Measurement of Plasma Beam Energy Ejected from Microwave Discharge Hall Thruster

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Abstract: Microwave discharge Hall thruster is a double-stage type Hall thruster which generates plasma using 2.45 GHz microwave. In order to examine the effect of microwave launching and radial magnetic field strength peak position in the acceleration channel, the plasma beam energy distribution in a Microwave discharge Hall thruster was estimated from data measured with a Retarding Potential Analyzer (RPA). The RPA was placed at the central axis and at a distance of 30cm from the thruster exit plane. Each measurement was carried out at two different operating modes. One is "no microwave launching" mode; the other is "net 300W input microwave power" mode. Also, each measurement was carried out at the condition that radial magnetic field strength peak exists in three different positions in the channel: relatively upstream, at the middle, and the downstream. As for the amount of a total ion beam current collected with RPA, it was found that operating the thruster at the microwave launching mode, a larger ion current value is obtained compared to the case without microwave launching. The same was true for the average ion beam energy. This trend appeared more remarkable when position of the radial magnetic field strength peak is closer to the upstream part of the channel.

I. Introduction

Hall thrusters are now considered as one of the most promising propulsion system for the station-keeping of geostationary satellites because of their high specific impulse, high thrust efficiency, and high density thrust. The performance of these devices has been improved gradually since the initial experiments carried out in the former Soviet Union in 1960s[1]. However, several key aspects are not well understood yet, such as the physical processes of plasma ionization and acceleration. Also, from the performance point of view, the amplitude of discharge current oscillations at the 10-100 kHz frequency range need to be suppressed as efficiency as possible. In order to investigate the processes of plasma ionization and acceleration, as well as to improve the thrust performance, research is being conducted on a Microwave discharge Hall thruster.

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Hall thrusters are classified into two types from the standpoint of the plasma generation method. As it is well known, single-stage type enables plasma generation and acceleration by the same source of electrons. On the other hand, double-stage type has a plasma source working independent of the acceleration region. During the 1970s, double-stage Hall thruster with a radio-frequency ionization stage was first investigated by Morozov et al.[2] They concluded that the displacement of the ionization region towards the anode leads to an increase in ion energy. A 2.45GHz microwave signal penetrates into the acceleration channel from the upstream of the channel in Microwave discharge Hall thruster. Therefore, dense plasma was expected to be generated the upstream region in the channel. Actually, it was confirmed that dense plasma region existed on the upstream region in the channel only when microwave was launched. Additionally, an increase in the amount of a total ion beam current and the rise of the average ion beam energy were confirmed[3]. In this research, the influence that the radial magnetic field shape exerts on thruster performance has been investigated.

II. Experimental apparatus

Vacuum tank

All experiments described in this report have been performed using a stainless-steel tank of 1.5 m in diameter and 2.8 m in length. It was evacuated by two 22-inch diffusion pumps, backed by a mechanical booster, which in turn is backed by three rotary pumps. The vacuum tank pressure was kept at about 3.7 x 10^{-2} Pa with 1.76 mg/s xenon mass flow rate.

Microwave discharge Hall thruster

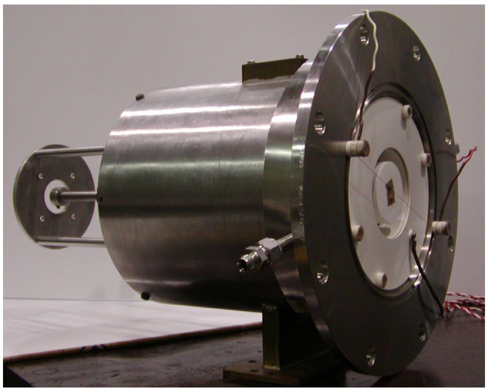


Figure 1. Microwave discharge Hall thruster.

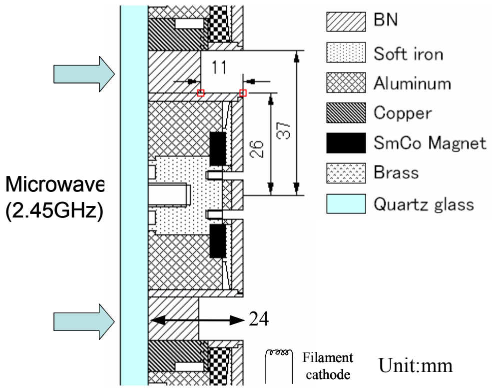


Figure 2. Cross-sectional view of Microwave discharge Hall thruster.

The Microwave discharge Hall thruster investigated herein is shown in Fig. 1. Cross-sectional view of Microwave discharge Hall thruster is shown in Fig. 2. This thruster has an acceleration channel of 11 mm wide and 24 mm long, and channel geometry resembles that of a traditional “Linear type Hall thruster.” However, during plasma beam energy measurements, a boron nitride (BN) ring (13 mm in thickness) was placed in the upstream side of the channel, thereby shortening channel length to 11 mm. The reason for adopting this configuration was based on the experimental fact that thruster performance improves when the plasma region generated by the microwave that penetrates from upstream, as the microwave energy absorption layer is brought closer to the ion acceleration region. With such configuration, it can be assumed that there is a negligible loss of net input microwave power by inserting this BN ring.

The wall material of the acceleration channel is BN as well. The anode is ring-shaped and made out of copper. A 0.27 mm diameter thoriated tungsten wire was used as the main cathode. A cylindrical cavity resonator with an internal diameter of 208 mm and a length of 200 mm, inside of which a TM_{011} mode standing wave is established, was fitted to the upstream side of the thruster channel. A 2.45GHz microwave penetrates into the channel separated from the cavity resonator by a 12 mm-thick quartz glass and produces plasma by surface wave absorption at the plasma cut-off. In order to achieve a radial magnetic strength peak near the channel exit, Samarium-Cobalt permanent magnets were utilized. These magnets were placed both in the inner core of the thruster and on the cylindrical cavity wall, being lined up concentrically.

Microwave discharge Hall thruster can be operated by two operating modes. The first one is “no microwave launching” mode, thus having the thruster operating as single-stage type. The other mode is referred herein as “microwave launching” mode, with the thruster operating as double-stage type. A typical profile of the plasma potential variation along the acceleration channel of this thruster is shown in Fig. 3. The plasma density variation along the channel is shown in Fig. 4. In these figure, “DC” corresponds to the single-stage operating mode, and “P_{net} = 100 W” corresponds to double-stage operating mode with a net microwave power of 100 W being launched. The plasma potential distributions are approximately the same for both single-stage and double-stage operation. This potential variation is in concordance with experimental results for traditional SPT thrusters[4]. However, the plasma density profile changes significantly in the case of single-stage operation mode and double-stage operation mode of the Microwave discharge Hall thruster. When operating under the double-stage operating mode, a dense plasma region is generated near the anode. It can be inferred that the dense plasma region near the anode is due to electron heating by the microwave signal.

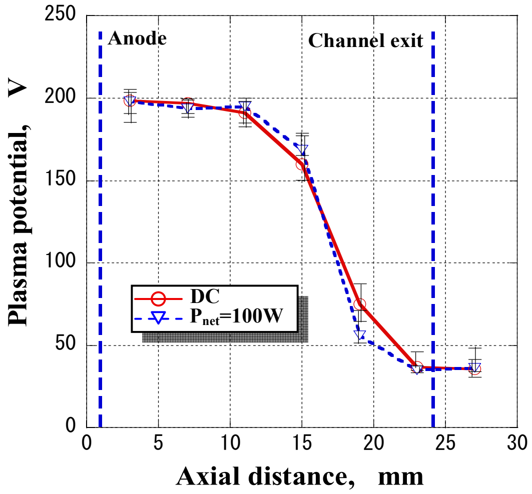


Figure 3. Plasma potential variation along the channel. Discharge voltage was kept at 200 V. Xenon mass flow rate was kept at 1.76 mg/s.

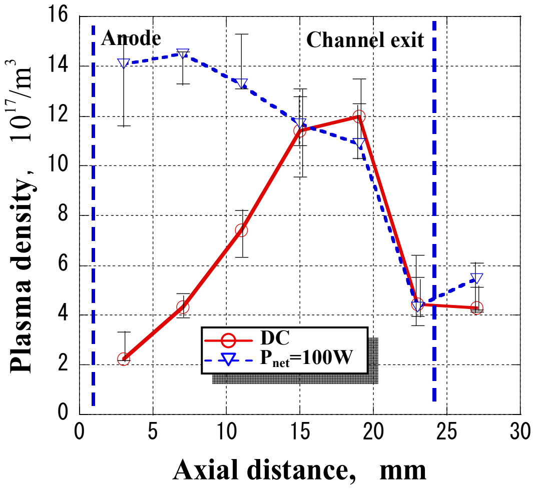


Figure 4. Plasma density variation along the channel. Discharge voltage was kept at 200 V. Xenon mass flow rate was kept at 1.76 mg/s.

<u>**Retarding potential analyzer**</u>

The retarding potential analyzer (RPA) measurement setup is shown in Fig. 5. RPA allows the collection of selectively filtered ions by applying a retarding potential to the internal grid. The outer body of the RPA is constructed of a stainless-steel tube, which was held at ground potential. The inner structure of the RPA consists of a floating grid (FG), an electron retarding grid (ERG), an ion retarding grid (IRG), and a copper collector. Each grid and the collector are isolated electrically with separators made out of Alumina. A 200 mesh / inch stainless-steel sheet was utilized for both the FG and ERG. A 400 mesh / inch stainless-steel sheet was utilized for the IRG. The interspacing is 2 mm between FG and ERG, 3.3 mm between ERG and IRG, and 10 mm between IRG and the collector.

For a given ion retarding grid potential, only ions possessing energy that is higher than the ion retarding grid potential can pass through and reach collector. The value of

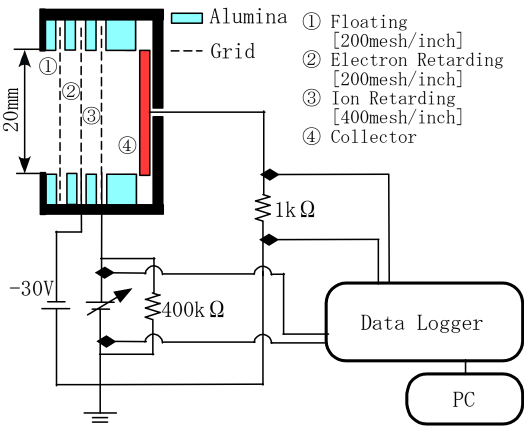


Figure 5. RPA measurement setup.

the derivative of the measured current - voltage characteristic is proportional to the ion energy distribution.

III. Measurement of plasma beam energy distribution

Experimental approach

The Microwave discharge Hall thruster shown in fig. 2 was operated at a xenon mass flow rate setting of 0.98 mg/s. The discharge voltage was set to either 150 V or 200 V. The main purpose of experimental study was to find the best radial magnetic field distribution along the channel for double-stage type operation. In the experimental runs, the peak position of the radial magnetic field strength in the channel was varied axially. Fig. 6 shows the measurement result of radial magnetic field strength along the centerline of the channel. For the A-type thruster channel configuration, the peak of the radial magnetic field strength appears downstream. For the C-type configuration, this peak appears upstream. For the B-type configuration, this peak is generated in a point halfway between the peaks corresponding to configurations A-type and C-type.

Each measurement was carried out at two different operating modes. The first one is "no microwave launching" mode, and the second one is "net 300 W microwave launching" mode. Under these conditions, the measurement of the plasma beam energy distribution was carried out with RPA located at the central axis of the thruster and 30 cm downstream the thruster exit. The ERG was biased to -30 V in order to repel any incoming electrons. The IRG was swept from 0-250 V. In order to estimate of energy efficiency η_e, the following expression was employed,

$$\eta_e = E_m/(eV_d) \tag{1}$$

where E_m is average of ion beam energy estimated from plasma beam energy distribution function, e is the electronic charge, and V_d is the discharge voltage.

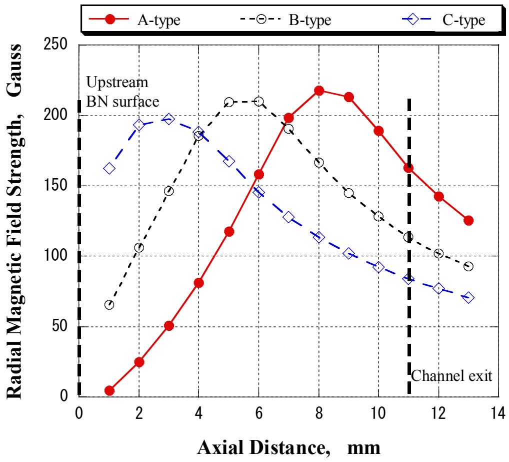


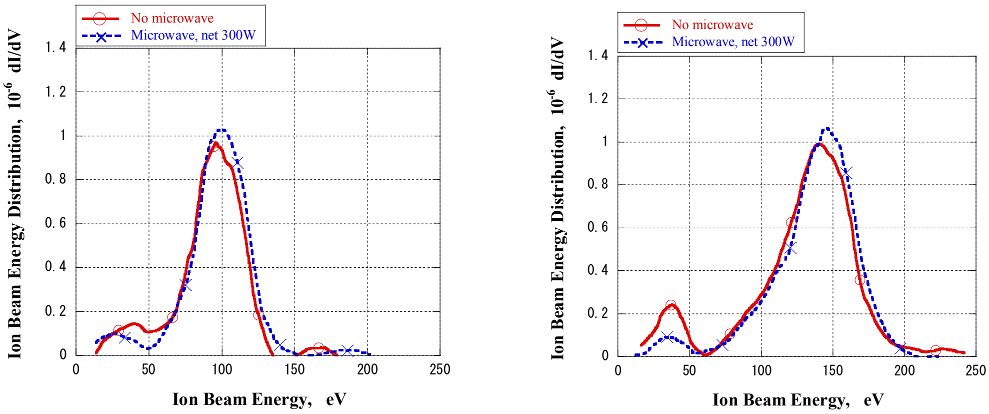
Figure 6. Radial magnetic field strength variation in the channel.

Results and discussion

Figs. 7-9 show the ion beam energy distribution characteristics for radial magnetic field profiles corresponding to A-type, B-type, and C-type channel configurations. Table 1 provides a brief summary of performance results for each measurement case. In this table, the *total ion beam current* refers to the value collected by RPA when the IRG voltage is 0 V; *increase rate* refers to the value obtained by dividing the total ion beam current at "microwave launching" mode by the total ion beam current at "no microwave launching" mode. Accordingly, the effect of microwave launching will be significant when the increase rate is larger than 1.

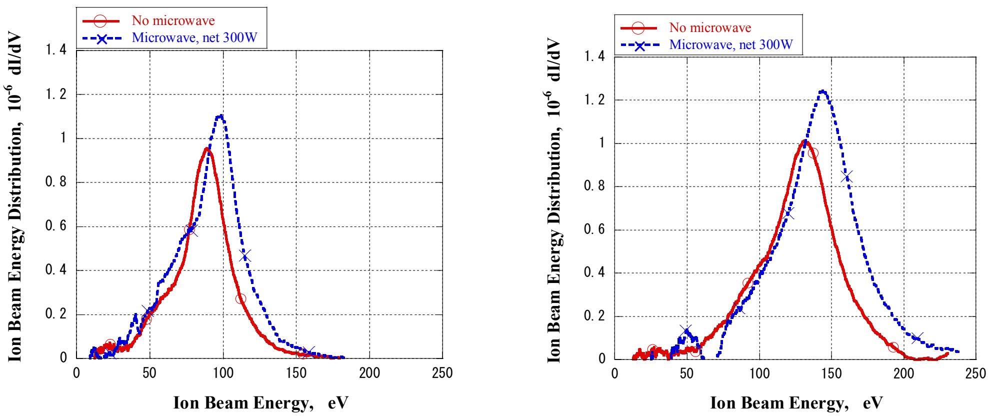
In the case of the A-type configuration, the variation in total ion beam current based on the operating mode is insignificant. In the result of B-type and C-type, a striking difference is exhibited, depending on the operation mode. An increase in both the total ion beam current and the ratio of the high energy ions was confirmed in the "microwave launching" mode. The maximum total ion beam current was obtained when the radial magnetic field shape was the one corresponding to the B-type configuration, with a discharge voltage of 150 V, and microwave launching. The maximum energy efficiency was found to be 0.72, again with a radial magnetic field corresponding to the B-type, a discharge voltage of 200 V, and microwave launching.

For the microwave launching mode, the total ion beam current increased as the radial magnetic field strength peak was moved upstream. To this respect, if the radial magnetic field strength peak is moved upstream of the channel, it may be assumed that the acceleration region is also moved upstream. Therefore, it may be inferred that the generated ions came to be effectively pulled out from the dense plasma generated by the heating of the electrons by the microwave in the channel upstream region. Additionally, since the plasma generated upstream of the channel is near the anode, it has high plasma potential. Therefore, it is considered that the average of ion beam energy also increases and energy efficiency is improved. However, the effect of the microwave launching was found to be small when the peak position of radial magnetic field strength was brought close to the upstream, such as in C-type configuration. It is considered that bringing the plasma generation region and the plasma acceleration area close to a suitable position for Microwave discharge Hall thruster of double-stage type will lead to the an improvement in performance.



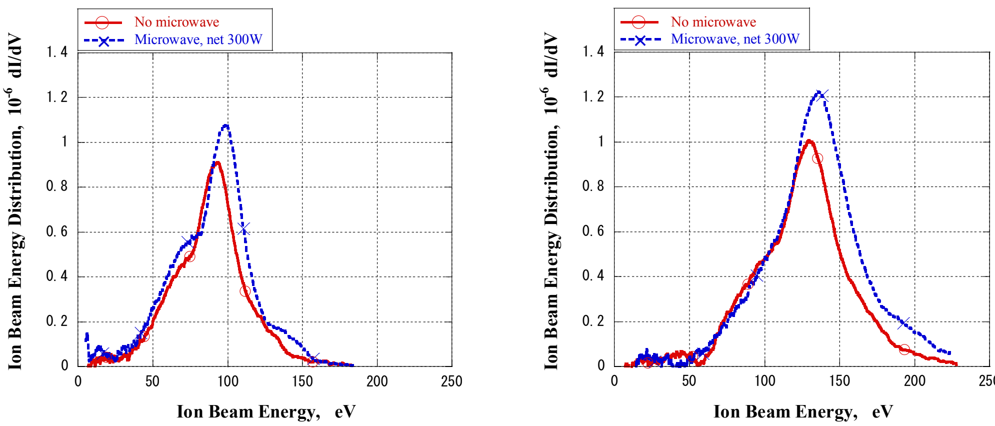
(a) Discharge voltage is 150 V. **(b) Discharge voltage is 200 V.**

Figure 7. Ion beam energy distributions measured with the RPA. (0.98 mg/s xenon mass flow rate; radial magnetic field strength profile is as in A-type)



(a) Discharge voltage is 150 V. **(b) Discharge voltage is 200 V.**

Figure 8. Ion beam energy distributions measured with the RPA. (0.98 mg/s xenon mass flow rate; radial magnetic field strength profile is as in B-type)



(a) Discharge voltage is 150 V. **(b) Discharge voltage is 200 V.**

Figure 9. Ion beam energy distributions measured with the RPA. (0.98 mg/s xenon mass flow rate; radial magnetic field strength profile is as in C-type)

Table 1. Performance summary

Magnetic field type	*Disch. voltage, V*	*Operating mode*	*Total ion beam current, 10^{-5} A*	*Increase rate*	*Energy efficiency, η_e*
A	200	No microwave	6.2	0.96	0.68
		Microwave net 300W	6.0		0.69
	150	No microwave	4.1	1.09	0.67
		Microwave net 300W	4.5		0.68
B	200	No microwave	5.8	1.31	0.68
		Microwave net 300W	7.6		0.72
	150	No microwave	3.8	1.34	0.62
		Microwave net 300W	5.1		0.66
C	200	No microwave	6.0	1.23	0.64
		Microwave net 300W	7.4		0.69
	150	No microwave	4.1	1.26	0.63
		Microwave net 300W	5.2		0.65

IV. Conclusion

Measurements of the ion beam energy distribution in a double-stagy type Microwave discharge Hall thruster, which has an independent plasma generator, were carried out with a RPA in order to examine the effect of microwave launching and radial magnetic field strength peak position in the channel. In almost all measurement cases, the total ion beam current and energy efficiency were higher with microwave launching. In this microwave launching mode, the total ion beam current and efficiency were found to increase as the radial magnetic field strength peak was brought upstream.

References

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