The Effect of Discharge Mode on Ion Energy and Plasma Potential in the Plume Plasma Region*

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The ion energy angle distribution and its relationship to plasma parameters for spot and plume modes are elucidated for a LaB₆ hollow cathode with a radiative heater. Measurements were conducted using a retarding potential analyzer (RPA) and a single Langmuir probe. The ion energy distribution function (IEDF) characteristics showed different tendencies in the current density and mass flow-rate dependence under different plasma modes. The IEDF peak potential for the spot mode varied from 16 to 23 V with increasing current density, and the IEDF peak potential for the plume mode varied from 16 to 32 V with decreasing mass flow rate. Considering angle dependency of ion energy, when the observation angle was changed from the radial direction to the axial direction, the IEDF peak potential increased from 29 to 40 V for the plume mode (10 A, 10 sccm) and increased slightly from 16 to 18 V for the spot mode (20 A, 30 sccm). The probe measurement analysis revealed that the IEDF peak energies are the same as, or exceed, the plasma potential and have a qualitative correlation with the electron temperature spatial distribution.

Key Words: Hollow Cathode, Plasma Diagnostics, Ion Energy Distribution Function

Nomenclature

V: electric potential
I: current
θ: angle
L: characteristic length
e: elementary charge
k: Boltzmann constant
σ: standard deviation

Subscripts

e: electron
p: plasma
p-max: maximum plasma
p-min: minimum plasma

1. Introduction

A Hall-effect thruster has high thrust density and a high thrust-to-power ratio, making it promising for applications such as use in all-electric satellites and space cargo missions. Research teams in several countries, including the United States, Russia, France, and Japan, have thus developed and studied its applications and technologies.1–5 In particular, the Japan Aerospace Exploration Agency (JAXA) is developing Engineering Test Satellite-9 (ETS-9), for which a 6-kW-class Hall-effect thruster is under development. This thruster achieved a high thrust level of 392 mN with a specific impulse of 1,940 s.6 A hollow cathode is utilized as the neutralizer of this ion-emitting Hall-effect thruster; and therefore, the development of a high-current hollow cathode is critically important for achieving high power. Hall-effect thrusters generally create plasma by ionizing the introduced precursor gas with electrons emitted from a low-work-function material (i.e., thermionic emitter). In the plasma ignition phase, pre-heating of the thermionic emitter is necessary to initiate electron emission. Continuous electron emission and plasma generation are realized by self-heating of the thermionic emitter, which is achieved via ion bombardment derived from the generated plasma.

During operation, the hollow cathode is eroded by the plasma, and this wear increases as the discharge current increases.7–9 It is presumed that the presence of high-energy ions in the hollow cathode plasma causes the wear. Because the electric propulsion systems are expected to operate under a time scale of tens of thousands of hours, materials used in the cathodes can be sputtered by the continuous incidence of ions in the hollow cathode plasma even though the sputtering amount of one ion incidence is low. Ohkawa et al. performed a 45,660-h life test on a graphite hollow cathode.10 The hollow cathode had sufficient life capability under typical operating conditions; however, there was erosion of the graphite orifice after the life test. Wear due to the high-energy ions is presumed; however, their generation method and energy-gaining mechanism are not completely understood.

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*Received 5 August 2020; final revision received 10 February 2021; accepted for publication 2 June 2021.
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DOI: 10.2322/ijss.65.1
Several studies on high-energy ion production in hollow cathode plasmas have been conducted. Siegfried and Wilbur reported the characteristics of a Hg hollow cathode. They used the Langmuir probe technique to measure the on-axis spatial distribution of plasma parameters, and observed the presence of steep electron temperature and plasma potential gradients in the plume mode downstream plasma.11 Friedly and Wilbur directly measured the ion energy characteristics using a retarding potential analyzer (RPA), and proposed the generation of high positive potentials (i.e., potential hill) just downstream of the cathode orifice via positive space charge accumulation induced by high-rate ionization, which supports the idea of ion acceleration due to the potential gradient.7) Goebel et al. reported the measurement results of a fast scanning probe for the elucidation of plasma parameters, including the on-axis and on-radius plasma potential structure, electron temperature, and plasma density for several plasma conditions, and found no large potential hills in the experiment.12)

In other research, Goebel et al. measured the ion energy distribution function with plasma parameters and found that higher gas flows and lower discharge currents reduce the energy of the ions produced in the plasma.13) They focused on the plasma potential fluctuation and proposed that oscillations related to ionization instability affect the generation of high-energy ions. Ionization instability can be explained by understanding the balance of the inflow and outflow of the neutral particle and electron densities, known as the predator-prey model.14) When the electrons ionize an excessive number of neutral particles, the ionization rate decreases due to reducing the number of neutral particles, which leads to a decrease in electron density. This fluctuation of electron density results in potential fluctuation, which can transfer energy to ions based on the relationship between the wave phase velocity and velocity of each particle via Landau damping. This energy transfer occurs when the particle velocity is close to the wave phase velocity, and the energy is transferred to particles when the particle velocity is less than the wave phase velocity. Ionization oscillation is observable in the 10–30 kHz band and is known to be influenced by several parameters, including the magnetic field, discharge potential, and mass flow rate.15,16) In the predator-prey model of ionization instability, the effect of suppressed neutral particle exhaustion on suppressing the ion energy has been studied.17,18) The increased mass flow suppresses the exhaustion of neutral particle density, which also suppresses ionization instability.

The correlation between ion acoustic turbulence (IAT) wave energy and ion energy was discussed by Dodson et al.19) The transfer of electron kinetic energy to ion kinetic energy through wave energy can be caused by the electrostatic instability in IAT. The existence of IAT and its contribution to ion heating were examined by Jorns et al. and Dodson et al.19,20) The wave in IAT is the fluctuation of potential created by the difference in the velocities of electrons and ions. When the drift velocity of electrons is higher than the ion acoustic velocity, the ions cannot follow the electrons and are left behind. The preceding electrons create an electric field in the vector of electrons, pulling the ions forward, and then the electric field is relaxed. In this fluctuation, because the phase velocity of potential fluctuation, which should be close to the ion acoustic velocity, is slower than the electron drift velocity, electrons transfer energy to the wave through inverse electron Landau damping. The ions then gain energy from the potential fluctuation via ion Landau damping. In previous research, fluctuations in the high-frequency region of 400–1000 kHz were observed under high-discharge-current conditions; these fluctuations generated high ion energy.20) A qualitative correlation between the wave energy and ion heating that includes a scaling parameter that depends on plasma parameters and a low cutoff frequency was reported.

Regarding the ion energy distribution function (IEDF) structure, Kameyama and Wilbur conducted a detailed analysis using an electrostatic energy analyzer on axis, and reported the effect of the discharge current and flow rate on IEDF, including the difference between the spot and plume plasma modes.21)

Although the relationships among hollow cathode plasma modes, the high-energy ion generation mechanism, and plasma parameters have been investigated, the ion acceleration mechanism and its relationships with plasma operating conditions for different modes are still unclear. There is a possibility that the multiple factors have a combined effect on ion acceleration, and there are different factors involved for spot and plume modes.

In this research, aiming to develop a highly durable hollow cathode, relationships between the ion energy distribution function and the plasma conditions are discussed in and effort to elucidate the high-energy-ion generation mechanisms. More specifically, the angle distribution, mass flow rate dependence, and discharge current dependence of IEDF for spot and plume modes are elucidated in Chapter 3. Then, in Chapter 4, their relationships with plasma parameters from the perspective of two-dimensional distribution are discussed parametrically. The angle distribution of IEDF is measured to evaluate its correspondence to plasma parameter spatial dependence from the perspectives of isotropy and anisotropy.

2. Experimental Setup

2.1. Hollow cathode with radiative heater

In this research, a LaB₆ hollow cathode with a radiative heater was used. A schematic diagram of the hollow cathode is shown in Fig. 1. The hollow cathode was composed of a cylindrical LaB₆ insert, a cathode tube as an insert container, a radiative heater with a covered radiation shield to isolate radiation, and a keeper to cover all of these components. The keeper diameter was 34 mm and the orifice inner diameter was 2 mm. The LaB₆ insert was pushed to the edge using a sleeve and spring. The radiative heater was placed between the cathode tube and a heat shield; the heater and the tube did not make contact. The performance and characteristics of the hollow cathode with a radiative heater are described in previous research.22–25)
2.2. Plasma discharge setup

A schematic diagram of the plasma discharge setup is shown in Fig. 2. The vacuum chamber had a diameter of 600 mm and a length of 1000 mm. Two sets of turbo-molecular pumps with a pumping speed of 4300 L/s and a rotary pump with a pumping speed of 1500 L/s were used for exhaust. The plasma was ignited after the background pressure reached a value on the order of $10^{-4}$ Pa. Xe gas, used as a propellant gas, was pumped into the cathode from the backside of the cathode tube. Here, the Xe gas input amount was controlled to be 10, 20, 25, or 30 sccm using a mass flow controller. The power supplies (PSs) for the cathode heater and the keeper were connected to the cathode, and a PS for the anode was connected to a graphite cylindrical anode (outer diameter: 63 mm; inner diameter: 59 mm; length: 69 mm). The anode was placed 40 mm downstream of the hollow cathode. The plume and spot modes of the plasma mode are determined by the appearance of plasma and the standard deviation of discharge voltage.25) The mode is determined as spot mode if \( \sigma^2 < 0 \):, and is determined as plume mode if \( \sigma > 0.2 \) V.

2.3. Ion energy measurement setup

Figure 3 explains the experimental setup for ion energy measurement. A RPA composed of one ion collector and three grids was used. The first grid, which was the first grid to contact the plasma, was electrically floated to block the disturbance caused by the controlled potential changes of the second and third grids. A bias potential of -30 V was applied to the second grid for electron shielding, and the potential applied to the third grid was swept between 0 to 100 V for ion rejection and measurement. A 0.25-Hz single triangular wave (Fig. 3(c)) was generated and applied to the third grid. The corrected ions were measured at a sampling rate of 10 kHz. The distance from the RPA to the cathode \((L)\) was kept constant at 130 mm. The facing angle \((\theta)\) was controlled to 0°, 45°, or 90° to examine the angle dependence of ion energy.

2.4. Plasma diagnostics setup

Figure 4 is the experimental setup for analyzing the plasma parameters. A single Langmuir probe, namely a tungsten wire (diameter: 0.3 mm; length for plasma contacted volume: 0.9 mm) covered by a ceramic tube (inner diameter: 0.4 mm; outer diameter: 1 mm), was used for plasma diagnostics. The probe current-voltage (I-V) characteristics were measured to analyze the plasma potential distribution in the plasma plume region. Figure 4(a) shows the measurement positions for single-probe measurement. The origin point was 2 mm from the cathode exit on the axis. On the axis, the I-V characteristics were measured at 4-mm intervals up to 36 mm. In the radial direction, the I-V characteristics were measured at 5, 10, 20, and 28 mm from the origin. Additional points on the axis at 48, 68, 88, 108, and 128 mm from the origin are also measured as the inner anode region. For probe measurement, the I-V characteristics were measured by the sweeping rate of 1 Hz with a sampling rate of 50 kHz. High-frequency noise was removed by setting the frequency band limit of the oscilloscope/data acquisition recorder (DL850E ScopeCorder, Yokogawa Test & Measurement Corp.) to 10 kHz.

Electron temperatures were calculated from the I-V characteristics using Eq. (1), and the plasma potential was determined as the intersection point of two tangent lines of the transition region and the electron saturation region, respectively, in the semi-log plot of the I-V characteristics.

$$\frac{d\ln I_e}{dV_p} = \frac{e}{kT_e}$$  \hspace{1cm} (1)
The error calculation method is shown in Fig. 4(c). The dotted lines represent the inclination of the transition region line and electron saturation region line. The electron temperature was determined using this inclination and Eq. (1). Because this inclination varies with time oscillation, lines can be drawn based on the maximum and minimum inclination. The maximum and minimum electron temperatures were calculated from these inclinations and represent the error in electron temperature. Using these inclination lines and the maximum and minimum tangent lines in the electron saturation region, the maximum and minimum plasma potentials were determined from the intersection points, as shown in Fig. 4(c).

3. Results

3.1. Plasma modes and conditions

Table 1 shows the plasma modes, discharge voltage, and saturated current density measured using the RPA at a 0-V bias for the corresponding plasma parameters. Under the measured conditions, the trend indicates that the plasma mode is more likely to be plume mode when less Xe is introduced to the cathode and the discharge current is small. For a 10-A discharge current, the plasma mode is plume mode for all mass flow rates. For 20- and 30-A discharge currents, the plasma mode changes from plume mode to spot mode as the mass flow rate increases. The mode changes to spot mode at a lower mass flow rate when a higher current is applied to the cathode.

| Mass flow rate (sccm) | Discharge current (A) | Mode | $V_d$ (V) | $I_{RPA}$ (µA) | Mode | $V_d$ (V) | $I_{RPA}$ (µA) | Mode | $V_d$ (V) | $I_{RPA}$ (µA) | Mode | $V_d$ (V) | $I_{RPA}$ (µA) |
|-----------------------|-----------------------|------|---------|-------------|------|---------|-------------|------|---------|-------------|------|---------|-------------|------|
| 10                    | Plume                 | 26.5 | 6.99    |             | Plume | 23.8    | 10.34       | Plume | 24.3    | 15.80       |       |         |             |      |
| 20                    | Plume                 | 23.8 | 5.00    |             | Plume | 18.0    | 6.68        | Spot  | 13.6    | 2.85        |       |         |             |      |
| 25                    | Plume                 | 22.9 | 4.89    |             | Plume | 13.5    | 1.91        | Spot  | 13.1    | 2.72        |       |         |             |      |
| 30                    | Plume                 | 22.2 | 4.71    |             | Spot  | 13.0    | 1.77        | Spot  | 12.9    | 2.69        | Spot  | 14.1    | 5.39        |      |

Fig. 5. (a) I-V characteristics of RPA current and (b) IEDF for the spot mode (20 A, 30 sccm), and (c) I-V characteristics of RPA current and (d) IEDF for the plume mode (10 A, 10 sccm).

3.2. Typical IEDF for spot and plume mode plasma

Figure 5(a) and (c) show the I-V characteristics measured using the RPA. To reduce noise, the moving average of the measured current is also shown in the figure. Measurement point regions of 200–500 points and 1000–2000 points were chosen for the moving average calculation of spot and plume modes, respectively. The RPA current for the spot mode decreased slowly from the potential region of about 0 V to 15 V, and then decreased significantly from around 15 V to 20 V. This indicates that many ions are shielded at a bias potential of 15 to 20 V, and that some ions are shielded at lower bias potentials. For the plume mode, the variation of current...
density for the swept bias potential is small compared with that for the spot mode, which indicates that the shielded ions are distributed in a wider potential range. Based on the calculated gradients of the calculated moving average of the currents in Fig. 5(a) and (c), the IEDFs were calculated, as plotted in Fig. 5(b) and (d). To reduce noise, the moving average obtained with the measurement point region of 200 points was chosen to calculate the moving average of the calculated gradients for both spot and plume modes. It can be seen that the distribution peaks correctly reflect the variation of current density for both spot and plume modes.

Figure 6 shows a comparison of IEDFs between the spot and plume modes. The IEDF of the spot mode has a narrow peak and that of the plume mode has a wide peak. Furthermore, the spot mode peak seems to be the superposition of at least two peaks, with the main peak located at a potential of 16 V and a wider peak located at a lower voltage of around 8 V. In contrast, the IEDF of the plume mode seems to have a single Maxwellian distribution with a peak at 29 V. These differences in peak potential and the 95% population extent at the high-voltage tail, which is beyond 18 V for the spot mode and 51 V for the plume mode, clearly show higher energy ion generation in the plume mode, which can accelerate material erosion of the spacecraft and cathodes.

3.3. Effect of mass flow rate and discharge current

Figure 7 shows the mass flow rate and discharge current dependences of the IEDFs for the spot and plume modes. For some conditions, the IEDFs seem to be composed of multiple peaks. The main peak is defined as the peak at higher potential, and the peak position is defined as the potential where the peak has the highest distribution probability. On the IEDFs, dotted lines are plotted to show the peak positions for the main peaks. When the mass flow rate increases, the peak position shifts to a lower potential for the plume mode, from 29 to 16 V, but remains unchanged for the spot mode. When the discharge current is increased, the peak potential shift shows no trend for the plume mode, whereas the peak position shifts to a higher potential, from 16 to 23 V, for the spot mode. The results indicate that the ions generated in spot (plume) mode plasma have high (low) sensitivity to discharge current, but low (high) sensitivity to the mass flow rate.

3.4. Angle dependence of IEDF

Figure 8 shows the angle dependence of the IEDFs for the spot and plume modes. It can be seen that the peak potentials of the IEDFs shift to a higher energy when the measurement angle changes from 0° to 90°. Furthermore, there is a difference in shift magnitude; the spot mode IEDF shifts less than the plume mode IEDF. The peak potential shows almost no
change from 0° to 90° for the spot mode (20 A, 30 sccm). The peak potentials are 16, 16, and 18 V for 0°, 45°, and 90°, respectively. For the plume mode (10 A, 10 sccm), the peak potential increased from 0° to 90°. Specifically, the peak potentials are 29, 37, and 40 V for 0°, 45°, and 90°, respectively. Furthermore, there is a difference in peak structure between the spot and plume modes; the IEDF peak for the spot mode does not greatly change from 0° to 90°, whereas that for the plume mode becomes wider. Regarding the 95% population extent, the border of the population for the spot mode is 18 V at 0°, and then increases to 20 V at 90°. For the plume mode, the border is 51 V at 0°, and then increases to 70 V and 79 V at 45° and 90°, respectively. Here, 0° (90°) is the condition in which the RPA is placed at, and is facing, the side (front) of the cathode. These results indicate that the energy of the ions generated in the plasma is higher for the front direction of the cathode compared with that for the side direction for both spot- and plume-mode plasma. The two modes had the same tendency for the angle dependence regarding the position of IEDF peak potentials, but different tendencies in the IEDF peak structures. The ion energy being higher in the axial direction is inconsistent with the study by Goebel et al., who found that it was lower. The reason for this inconsistency is unclear, although differences in anode structure and positions, and the existence or absence of an applied magnetic field may be responsible. Further study is needed.

4. Discussion

4.1. Ion energy and plasma parameters

Figure 9 shows the plots of IEDF peak potentials measured at 0° for several plasma conditions (i.e., controlled discharge current and mass flow rate). Peak potentials for spot-mode plasma show no dependence on the mass flow rate, but an increase as the discharge current increases. In contrast, peak potentials for the plume-mode plasma decrease significantly as the mass flow rate decreases, but there is no clear trend in terms of discharge current dependence. The ions generated in the plume-mode plasma have a higher dependence on the mass flow rate, whereas those generated in the spot-mode plasma have a higher dependence on the discharge current. The peak potentials of the IEDFs are equivalent to the energy of ions with the highest abundance ratio (i.e., the ion energy peak). The results in Fig. 9 indicate that the energies of the most abundant ions are higher in plume-mode plasma than in spot-mode plasma, especially in the low-mass-flow-rate region. When the mass flow rate is 30 sccm, the plume-mode plasma (10 A) has the lowest ion energy peak, namely, 16 eV; and the spot-mode plasma has higher or equal ion energy peaks, namely 16, 19, and 23 eV for 20, 30, and 40 A, respectively.

Three conditions for the mass flow rate dependence of the plume-mode plasma at a 10-A discharge current and one condition of the spot-mode plasma are considered for comparing the spot and plume modes at an equivalent ion energy (plume mode: 10 A, 10–30 sccm; spot mode: 20 A, 30 sccm). The relations between the plasma parameters and ion energies are discussed further below. Probe measurement at 10 A and 26 sccm was chosen for a comparison with RPA measurement at 10 A and 30 sccm due to the slight instability of the plume-to-spot mode change threshold. The conditions were chosen to fix the plasma to be in the plume mode. Figure 10(a) shows the radial distribution of plasma potentials for these conditions. If the main factor for ion acceleration in the radial direction is plasma potential, ion energies should follow the values of the radial plasma potential distribution. Regarding the mass flow rate dependence, the plasma potentials decrease when the mass flow rate increases, which is the same trend as that for the ion energy peaks of the plume-mode plasma. However, for plume-mode plasma with
4.2. Angle dependence of ion energy and plasma parameters

Figure 11 shows the angle dependence of the IEDF main peak potentials for several conditions. When the mass flow rate is 10 sccm, the highest plasma potentials in the measured region are 20, 18, and 16 V for mass flow rates of 10, 20, and 26 sccm, respectively. The corresponding ion energies for the RPA measurement conditions are 29, 26, and 16 eV, which significantly exceed the potentials. For the spot-mode plasma, the highest plasma potential in the region is 15 V for 20 A and 30 sccm, and the ion energy is 16 eV for the corresponding conditions. For 10 A, 30 sccm and 20 A, 30 sccm, the ion energies are almost equivalent to the plasma potentials. In contrast, for 10 A, 20 sccm and 10 A, 10 sccm, the ion energies exceed the corresponding plasma potentials. Plasma potentials may determine the base energy of ions. Some other factors may act as additional ion accelerators.

Figure 10(b) shows the electron temperature distribution in the radial direction for four plasma conditions. At the probe measurement point of 0 mm, the electron temperatures are 2.1, 1.2, and 0.9 eV for 10 sccm, 20 sccm, and 26 sccm at a discharge current of 10 A, respectively, and 1.0 eV for 20 A, 30 sccm. Regarding the radial electron temperature distribution, the electron temperatures for 10 A, 26 sccm (plume mode) and 20 A, 30 sccm (spot mode) have similar distributions, and are between 0.6 and 1.0 eV for the measured regions. The plasmas generated at 10 A, 20 sccm (plume mode) and 10 A, 10 sccm (plume mode) have the highest electron temperatures, which are in the ranges of 1.0 to 1.5 eV and 1.3 to 2.1 eV, respectively, for the measured conditions. The ion energy and the electron temperature have the same tendencies in terms of mass flow rate dependence. The electron temperature distributions for 10 A, 26 sccm and 20 A, 30 sccm, which have equivalent ion energies for the corresponding conditions, have similar electron temperatures. Based on these experimental results, there is a possibility that increased electron temperature correlates to ion acceleration to some extent.

Figure 13 shows the spatial distribution of electron temperature for (a) 10 A, 10 sccm, (b) 10 A, 20 sccm, (c) 10 A, 26 sccm, and (d) 20 A, 30 sccm.
tions. The ions generated in the 10 A, 20 sccm region are more likely to pass through the high-electron-temperature region only when they move in the 90° direction. The angle dependence of the ion energies for 10 A, 10 sccm and 10 A, 20 sccm have different tendencies: the former conditions lead to increased ion energy when the angle changes from 0° to 45° and the latter conditions lead to increased ion energy when the angle changes from 45° to 90°. This correlation between the angle dependency of ion energy and the electron temperature spatial distribution may explain the involvement of electron temperature in ion acceleration. For 10 A, 26 sccm, there is no high-electron-temperature region in front of the anode (Fig. 13(c)), while the on-axis electron temperature measurement (Fig. 14) reveals that there is a high-electron-temperature region inside the anode. This result still suggests a correlation between the angle dependency of the IEDF main peak potentials and the high-electron-temperature region, where the ion energy is high only under the conditions of a 90° direction for 10 A, 30 sccm (Fig. 11) while the high-electron-temperature region exists only inside the cylindrical anode under the conditions of 10 A, 26 sccm.

4.3. Factors for ion acceleration

Figure 15 shows the potential fluctuation for several conditions. If the ions are selectively accelerated at the highest potential under the potential fluctuation, they may gain higher energy as compared to the average plasma potential. However, the on-axis plasma potential fluctuation for 10 A, 10 sccm is approximately +4 V to −2 V (Fig. 15(a)), and the maximum instantaneous plasma potential is about 24 V. This potential is far below the peak potentials shown in Fig. 12. This indicates that the potential fluctuation amplitude may not directly affect the ion energy increment from the base ion energy, which may be determined by the plasma potential.

Three other factors can also be considered as sources of ion acceleration: (1) the existence of a potential hill, (2) ionization instability in the prey-predator model, and (3) energy transfer from electron kinetic energy to ion kinetic energy via the wave energy of potential fluctuation. The possibility of these sources affecting ion acceleration is discussed below.

(1) The probe measurements in our research indicate the lack of a local region with high potential. However, because the plasma potential measurements were conducted using a probe, the plasma was disturbed at the time of probe insertion. The possibility of potential hill existence that could cause ion acceleration cannot yet be eliminated.

(2) The energy transfer by ionization instability at the time of ionization oscillation can be a factor for ion acceleration. However, for probe measurement, the high-frequency noise (>10 kHz) was removed by the data acquisition recorder. Therefore, in the results shown in Fig. 15, the effect of potential fluctuation in only the frequency region of less than 10 kHz is taken into consideration. Accordingly, the elucidation of plasma fluctuation in the frequency region higher than 10 kHz is necessary for further understanding the effect of ionization oscillation on ion energy.

(3) The fluctuations in IAT should be in the frequency regions above several hundred kHz. Therefore, to discuss the effect of IAT, elucidation of the plasma fluctuation at frequencies higher than 100 kHz is necessary. The elucidation of fluctuations in the frequency regions of 10–30 kHz and above 100 kHz is necessary in order to further understand the effects of fluctuations on ion energy.

The results obtained in this research indicate the existence of a correlation between additional ion acceleration and electron temperature changes. However, the existence electron temperature changes having a direct effect on ion acceleration has not been confirmed. The results suggest that the electron temperature changes may have an indirect effect on ion acceleration.

It is still an inference; however, the following logic can be conceived for the relationship among mass flow, electron temperature, and ion energy. When the mass flow rate increases, the density of the neutral Xe atoms increases, which leads to an increase in the frequency of neutron and electron collision. With this increased collision frequency, the chances that electrons will distribute their energy to neutrons
via collision increases, leading to a decrease in electron temperature. On the other hand, when the mass flow rate increases, ionization instability is suppressed in the predator–prey model. Here, the suppression of ionization instability and electron temperature occur independently. However, since the suppression of both is the result of mass flow suppression, the high-electron-temperature regions may indicate regions with high ionization instability (i.e., electron temperatures may be the implied parameter for ion acceleration).

In the case of IAT, when the mass flow decrease, electron flux increases to preserve the constant current density because the current density can be expressed as the product of electron number density and electron flux. Then, the increase in electron flux kinetically enforces IAT to increase ion acceleration. In this mass flow–IAT relationship, electron temperature independently increases as the mass flow decreases, as was the case for ionization instability. In IAT, electron energy transfer via Landau damping should also be considered. Because the thermal energy of electrons is transferred to ions, the electron energy should continue decreasing in IAT, and the difference in the thermal velocity of electrons and ions should continue decreasing as well. However, under low-mass-flow-rate conditions, the electrons continuously gain energy under low-collision-frequency conditions, which can maintain IAT.

In the process, the electron temperature independently increases as the mass flow rate decreases, as was the case for ionization instability. However, the increased electron temperature may be suppressed by energy transfer. Therefore, in the case of IAT, the relationship between electron temperature and IAT may be more complicated than that in the case of ionization instability. This is still an inference; however, the high-electron-temperature regions may strongly indicate the regions with ionization instability and weakly indicate the regions with IAT.

5. Conclusion

For the development of a highly durable hollow cathode and understanding the ion energy produced in spot and plume modes, the ion energy angle distribution and its relationship with plasma operating conditions were elucidated. The discharge current and mass flow rate dependency had different tendencies in the different plasma discharge modes: the ions in the spot-mode plasma showed a stronger dependency on the discharge current, and those in the plume-mode plasma showed a stronger dependency on mass flow rate. Regarding angle distribution, the ion energy peak potential for the plume mode clearly shifted to a higher energy when the angle changed from the radial direction to the axial direction. A comparison of plasma potential and ion energy peak potential indicated that ion energy peak potentials were the same as, or exceeded, the plasma potential for each condition, which indicates that the ion energy peak potential is determined by plasma potential as the base energy with some other factors responsible for additional ion acceleration. Although the factor for ion acceleration could not be found, the ion energy measured using angle distribution had a qualitative correlation with the electron temperature, which suggests the possibility of a correlation between the ion acceleration region and the high-electron-temperature regions. Further research on plasma fluctuations and wave energies is necessary for understanding the ion acceleration mechanism in order to realize a highly durable, high-current hollow cathode.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 17H01353.

References

1) Dudzinski, L. A., Hack, K. J., Gefert, L. P., Kerslake, T. W., and Hewston, A. W.: Design of Solar Electric Propulsion Transfer Vehicle for a Non-Nuclear Human Mars Exploration Architecture, IEPC-99-181, October 1999.
2) Manzella, D. and Hack, K.: High-Power Solar Electric Propulsion for Future NASA Missions, AIAA-2014-3718, 50th AIAA/ASME/ASEE Joint Propulsion Conference, Cleveland, OH, July 28–30, 2014.
3) Kim, V., Popov, G., Arkhipov, B., Murashko, V., Gorskow, O., Koroteyev, A., Garkusha, V., Semenkin, A., and Tverdokhlebov, S.: Electric Propulsion Activity in Russia, IEPC-2001-005, 2001.
4) Cadiou, A., Darmon, F., and Jolivet, L.: An Overview of the CNES Electric Propulsion Program, IEPC-03-169, 2003.
5) Kuninaka, H. and Kajiwara, H.: Overview of JAXA’s Activities on Electric Propulsion, IEPC-2011-332, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11–15, 2011.
6) Funaki, I., Cho, S., Sano, T., Fukatsu, T., Tashiro, Y., Shioki, T., Nakamura, Y., Watanabe, H., Kubota, K., Matsunaga, Y., and Fuchigami, K.: Development of a 6-kW-class Hall Thruster for Geostationary Missions, Acta Astronautica, 170 (2020), pp. 163–171.
7) Friedly, V. J. and Wilbur, P. J.: High Current Hollow Cathode Phenomena, J. Propul. Power, 8, 3 (1992), p. 635.
8) Goebel, D. M., Jameson, K. K., Katz, I., and Mikeldes, I. G.: Plasma Potential Behavior and Plume Mode Transitions in Hollow Cathode Discharges, Proceedings of 30th IEPC, IEPC-2007-277, 2007.
9) Mikeldes, I. G., Katz, I., Goebel, D. M., Jameson, K. K., and Polk, J. E.: Wear Mechanisms in Electron Sources for Ion Propulsion, 2: Discharge Hollow Cathode, J. Propul. Power, 24, 4 (2008), p. 866.
10) Ohtaka, Y., Higuchi, T., Hayakawa, Y., Miyazaki, K., and Nagano, H.: Observation and Analysis of Graphite Hollow Cathode after 45,000-Hour Life Test, Proceedings of 33rd International Electric Propulsion Conference, IEPC-2013-364, The George Washington University, USA, October 6–10, 2013.
11) Siegfried, D. E. and Wilbur, P. J.: An Investigation of Mercury Hollow Cathode Phenomena, IEPC-78-705, 1978.
12) Goebel, D. M., Jameson, K. K., Watkins, R. M., Katz, I., and Mikeldes, I. G.: Hollow Cathode Theory and Experiment. I. Plasma Characterization Using Fast Miniature Scanning Probes, J. Appl. Phys., 98 (2005), 113302.
13) Goebel, D. M., Jameson, K. K., Katz, I., and Mikeldes, I. G.: Potential Fluctuations and Energetic Ion Production in Hollow Cathode Discharges, Phys. Plasmas, 14 (2007), 103508.
14) Barral, S. and Abedo, E.: Low-frequency Model of Breathing Oscillations in Hall Discharges, Phys. Rev. E, 79 (2009), 046401.
15) Gascon, N. and Dudeck, M.: Wall Material Effects in Stationary Plasma Thrusters. I. Parametric Studies of an SPT-100, Phys. Plasmas, 10 (2003), 4123.
16) Yamamoto, N., Yokota, S., Watanabe, K., Sasoh, A., Komurasaki, K., and Arakawa, Y.: Suppression of Discharge Current Oscillations in a Hall Thruster, Trans. Jpn. Soc. Aeronaut. Space Sci., 48, 161 (2005), pp. 169–174.
17) Kameyama, I. and Wilbur, P. J.: Effects of External Flow near High-
Current Hollow Cathodes on Ion-Energy Distributions, IEPC-97-173, 1997.

18) Chu, E., Goebel, D. M., and Wirz, R. E.: Reduction of Energetic Ion Production in Hollow Cathodes by External Gas Injection, *J. Propul. Power*, 29, 5 (2013), 1155.

19) Dodson, C. A., Perez-Grande, D., Jorns, B. A., Goebel, D. M., and Wirz, R. E.: Ion Heating Measurements on the Centerline of a High-Current Hollow Cathode Plume, *J. Propul. Power*, 34, 5 (2018), 1225.

20) Jorns, B., Mikellides, I. G., and Goebel, D. M.: Ion Acoustic Turbulence in a 100-A LaB6 Hollow Cathode, *Physical Review E*, 90 (2014), 063106.

21) Kameyama, I. and Wilbur, P. J.: Measurements of Ions from High-Current Hollow Cathodes Using Electrostatic Energy Analyzer, *J. Propul. Power*, 16, 3 (2000), p. 529.

22) Oshio, Y., Kubota, K., Ohkawa, Y., Cho, S., Watanabe, H., and Funaki, I.: Thermal Analysis of Lanthanum Hexaboride Hollow Cathode with Radiative Carbon Heater, Proceedings of 34th International Electric Propulsion Conference, IEPC-2015-455, Hyogo, Kobe, 2015.

23) Kubota, K., Oshio, Y., Watanabe, H., Cho, S., Ohkawa, Y., and Funaki, I.: Hybrid-PIC Simulation on Plasma Flow of Hollow Cathode, *Trans. JSASS Aerospace Technology Japan*, 14, ists30 (2016), pp. Pb.189–Pb.195.

24) Kubota, K., Oshio, Y., Watanabe, H., Cho, S., Ohkawa, Y., and Funaki, I.: Numerical and Experimental Study on Discharge Characteristics of High-Current Hollow Cathode, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, 2016, 4628.

25) Oshio, Y., Kubota, K., Watanabe, H., Cho, S., Ohkawa, Y., and Funkai, I.: Experimental Investigation of LaB6 Hollow Cathode with Radiative Heater, *Trans. JSASS Aerospace Technology Japan*, 17, 2 (2019), pp. 203–210.

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