Influence of Doubly-ionized Xenon on the Lifetime of Microwave Discharge Cathode

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Yoshitaka Tani[1]
The University of Tokyo, Bunkyo-ku, Tokyo, 113-8656, Japan

Abstract: **Microwave ion thruster μ10 was firstly demonstrated in space through the Japanese asteroid sample returner "HAYABUSA". Prior to the mission, the endurance tests of the thrusters were conducted. Based on the results, it turned out that the lifetime was limited up to 20,000 hours due to the microwave neutralizers. Additionally, in the operation of "HAYABUSA," the neutralizers stopped working from 10,000 hours to 15,000 hours. The difference of the lifetime between the endurance tests and the space operation is not clearly understood. To make the difference clear, this study measures doubly-ionized xenon in the neutralizer with respect to propellant flow rates using the quadrupole mass spectrograph (QMS). The result shows that the abundance ratio of doubly-ionized xenon to singly-ionized xenon increases with respect to the decrease of propellant flow rates. It implies that the propellant throttling operation conducted only in space reduced the lifetime of the neutralizer for the sputtering of the doubly-ionized xenon.**

Nomenclature

R^{2+}	=	degradation rate by doubly ionized xenon
V_c	=	contact voltage
α	=	unit conversion constant
ε	=	abundance ratio
I_s	=	ion saturation current
Y^{2+}	=	sputtering yield by doubly ionized xenon to moribudenn

I. Introduction

THE ion thruster is one of the electric propulsion systems for spacecrafts. It accelerates ions the arc discharge or microwave ion of the internal plasma generated by such, it is an electrostatic acceleration type propulsion device accelerated by accelerating electrode. Although thrust density is low, because a large specific impulse, is capable of long-term operation with less propellant is applicable to maneuver and deep space satellites.

Microwave discharge ion thruster, mounted on Japanese unmanned asteroid explorer "Hayabusa", reached the result of approximately 40,000 hours on the space operation. Although the DC discharge ion engine, which is generally adopted to spacecrafts, reach the lifetime because of degradation of insert cathode, the microwave discharge ion engine are expected long-life performance, for it doesn't have electrode. However, it is inevitable that neutralizer reaches the lifetime due to ion sputtering because it collects as much ion current as emission electron current at the surface of discharge chamber.

The neutralizer of μ10 ion engine, which mounted on "Hayabusa", demonstrated approximately 20,000 hours-life-performance on the ground test. But in the real operation, its lifetime was only about 10,000 to 15,000 hours and the cause of that has not been yet to clear. Neutralizer is the rate-limiting device of microwave discharge ion engine

[1] Graduated School of Engineering, Department of Aeronautics and Astronautics, tani@ep.isas.jaxa.jp.

system, thus clarifying the difference of lifetime of neutralizer between ground test and space operation is extremely important to promote deep space in the future.

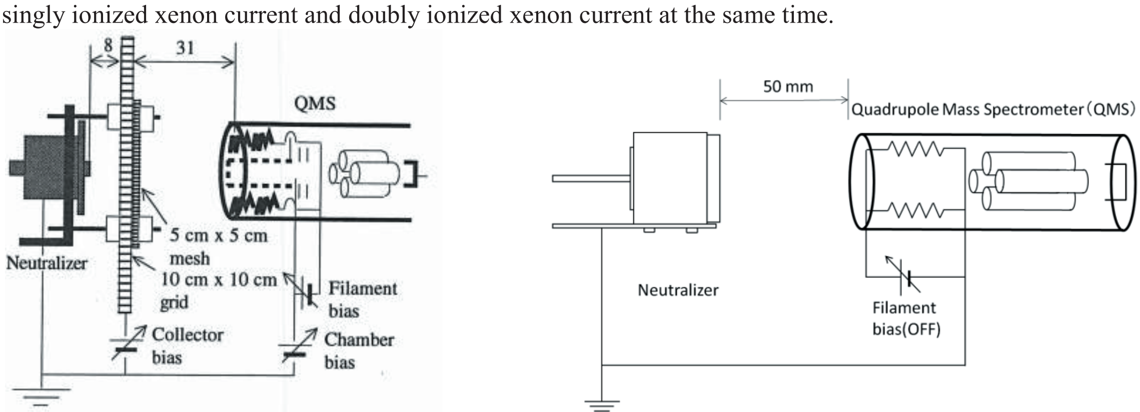
The prior research by Ohmichi shows that the wear by doubly ionized xenon slightly contained in discharge chamber is dominant cause of degradation of the microwave discharge neutralizer. It is considered that almost all the sputtering wear at the nominal operating voltage of the μ10 neutralizer is caused by doubly ionized xenon. Sputtering yield depends on the ion saturation current to the surface of discharge chamber, thus the sputtering impact by doubly ionized xenon is affected by the percentage of the doubly ionized xenon current in total ion current to the surface (i.e. ion saturation current). In the prior research by Onodera, et al, doubly ionized xenon in the discharge chamber was only measured at only one point, 1.0 sccm. It is significantly different from the nominal operating point in μ10 ion engine's neutralizer, 0.5 sccm. Therefore, flow rate dependence of the percentage of doubly ionized xenon to singly ionized xenon, abundance ratio, has not been revealed. Because the throttling operation, operation at lower flow rate than the nominal, is also carried out on the actual operation of spacecraft, it is necessary to clarify the flow rate dependence of that. In this research, we measure the doubly ionized xenon inside of the microwave discharge neutralizer using a quadrupole mass spectrometer (QMS), and reveal how the abundance ratio changes by the propellant flow rate and what kind of characteristic. Then, ultimately, we intend to explain the differences on life between on the ground endurance test and space operation.

II. Experimental Equipments and Method

A. Measurement of Ion Current

Figure 1 shows the schematic diagram of the experimental apparatus. In this experiment, we measured how the abundance ratio of doubly ionized xenon in the discharge chamber changes by the propellant flow rate. The configuration of the experimental apparatus is followed the prior research by Onodera, and the experiment is conducted by measurement at the same position and by using the same measuring device. However, in the experiments by Onodera et al, the collector grid affected on the measurement of the abundance ratio of doubly ionized xenon, for it was positively biased to draw electron current. Therefore, in this experiment we remove the collector grid and conduct the experiment with no drawing electrons.

We use the ANELVA quadrupole mass spectrometer (QMS), AQA-200 in this measurement. Install the QMS in the position of approximately 50 centimeters downstream from the orifice plate in the vacuum chamber, and measure ions which leak by heat motion through orifice from the discharge chamber. The interior filaments of QMS are not turned on. Input microwave power to the neutralizer is 8 W, 4.25 GHz, and the propellant gas is xenon. In this experiment, we measured doubly ionized xenon at four points of flow rate, 0.5 sccm of "Hayabusa" nominal operating point, 0.3 sccm of equivalent to throttling operation, 0.7 sccm of "Hayabusa 2" nominal operating point, and 0.9 sccm. To determine the abundance ratio of doubly ionized xenon at each measurement point, we measure the singly ionized xenon current and doubly ionized xenon current at the same time.



a) setup of prior research by Onodera b) setup in this research

Figure 1. Schematic of Doubly-ionized Xenon measurement of microwave discharge neutralizer.

B. Measurement of Ion Saturation Current

III. Experimental Results and Discussion

A. Experimental Results

a. Measurement of Abundance Ratio

Figure 2 to 5 show the result of mass spectra of both singly ionized xenon and doubly ionized xenon together. The horizontal axis is the mass to charge ratio, the peak of singly ionized xenon will be observed around 133, and that of doubly ionized xenon around 66. It can be seen from Figure 2, the magnitude of the spectrum of doubly ionized xenon is two orders smaller than that of singly ionized xenon. Also, the table 1 shows the calculated abundance ratio of doubly ionized xenon to singly ionized xenon at each point of flow rate. Here we assume the velocities of ion inflow to the QMS are the same in singly and doubly ionized xenon. According to Table 1, magnitude of doubly ionized xenon current at 0.3 sccm is 10^{-11}A order, so it is 100 times as much as at 0.5 - 0.9 sccm

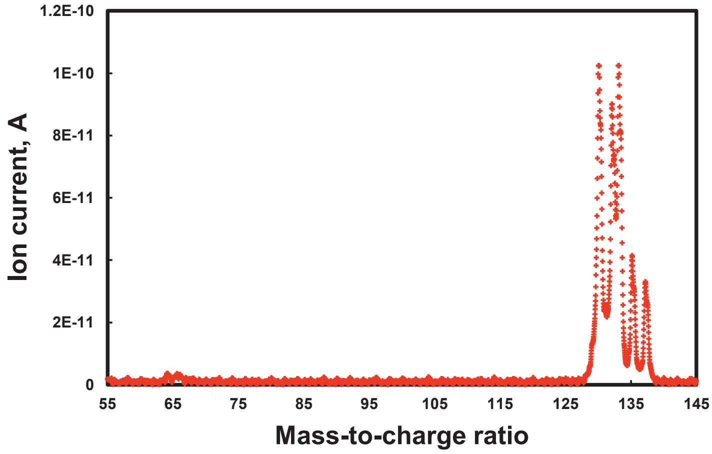


Figure 2. Spectrum of ionized Xenon of microwave discharge neutralizer at 0.3 sccm.

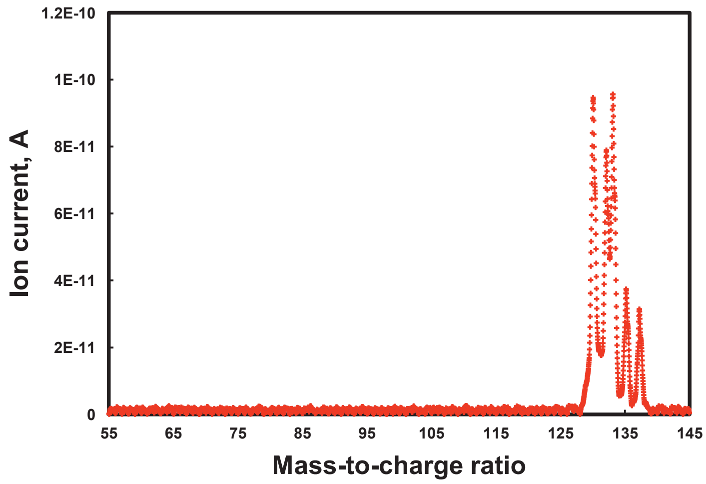


Figure 3. Spectrum of ionized Xenon of microwave Discharge neutralizer at 0.5 sccm

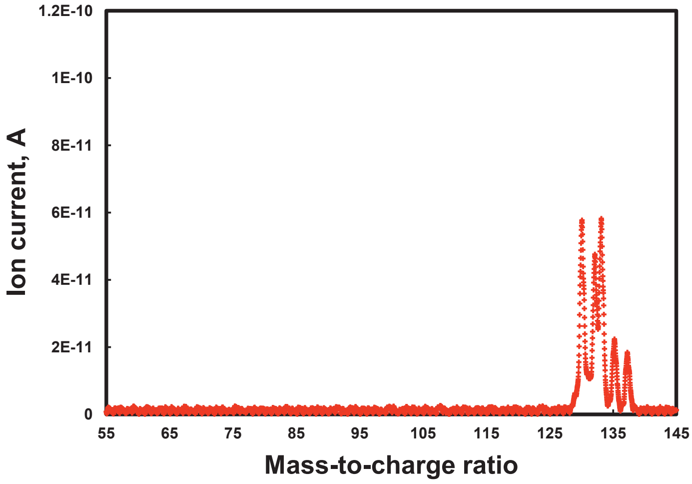


Figure 4. Spectrum of ionized Xenon of microwave discharge neutralizer at 0.7 sccm.

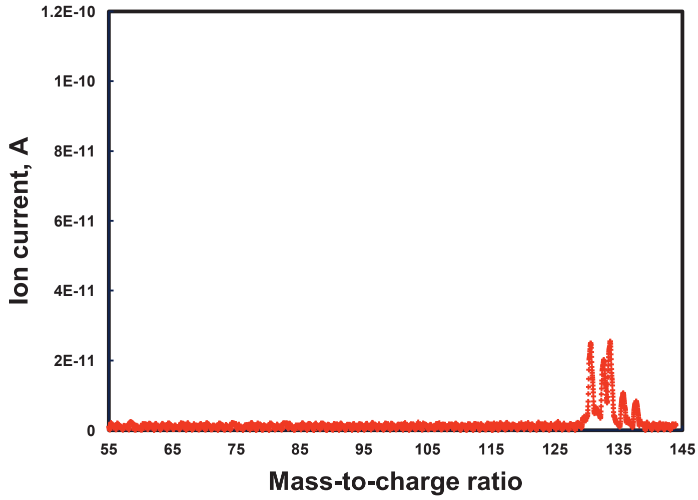


Figure 5. Spectrum of ionized Xenon of microwave discharge neutralizer at 0.9 sccm.

Table 1 Mass flow rate dependence of abundance ratio of Doubly-ionized Xenon.

flow rate, sccm	Xe^{1+} current, A	Xe^{2+} current, A	abundance ratio
0.3	3.36×10^{-10}	1.02×10^{-11}	0.015
0.5	2.93×10^{-10}	5.58×10^{-13}	0.00095
0.7	1.78×10^{-10}	2.19×10^{-13}	0.00061
0.9	7.53×10^{-11}	1.34×10^{-13}	0.00089

b. Measurement of Ion Saturation Current

B. Discussion

a. Doubly Ionized Xenon Ratio

First, we verify the experimental result by Onodera et al. According to Onodera, the abundance ratio of doubly ionized xenon to singly ionized xenon was substantially constant at 0.2% at 1.0 sccm. In this experiment, the abundance ratio of doubly ionized xenon is approximately at 0.1% at from 0.5 sccm to 0.9 sccm. The order of each result has been consistent.

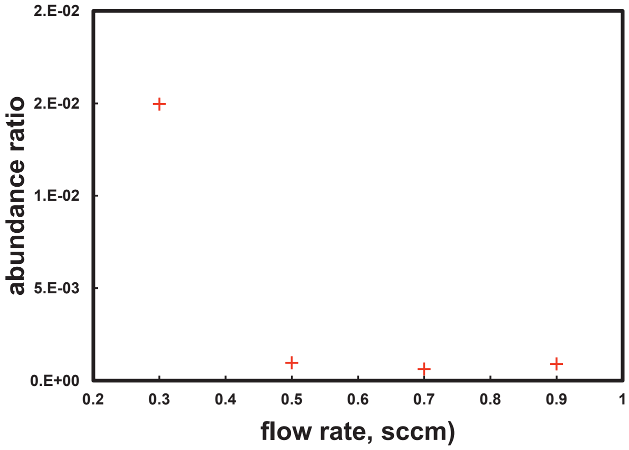


Figure 6. Flow rate dependence of abundance ratio of Doubly-ionized Xenon.

Next, we discuss the relationship of the propellant flow rate and the abundance ratio of doubly ionized xenon. Figure 6 shows the flow rate dependence of abundance ratio of doubly ionized xenon. The result of this experiment shows that the abundance ratio of doubly ionized xenon takes almost constant value at 0.5, 0.7, and 0.9 sccm, and takes minimum value at 0.7 sccm. On the other hand, it increases greatly at 0.3 sccm. Compared with the value of abundance ratio at 0.5 sccm, the nominal operating point of "Hayabusa", that is approximately ten times greater at 0.3 sccm, the throttling operating point. In contrast, Table 1 teaches us that the abundance ratio at 0.7 sccm, the nominal operation point of “Hayabusa 2”, is approximately 30% lower than at 0.5 sccm. When we increase the flow rate from 0.7 sccm to 0.9 sccm, the abundance ratio begins to increase again, thus the abundance ratio does not simply decrease as the flow rate increases. When the contact voltage is constant with respect to propellant flow rate, the flow rate at 0.7 sccm is optimal for life performance.

The characteristic that the abundance ratio of doubly ionized xenon rapidly increases at 0.3 sccm is considered to be a specific feature of microwave discharge neutralizer. On microwave discharge neutralizer, electrons are trapped at ECR area and accelerated, and then plasma is generated by ionizing collisions. Qualitatively speaking, when the flow rate decreases, the generation rate of doubly ionized xenon rises by the following process and the abundance ratio increased in the discharge chamber.

1) Neutral particle density is reduced by the reduction of flow rate.
2) Mean free path is extended by the reduction of neutral particle density.
3) Electron trap time is extended in the ECR area by extension of the mean free path.
4) The number of electrons of enough energy to ionize increases due to extend electron trap time.
5) The generation rate of doubly ionized xenon generation rises.

b. The difference between the ground endurance test and Space Operations

According to the prior research, neutralizer degradation is caused by flakes generated by sputtering from discharge chamber. The degradation rate due to doubly ionized xenon at the contact voltage can be written as follows.

$$R^{2+}(V_c) = \alpha\varepsilon I_s Y^{2+}(V_c) \quad (1)$$

We adopt the Yamamura model to calculate sputtering yield in this paper. Figure 7 shows the relationship between contact voltage and sputtering yield when the abundance ratio ε equal to 0.002.

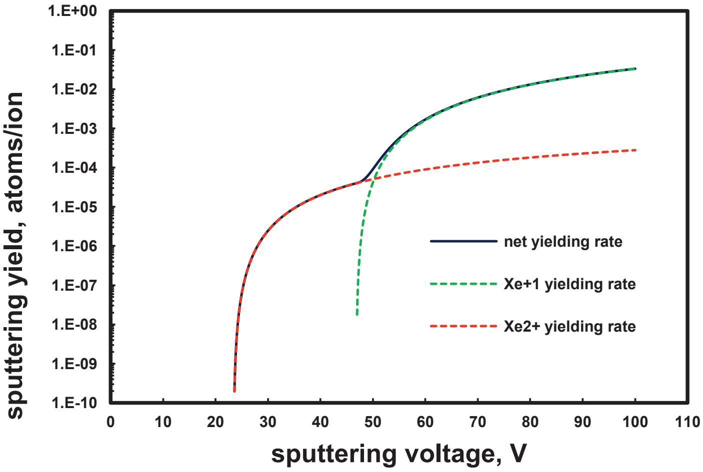


Figure 7. Sputtering voltage dependence of sputtering yield.

Because the contact voltage on the nominal operation of "Hayabusa" is approximately 30-40 V, sputtering wear should be considered to be only contributed by doubly ionized xenon. The difference of lifetime between ground endurance test and space operations is considered to be caused as follows: the abundance ratio changes as the flow rate changes and the degradation rate shown Eq. (1) changes.

Now we consider how the degradation rate changes as the abundance ratio changes. Figure 8 shows the flow rate-current characteristic curve of the ion source, and Figure 9 shows the current-voltage characteristic curve of neutralizer. The nominal flow rate of neutralizer is 0.5 sccm, and that of ion source is 2.2 sccm in "Hayabusa". Using this nominal-flow-ratio, calculate the flow rate of the ion source corresponding to the each of the four measured flow rate points. Read the beam current corresponding to the respective flow rates from Figure 8, and determine the respective contact voltages from Figure 9. Table 2 shows the results calculated by this way. And Fig.10 shows the ratio of the degradation rate between each flow rate and 0.5 sccm when the degradation rate at 0.5 sccm is defined as 1.

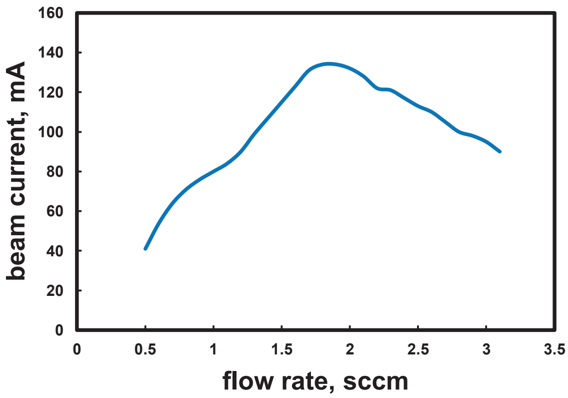


Figure 8. Flow rate dependence of beam current of ion source.

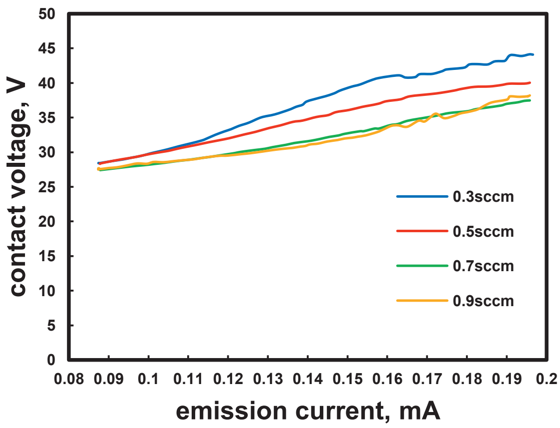


Figure 9. Emission current dependence of contact voltage of neutralizer at each flow rate.

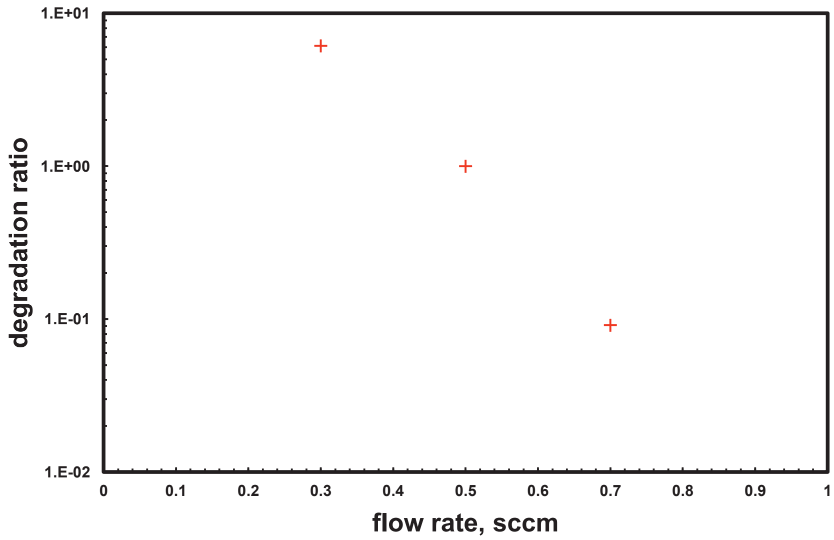


Figure 10. Flow rate dependence of degradation ratio.

Table 2 Flow rate dependence of yielding rate of Doubly-ionized Xenon to discharge chamber.

neutralizer flow rate, sccm	sputtering yield, atoms/ion	abundance ratio	degradation ratio
0.3	1.12×10^{-3}	0.015	6.13
0.5	2.83×10^{-3}	0.00095	1
0.7	4.00×10^{-4}	0.00061	0.0912
0.9	-	0.00089	-

We can find from Figure 10 that the degradation rate at 0.3 sccm, corresponding to 60% throttling operation, becomes approximately six times as much as at the nominal flow rate. Since the degradation-rate-ratio increases exponentially, it is predicted that the degradation rate will be nearly 10 times larger on the throttling operation on which the flow rate is throttled.

IV. Conclusion

In this research we changed the propellant flow rate of the microwave discharge neutralizer and measured ion currents, and calculate the abundance ratio. The following facts are confirmed in this experiment.

1) The abundance ratio of doubly ionized xenon increases in the discharge chamber of microwave discharge neutralizer as the propellant flow rate decreases.
2) The abundance ratio of doubly ionized xenon is the lowest at 0.7 sccm.
3) The ion saturation current doesn't change regardless of the flow rate change.
4) The degradation rate exponentially increases as the propellant flow rate decreases.

Based on these facts, we conclude that the difference of neutralizer's lifetime between the ground test and the space operation is caused the lower propellant flow rate operating due to the throttling operation. Because of the throttling operation, the doubly ionized xenon increased in the discharge chamber of neutralizer, and the degradation due to sputtering was accelerated. To extend the lifetime, it is important to minimize the abundance ratio of doubly ionized xenon to singly ionized xenon. To speak about "Hayabusa 2", the nominal flow rate of the neutralizer is changed from a conventional 0.5 sccm to 0.7 sccm, and this nominal propellant flow rate change will contribute to extend the neutralizers' lifetime.

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