and we have flexibility in thruster mechanical design. We have selected an optimized position i) as the operating point for the life-test, after performance investigation at h) where more resources were required than any other locations. Pictures of thruster setting and thruster operation are shown in figures 8 and 9.

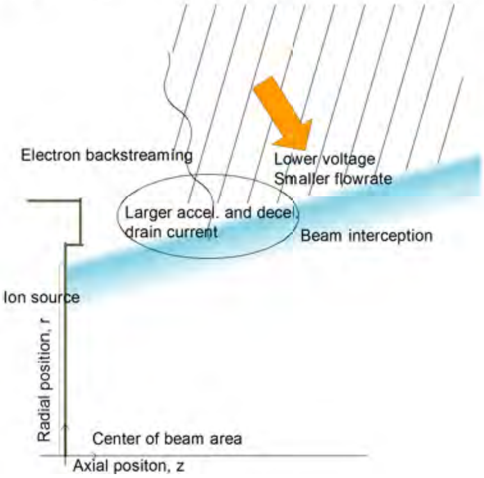

Fig. 7. Schematic for neutralizer position selection.

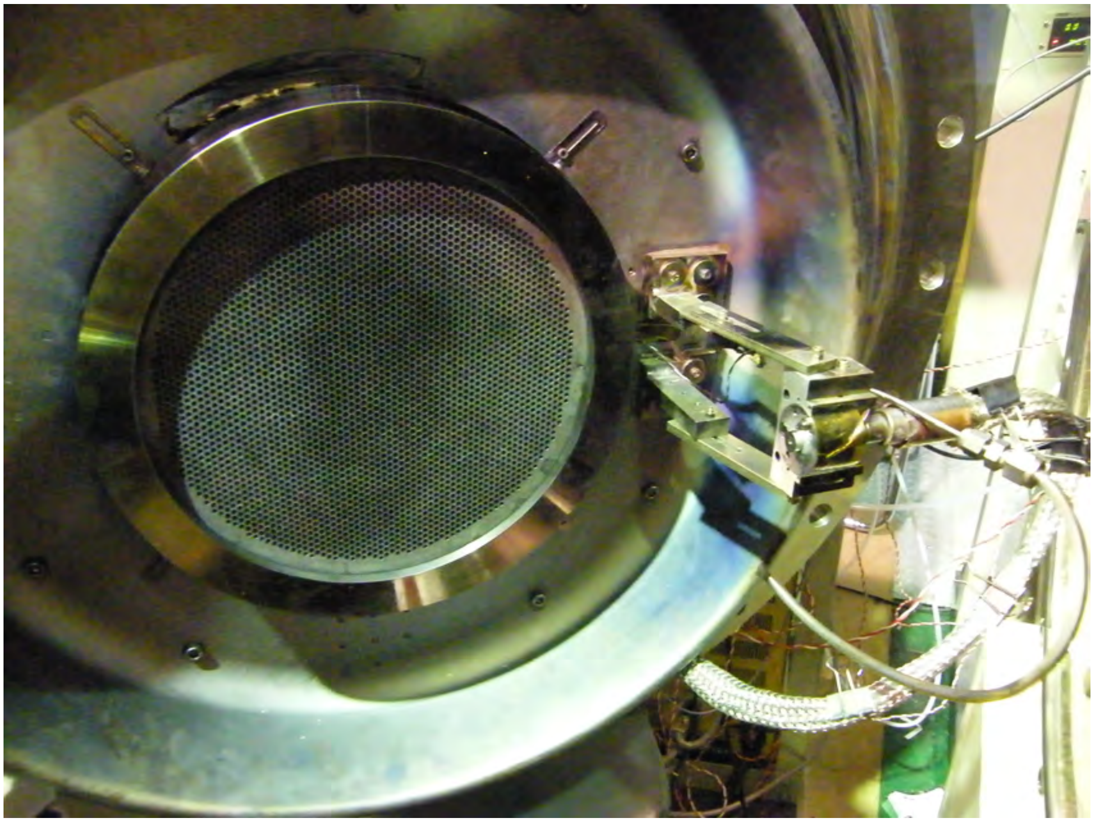

Fig. 8. A picture of ion source and the neutralizer installed at the position i) in Fig. 3 selected for the thruster life test.

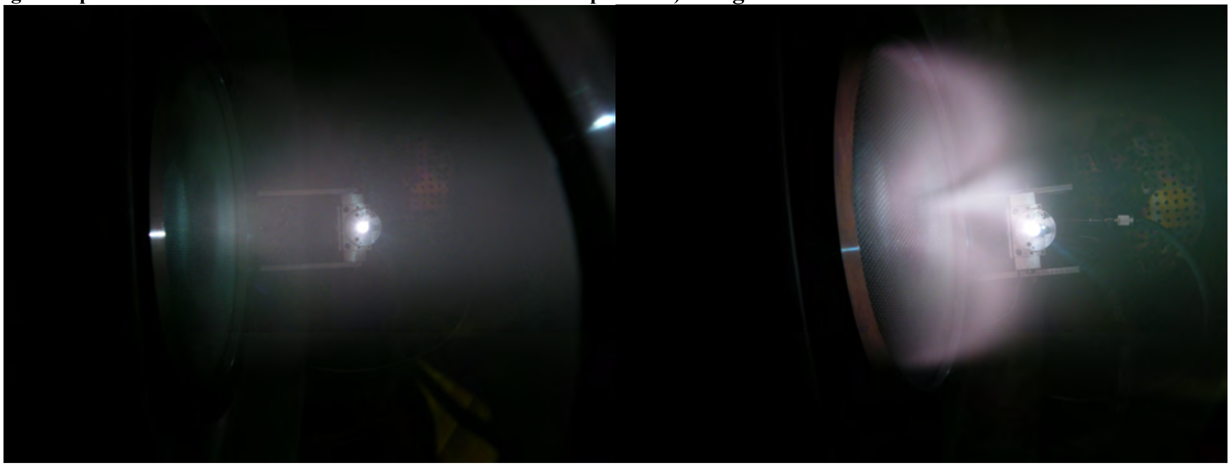

Fig. 9. Side view of the broad thruster plume ejected from left to right and front view of the bright spot of neutralizer plume through a view port when the neutralizer was located at the position i) and the beam current was 540 mA (Left picture). When the neutralizer was moved upstream to the position a), dense plume production between the ion source and the neutralizer was obserbed (Right picture). Exposure time and F-number of these pictures are almost the same.

E. Impact of microwave power on neutralizer performance at the best location

The position i) is the best position so far investigated that enables thruster operation at maximum beam current of 540 mA with lowest coupling voltage below 30 V at a flow rate of 1 sccm. The detail of the neutralizer performance has been obtained at three microwave power levels: 11, 18 and 22 W as shown in Fig. 10 and Fig. 11. There are no plots for smaller flow rates than 1.0 sccm in Fig. 10 at the microwave power of 22 W. This is because stable operation in such lower flow rates was impossible at higher microwave powers. The reason is not clear but the flow rate should be increased as microwave power increased for higher current operation. Fig. 11 suggests that increase of microwave power will widen the flow rate range where the coupling voltage remains low.

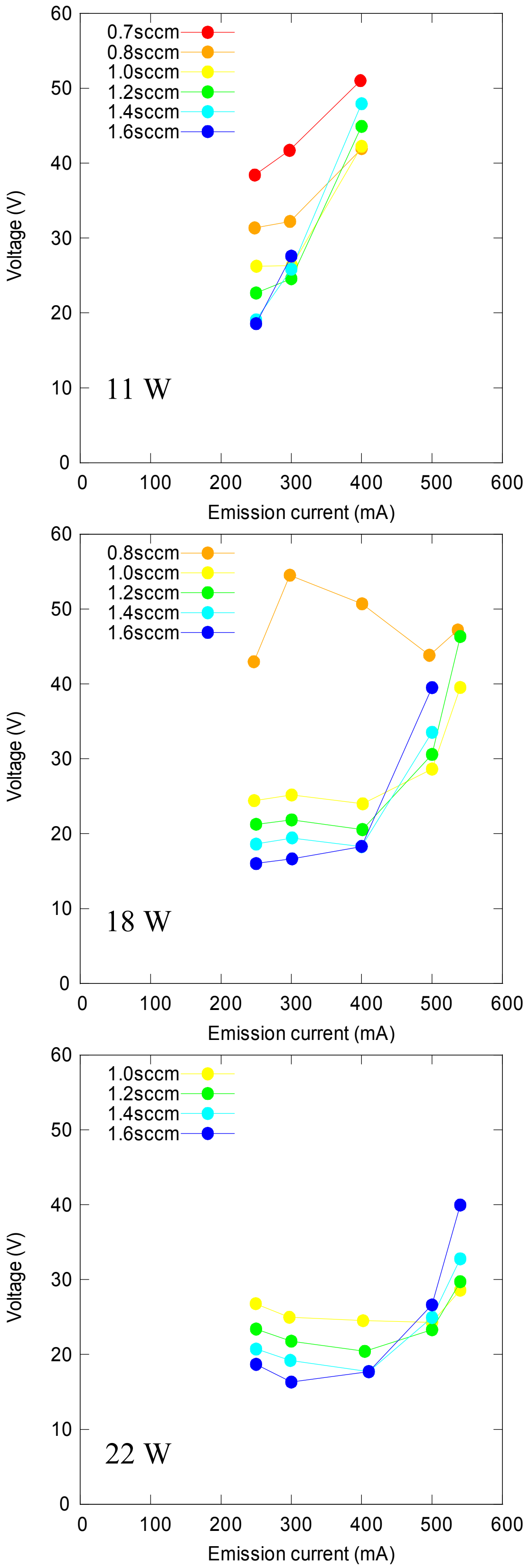

Fig. 10. Voltage – current characteristics at various flow rates for different microwave powers.

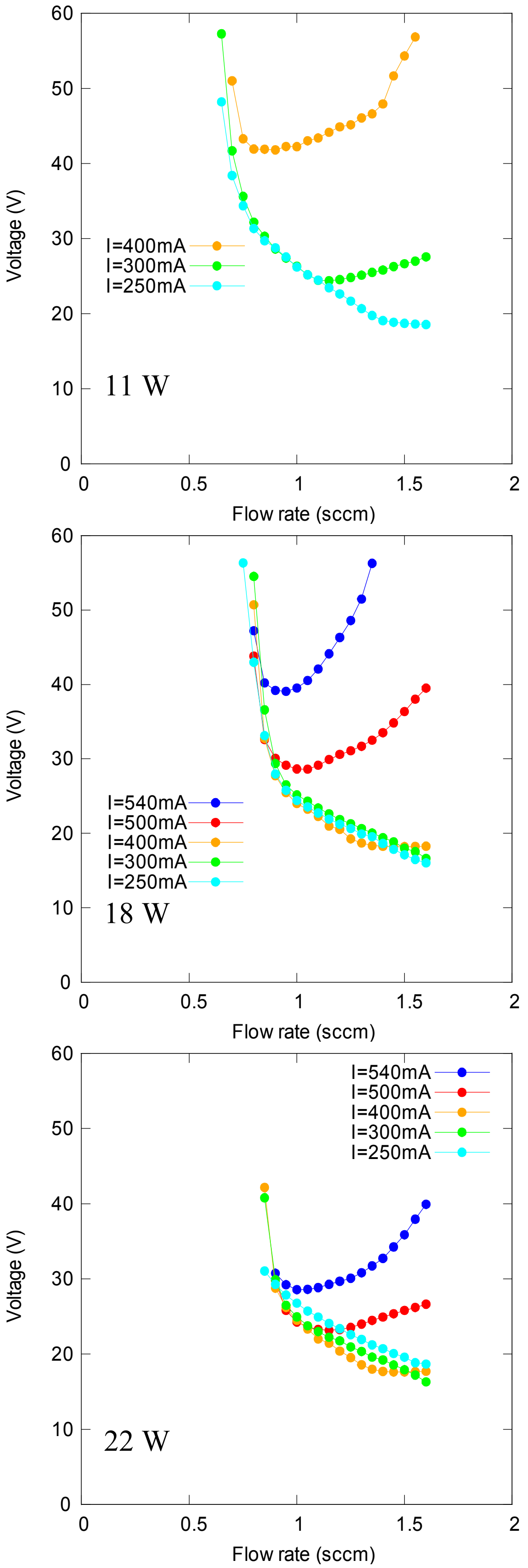

Fig. 11. Voltage – flow rate characteristics at various neutralizer currents for different microwave powers.

F. Flow rate control strategy

Flow rate ratio between ion source and neutralizer is maintained constant in the case of Hayabusa ion engine system. This is because each flow rate is determined by the flow restrictor and all the flow restrictors are located downstream of the common accumulator. The benefit of this design is its simplicity. Let us consider if it is possible with the µ20 ion thruster. The answer shown in Fig. 12 is negative. If the coupling voltage below 40 V is acceptable, available beam throttling range of the µ20 ion thruster is limited between 400 and 540 mA. This is much narrower than the target dynamic range of 250 – 540 mA. The neutralizer for µ20 should be operated at almost constant flow rate regardless of the required electron emission current. This means the flight system must have flow control lines for neutralizers independently from ion sources.

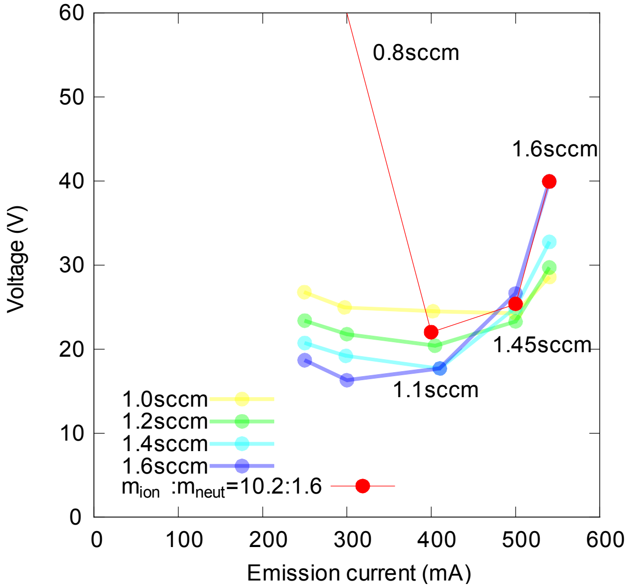

Fig. 12. Voltage – current characteristic when the flow rate ratio between ion source and neutralizer is kept constant as 10.2:1.6 (red line). The ion source flow rate at maximum 540 mA operation is 10.2 sccm.

IV. Conclusion

Operational characteristics of a microwave discharge neutralizer for a 20-cm diameter electron cyclotron resonance ion thruster have been experimentally investigated. The impact of neutralizer axial and radial position, and microwave power on neutralizer performance is discussed. An optimum position was determined that decreases coupling voltage, required xenon flow rate, direct impingement current by beam ions, and drain currents to the accelerator and decelerator grids. The thruster life test has been started with this neutralizer configuration. The final goal is to achieve more than 20,000 hours of operation.

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