Estimation of Erosion Rate for Surface Material on HAYABUSA2 by Measurement of Backflow Ions from 10-cm-class Ion Thruster

IEPC-2019-337

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: Erosion of the surface material around the ion thrusters has been detected on HAYABUSA2 spacecraft by its onboard surface contamination sensors during the operation of its µ10 ion thrusters. It is considered that the erosion is caused by the backflow ions from the thruster plume because the erosion clearly has correlation with the operation of the ion thrusters. To evaluate this presumption, we made a ground testing using a rotating retarding potential analyzer to obtain parameters of the backflow ions from µ10, the angular dependent energy distribution of the backflow ions. The erosion rate was estimated by the experiment results adopting Yamamura's formula, and the estimated erosion rates at a distance of 15 cm and 40 cm from the thruster center showed good agreement with the flight data detected onboard HAYABUSA2. This result show that the detected erosion must be caused by the impingement of the backflow ions from the thruster and also showed the ground testing procedure can make an order estimation of the erosion around the ion thrusters in space operation.

Nomenclature

I_i	=	ion current onto collector, A
I_{i0}	=	total ion current onto collector, A
V_C	=	bias voltage to collector, V
V_{ERG}	=	bias voltage to electron retarding grid, V
V_{IRG}	=	bias voltage to ion retarding grid, V

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I.Introduction

THE Japanese asteroid explorer "HAYABUSA2"[1] had been developed as the follow on spacecraft after "HAYABUSA" mission, and launched on December 2014 to the asteroid "RYUGU" by JAXA. HAYABUSA2 is powered by ion engines[2] and is now traveling to the asteroid for the sample return mission from the asteroid. Since it has been launched in 2014, the total operation time of the thrusters have exceeded to 6,000 hours on June 2018, and successfully reached the target asteroid "Ryugu" on schedule.

Meanwhile, HAYABUSA2 has two sensors of Quartz Crystal Microbalance (QCM)[3] near the ion thrusters to measure the amount of its surface contamination mostly from the thruster-oriented particles. During the operation of the thrusters, the sensors have detected the reduction of the mass although the gain of the mass was expected due to the contamination at first. It is considered that the reduction of was occurred due to the surface sputtering by the propellant ions flowing to the spacecraft, because the reduction has correlation between the operation of the thrusters. So, it is of importance for designing the spacecraft with ion thrusters to estimate the sputtering because it can cause degradation of the surface properties of the spacecraft surface, e.g. the thermal control materials around the ion thrusters installed on HAYABUSA2. The backflow ions, the incident of the sputtering, are considered to be the charge-exchange (CEX) ions accelerated toward the spacecraft by the potential difference between the spacecraft and the plasma plume. The CEX ions are originally produced in the plume by collisions between the fast beam ions and the thermal neutral gas emitted from the thruster, then the CEX ions have thermal velocity.

To evaluate the surface erosion measured by HAYABUSA2, we conducted the ground testing to obtain parameters of the backflow ions from the "μ10" ion thruster that was the same type of the thruster mounted on HAYABUSA2. In the experiment, we measured the energy distribution using a retarding potential analyzer (RPA), and also angular dependent energy distribution using the rotating RPA with a collimator. We can calculate the sputtering yield (atoms/ion) for a surface material due to the impingement of a single ion with energy and an incident angle onto the surface by Yamamura's formula[4, 5], and then, also can calculate the erosion rate ($m^{-2} \cdot s^{-1}$) by multiplying the sputtering yield and the flux of the incident ions.

In this paper, we introduce the flight data detected onboard HAYABUSA2, ground testing to measure the parameters of the backflow ions, and procedure to calculate the erosion rate from the experiment data. Comparison of the erosion rate estimated by the experiment and detected by HAYABUSA2 is also shown.

II.Flight Data of the Erosion Rate

Fig. 1 shows the picture of the ion thrusters "μ10" on HAYABUSA2. The spacecraft has four thrusters, and at most, three of four are simultaneously operated. The two QCM sensors are also shown in the figure. The head of the two sensors are made of 200 nm thick polyimide and gold foil for QCM1 and QCM2 in Fig. 1 to compare the difference of the erosion rate of these materials. Fig. 2 indicates the flight data for the erosion rate detected by the QCM sensors.[6] The data shown here is the erosion rate in the operation of at least one ion thruster against the distance between the sensor and the nearest operating thruster. We can recognize that the maximum erosion rate is about 90 ng/cm^2/h for gold foil of the QCM2 sensor head. That erosion rate is equivalent to about 0.046 nm/h in

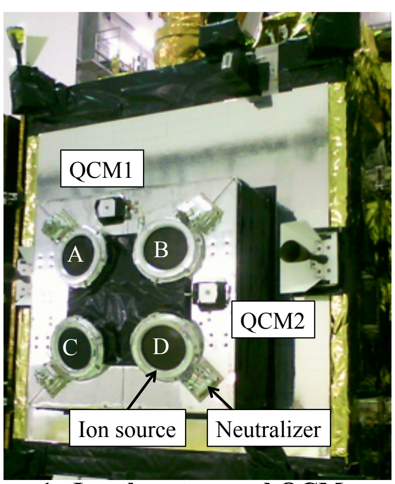

Figure 1. Ion thrusters and QCM sensors mounted on HAYABUSA2.

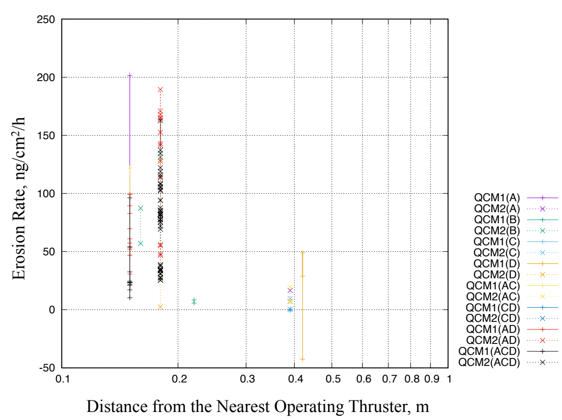

Figure 2. Erosion rate detected by the QCM sensors in the thruster operation onboard HAYABUSA2.

depth, and the total depth of the erosion will reach 0.60 μm in the scheduled total operation time of the ion thruster of 13,140 hours.[6]

III.Laboratory Experiment

A. Equipment of the ground testing

The ground testing to obtain the parameters of the backflow ions from the ion thruster was carried out in a large-scale vacuum chamber called "Endurance Test Chamber"[7] at ISAS/JAXA. Fig. 3 shows the appearance of the chamber. The cylindrical main vacuum tank of 2 m in diameter and 5 m in length achieves high vacuum of 4.6 × 10^{-4} Pa at the flow rate of 8 sccm of Xe gas for the propellant of the ion thruster. In the experiment, the ion thruster μ10 that was the same type of the thruster mounted on HAYABUSA2 was used to simulate the in-orbit thruster operation for HAYABUSA2 and the thruster was installed in the chamber as illustrated in Fig. 4. The operation parameters of μ10 in this experiment are summarized in Table I. The energy and current of the backflow ions from the thruster plume were measured by retarding potential analyzers and Faraday probes, respectively.

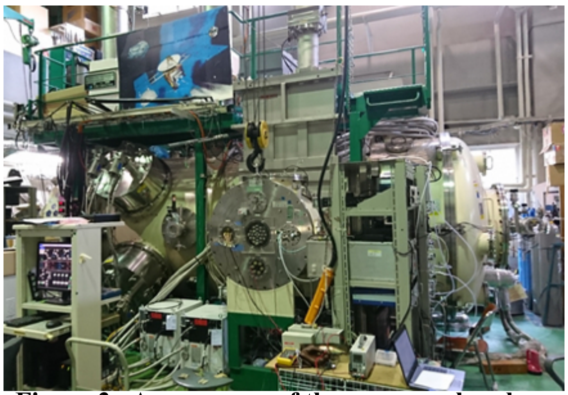

Figure 3. Appearance of the vacuum chamber.

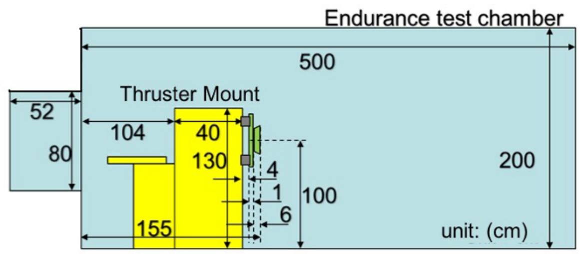

Figure 4. Experiment set up of the ion thruster installed in the vacuum chamber.

B. Energy measurement of the backflow ions

To obtain the energy of the backflow ions from the ion thruster, retarding potential analyzers (RPAs) were newly developed and used in the ground testing. RPA is one of the energy analyzers to obtain energy distributions for charged particles.[8] The appearance of the RPA is shown in Fig. 5 (a), and the schematics of the cross sections of the RPA connected to the simplified electrical circuit is also shown in Fig. 5 (b). The RPA has three electrode grids between the collector and the opening of the RPA to control the charged particle reaching the collector in terms of their energy and charge. Each electrode installed in the RPA is as follows: (1) Floating grid (FG) is biased to a certain potential to prevent leakage of the internal electric field of RPA that would affect the current collection into the opening of the RPA. (2) Electron retarding grid (ERG) is biased to a negative potential to the outer plasma potential to prevent electrons from passing through to the collector. (3) Ion retarding grid (IRG) is biased to a sweeping potential so that the incoming ions whose energy exceed the potential can only pass through the grid. (4) Ion collector collects ions that have passed through all the grids. The collector is biased to a negative potential to support the collection of the ions.

Table 1. Operation parameters for μ10 ion thruster.

	Ion source	Neutralizer
Flow rate of Xe, sccm	2.61	0.94
Input microwave power, W	26.9	8.42
Screen voltage, V	1500	–
Screen current, mA	180	–
Accelerating voltage, V	-350	–
Accelerating current, mA	1	–
Decelerating voltage, V	-36	
Bias voltage, V	–	-36
Current, mA	–	181

Figure 6 shows the biased voltage to each electrode and the ideal potential distribution in the RPA. The biased potential to ERG, V_{ERG}, is determined to the lower potential than the biased potential to the neutralizer to reflect the incoming neutralizer electrons. The biased potential to the collector, V_C, is biased to –40 V due to the limitation from the amperemeter. The three electrode grids are made of stainless mesh whose hole size is 0.062 mm that is comparable to or smaller than the Debye length of the plasma in the plume.

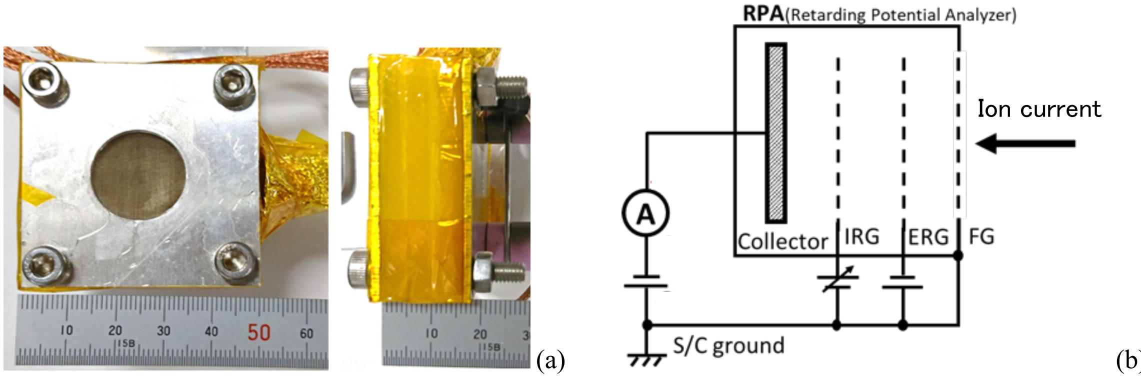

Figure 5. (a) Appearance of the RPA: front view (left) and side view (right), and (b) schematic of the cross section of the RPA connected to a simplified circuit.

As mentioned before, the collector collects ions only exceed the potential biased to IRG, V_{IRG}, hence the collector current as a function of the ion energy is obtained at a certain V_{IRG}. Therefore, the energy distribution of ions can be calculated by the differential of the collector current with respect to the V_{IRG}, that corresponds to the ion energy as Eq. (1), where I_i and I_{io} is the collector current at a certain V_{IRG} and at V_{IRG} of 0 V, respectively.

$$f = -(1/I_{i0})(dI/dV_{IRG}) = -d(I_i/I_{i0})/dV_{IRG} \qquad (1)$$

We carried out the ground testing to measure the energy of the backflow ions from the μ10 ion thruster by the RPA. Figs. 7 and 8 show the experiment setup and the location of the RPA. The RPA was located on the plate facing the exit direction of the thruster. It was located 15 cm apart from the center of the thruster duplicating the location of the QCM sensor from the nearest thruster mounted on HAYABUSA2. The procedure of the measurement was as follows; First, the ion current was measured five times at a certain IRG voltage during the voltage was swept from 0 V to 90 V by 1.0 V. Second, the first procedure was repeated three times. Then, the ion current against the IRG voltage was obtained as shown by crossed symbols in Fig. 9, where the current was normalized by 7.76×10^{-9} A that was the current at the IRG voltage of 0 V. The current was analyzed by generalized reduced gradient (GRG) non-linear least-squares method, and we obtained the fitted curve of double gaussian cumulative probability distribution as shown by dotted line in Fig. 9. Applying Eq. (1) to the obtained cumulative probability distribution, we can obtain the energy distribution as shown by the black solid line in Fig. 9. The energy distribution has two peaks, one is about 6 V and the other is about 22 V. Note that the voltage in V corresponds to the ion energy in eV. The two gaussian probability distributions decomposed from the energy distribution are shown by red and blue lines in Fig. 9.[9] Details of those peaks are summarized in Table II. The double peaks shown in the energy distribution can be explained by the difference of the origin of the backflow ions in the plume.

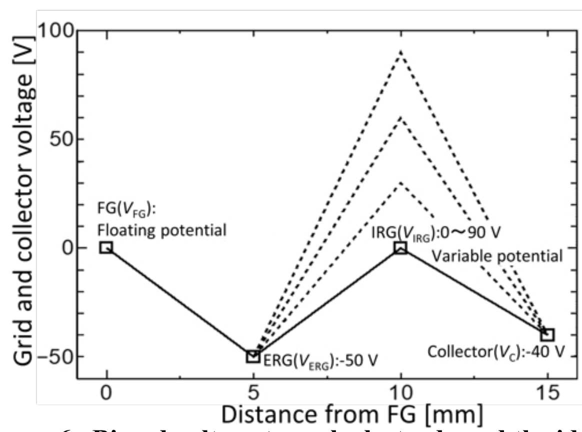

Figure 6. Biased voltage to each electrode and the ideal potential distribution in the RPA.

C. Angular dependency of the backflow energy

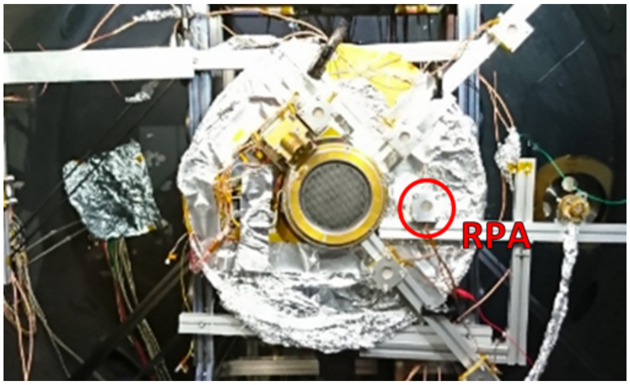

Figure 7. Experiment setup of the ion thruster and RPA.

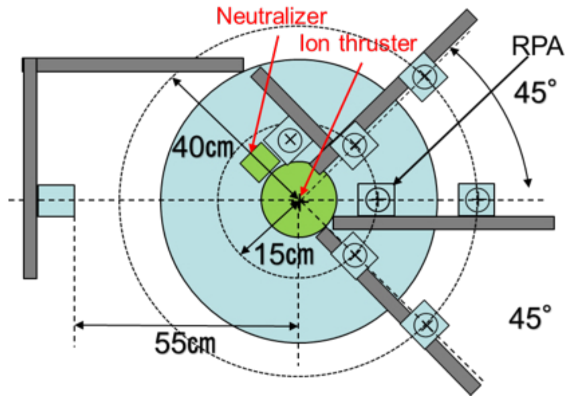

Figure 8. Schematic of the location of RPA.

The energy of the backflow ions is determined by the potential difference between the plume and the spacecraft. The plume potential is higher as the distance from the thruster approaches zero in the plume. Also, the incident angle is the parameter[5,10] to calculate the sputter yield for the incident ion. So, we had also conducted the experiments to obtain the angular distribution of the backflow energy. We modified the setup of the RPAs to detect the angular distribution of the backflow ions incoming the RPAs; the collimator was attached to the opening of the RPA to reduce the opening angle from the collector of the RPA from 50.0 deg. to 14.7 deg. as shown in Fig. 10. The appearance of the RPA with the collimator is shown in Fig. 11. The RPA was mounted on a stepper motor to control the normal direction of the opening of the RPA. Fig. 12 shows the setup of the RPA near the ion thruster. The RPA was located as its center was at a distance of 15 cm from the thruster center and was the same horizontal level. The tip of the collimator protruded about 6 cm from the thruster exit in the beam axis. We had also installed another rotating RPA whose center was located at a distance of 40 cm from the thruster and also measured the angular dependency of the backflow energy.

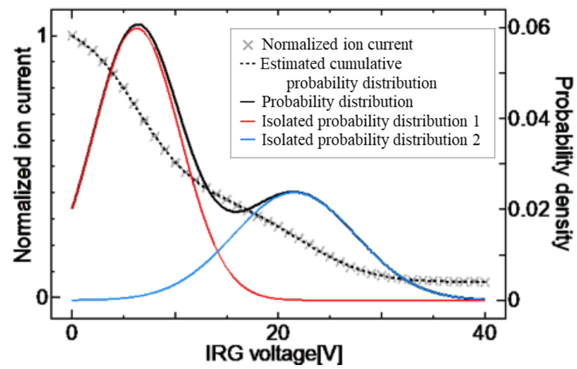

Figure 9. Experiment data and obtained normalized ion current and probability density of the ions as a function of energy at the distance of 15 cm from the thruster center.

Table 2. Parameters of the double Gaussian distribution functions.

	Height of peak	Average energy, eV	Standard deviation, eV
Lower energy	0.0601	6.56	4.21
Higher energy	0.0247	21.5	5.57

Fig. 13 shows the locations of the thruster and the RPA and definition of the angles that the collimator was faced. The backflow energy was measured with the RPA facing 10 angles defined in Fig. 14, -90, -60, -30, 0, 15, 30, 45, 60, 75, 90 deg. Currents obtained with the angle of -90 deg. and -60 deg. were very low signal to noise ratio so we could not use data to analyze the energy distributions.

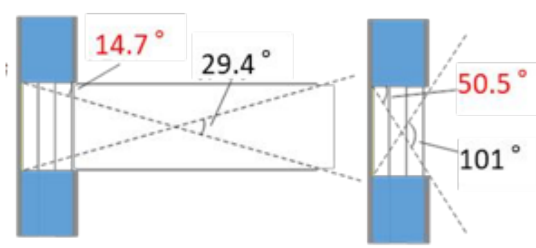

Figure 10. Opening angle of the RPA with or without collimator.

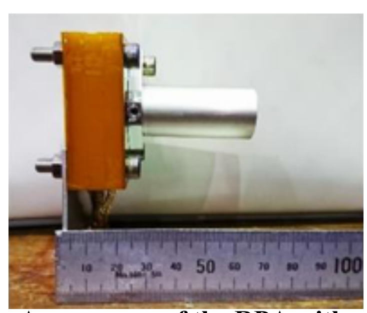

Figure 11. Appearance of the RPA with collimator.

At other eight facing angles of the RPA, we could obtain currents to analyze the energy distribution of the backflow. The currents were fitted by Gaussian cumulative probability distribution as described in previous section. In this procedure, we selected single or double Gaussian cumulative probability distribution to better reproduce obtained currents. Tables 3 and 4 shows the parameters of the Gaussian distribution functions obtained by the analysis with the RPA located at 15 cm and 40 cm showing the energy distributions of the backflow at each RPA facing angles, respectively. From the results, we can recognize increase of the backflow energy as well as the current as increase of the RPA facing angle. Figs. 14 and 15 indicate the backflow energy and the flux as a function of the angle. In Table 3, we can see that the backflow energy increases from 7.05 eV to 43.2 eV as the angle from -30 deg. to 90 deg. at the distance of 15 cm, and that increases from 0.10 eV to 37.46 eV at the distance of 40 cm. This tendency can be explained that the higher plume potential in the vicinity of the thruster exit will accelerate the backflow ions more than downstream region of the thruster. The maximum plume potential is expected to be about 43 V, which is almost equivalent to the maximum backflow energy measured by the RPA. Also, in Table 4, we can see that the backflow current greatly increases from 10-10 A to 10-7 A as the angle from -30 deg. to 90 deg. at the distance of 15 cm, and that increases from 10-10 A to 10-8 A at the distance of 40 cm. This tendency can be also explained as before that the higher plume potential in the vicinity of the thruster exit can accelerate the backflow ions more. In addition, in the vicinity of the thruster exit, the production rate of CEX ions, the backflow ions, is higher than downstream region, so the both current components of velocity and number density of the backflow ions will be magnified in the vicinity of the thruster exit.

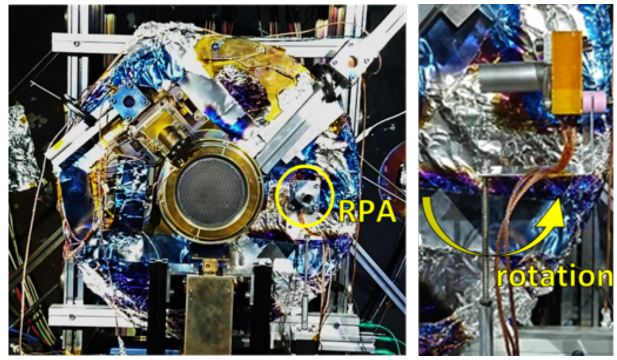

Figure 12. Setup of the rotating RPA. (at the distance of 15 cm)

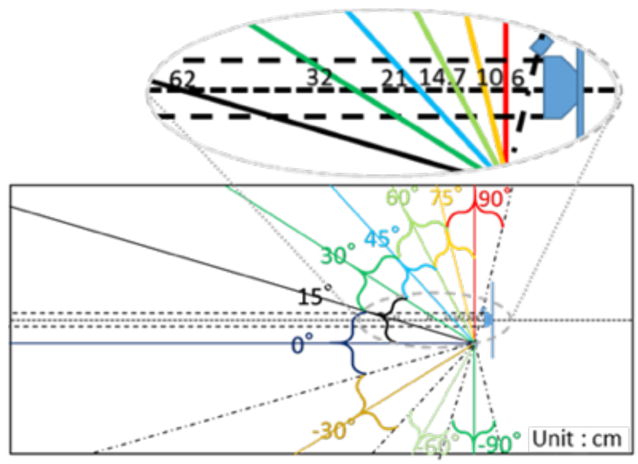

Figure 13. The cross-point of the centerline of the opening of the RPA and that of the thruster (top) and angle of rotation of the RPA at the distance of 15 cm.

D. Estimation of the Erosion Rate

The estimation of the erosion rate of a surface material on the spacecraft due to the impingement of the backflow ion is made as follows. The sputtering yield of a material due to the impingent of normal incident of a single ion (atoms/ion) can be obtained by the Yamamura's formula from Eq. (2) as a function of the energy of the ion, [4]

$$Y(E) = 0.042\frac{Q(Z_2)\alpha^*(M_1/M_2)}{U_s}\frac{S_n(E)}{1+\Gamma k_e \varepsilon^{0.3}}\times\left[1-\sqrt{E_{th}/E}\right]^s \tag{2}$$

The angular dependence of the sputtering yield $Y(\theta)$ to the sputtering yield for normal incident of ion $Y(0)$ can also be expressed by Yamamura at al. as Eq. (3) , [5]

$$\frac{Y(\theta)}{Y(0)} = t^f \exp\left[-\Sigma(t-1)\right] \tag{3}$$

Details of the parameters in Eqs. (2) and (3) are described in the literature. (4) and (5), respectively.

Applying the experiment data obtained by the RPAs at 15 cm and 40 cm facing at a certain angle to Eqs. (2) and (3), we analytically calculated the erosion rate as follows. We decomposed the obtained energy distribution (e.g. Fig.

Table 3. Parameters of the Gaussian distribution functions obtained by RPA located at 15 cm from the thruster center.

RPA angle, deg	Hight of peak	Average energy, eV	Standard deviation, eV	Total current, A
-30	0.0906	1.67	0.54	4.56E-10
	0.184	7.05	1.59	
0	0.123	9.42	2.28	6.43E-10
15	0.0774	12.3	4.52	8.67E-10
30	0.0121	11.4	7.16	1.77E-09
	0.0833	20.4	2.71	
45	0.0104	2.29	9.76	7.37E-09
	0.0772	29.4	4.11	
60	0.005	2.01	4.47	3.55E-08
	0.0818	38.5	4.59	
75	0.0973	41.9	4.05	1.03E-07
90	0.117	43.2	3.23	1.49E-07

Table 4. Parameters of the Gaussian distribution functions obtained by RPA located at 40 cm from the thruster center.

RPA angle, deg	Hight of peak	Average energy, eV	Standard deviation, eV	Total current, A
-30	0.531	0.10	1.09	1.93E-10
0	0.0141	0.10	19.67	2.73E-10
	0.0950	0.10	2.80	
15	0.0202	9.11	12.86	3.52E-10
	0.0572	8.23	1.89	
30	0.0137	18.29	7.12	6.82E-10
	0.0697	13.63	3.72	
45	0.0256	20.04	7.04	4.50E-09
	0.0479	25.12	4.39	
60	0.0266	27.02	9.36	1.45E-08
	0.0366	35.61	3.71	
75	0.0209	25.20	8.88	2.53E-08
	0.0359	35.64	4.73	
90	0.0133	20.63	8.58	2.35E-08
	0.0372	37.46	5.56	

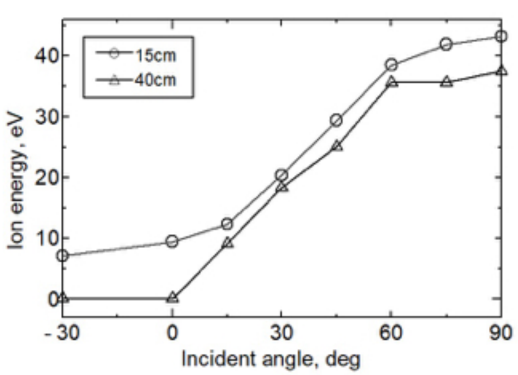

Figure 14. Angular dependence of the backflow ion energy.

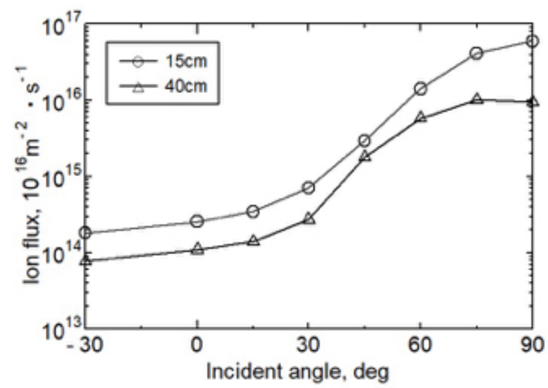

Figure 15. Angular dependence of the backflow ion flux.

9) into minute trapezoid whose width is of 0.1 eV, and obtained the flux corresponding to the energy. Substituting the energy into Eq. (2) and correcting the angular dependence by Eq. (3), we can obtain the minute sputtering yield for a single incident ion with the energy. Then, we can calculate the minute erosion rate ($m^{-2} \cdot s^{-1}$) by multiplying the minute sputtering yield and the flux of the backflow corresponding to the energy. Finally, we can obtain erosion rate by summation of the minute erosion rate for total backflow energy.

Table 5 shows the flux of backflow ions and the erosion rate that is calculated by the procedure mentioned above at 15 cm and 40 cm from the thruster center. The estimated erosion rate at 15 cm and at 40 cm is of 2.58×10^{14} $m^{-2} \cdot s^{-1}$ and 3.51×10^{13} $m^{-2} \cdot s^{-1}$, respectively. Meanwhile, the flight data that was detected onboard HAYABUSA2 shows the maximum erosion rate at 14 cm and at 39 cm from the nearest thruster center 7.42×10^{14} $m^{-2} \cdot s^{-1}$ and 1.41×10^{14} $m^{-2} \cdot s^{-1}$, respectively. The estimated erosion rate at the distance of 15 cm and 40 cm is 2.9 and 4.0 times greater than each flight data, but we can say the erosion rate estimated by the ground testing shows almost good agreement with the flight data. The difference of the erosion rate estimated by the ground testing and the flight data is considered due to the potential difference between the thruster plume and the spacecraft potential in the ground testing and space. The potential difference will result from the difference of the plume potential and the spacecraft potential between in the ground testing and space. In the ground testing, for example, the secondary electrons emitted from the chamber wall due to the impingement of the high-energy (up to 1.5 keV) xenon ion could reduce the plume potential, in space, spacecraft potential will have some non-zero value that has determined by the net current onto spacecraft reaches zero.

Table 5. Flux of backflow ions and the erosion rate estimated by RPA data located at 15 cm and 40 cm from the thruster center.

RPA angle, deg	15 cm		40 cm	
	Flux, $m^{-2}s^{-1}$	Erosion Rate, $m^{-2}s^{-1}$	Flux, $m^{-2}s^{-1}$	Erosion Rate, $m^{-2}s^{-1}$
-30	1.82E+14	9.21E-21	7.71E+13	7.80E-138
0	2.56E+14	2.29E-01	1.09E+14	4.91E+10
15	3.46E+14	1.00E+09	1.40E+14	5.25E+10
30	7.06E+14	2.87E+11	2.72E+14	9.70E+10
45	2.94E+15	3.61E+13	1.80E+15	6.55E+12
60	1.42E+16	2.21E+14	5.77E+15	2.83E+13
75	4.11E+16	4.92E+11	1.01E+16	5.12E+09
90	5.94E+16	2.20E-111	9.38E+15	1.40E-93
Total	1.19E+17	2.58E+14	2.76E+16	3.51E+13

IV.Conclusion

We have conducted the ground testing to obtain the energy distribution of the backflow ions from the 10-cm-class μ10 ion thruster to evaluate the detected surface erosion around the ion thrusters by the QCM sensors mounted on HAYABUSA2. The energy distribution was measured using RPA, and angular dependency of the distribution was also measured by the rotating RPA with the collimator. The erosion rates at the distance of 15 cm and 40 cm from the thruster center were estimated by the experiment results adopting Yamamura's formula. The experiment results show good agreement with the flight data detected onboard HAYABUSA2. That shows that our ground testing procedure to estimate the erosion rate due to the backflow ions from the ion thruster is appropriate to evaluate the erosion in space operation.

Acknowledgments

The authors would like to express our gratitude to the ISAS/JAXA and the member of Kuninaka-Nishiyama laboratory at ISAS/JAXA for their cooperation with this research.

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