Investigation of Internal Plasma Structure in an Anode-layer Hall Thruster

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Abstract: Internal plasma structure in a Hall thruster was measured with the objective of understanding physics in Hall thrusters. The plasma parameter, plasma potential, electron temperature and number density were measured by means of electrostatic probe using a 1 kW class anode layer type Hall thruster. The anode layer was observed under low magnetic field condition, and the position that the potential is falling, goes upstream, toward anode, with increase in magnetic flux density. The measurement electron temperature and number density in the acceleration channel are 20 eV and 3x10^{18} m-3, respectively. The ionization zone also goes upstream with increase in magnetic flux density. Electron diffusion coefficient was estimated using above results. These results showed that the transition in operational regime at critical magnetic flux density is caused by the transition in electron diffusion from classical to anomalous diffusion.

Nomenclature

B : magnetic flux density
D : diffusion coefficient
E : electric field strength
d : distance between two probes
e : electronic charge
I : current
L : ionization zone length
m : particle mass
$\dot{m}$: mass flow rate
N : number density
S : cross-section

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T : temperature
V_d : discharge voltage
z : axial direction
Δ : oscillation amplitude
μ : mobility
σ_{di} : atom ionization collision cross-section
σ_T : atom total collision cross-section
τ : measurement time =5 ms
ϕ : diameter

Subscripts

B : Bohm diffusion
c : classical diffusion
e : electron
eff : effective coefficient
d : discharge
i : ion
n : neutral atom
r : radial direction
0 : anode side
1 : exit side

I. Introduction

A Hall thruster is a promising thruster for satellite station keeping and orbit transfer applications[1-3] because it has a high thrust efficiency exceeding 50% with a specific impulse range of 1000–3000 s, delivering higher thrust-to-power ratio as compared to ion thrusters. Therefore, there were and will be many missions using a Hall thruster[4], e.g., SMART-1 lunar mission[5], MBSAT, and Lockheed-Martin Space Systems GEO satellites[6].

One of the challenges presented by Hall thrusters is the discharge current oscillation, particularly at a frequency range of 10–100 kHz.[7-14] Due to the reduction in the impact of the Power Processing Unit (PPU) and the enlargement of the surplus for the power supply of the satellite system, it is preferable to maintain a low level of discharge current oscillations. The oscillation may also affect the erosion of the acceleration channel or the ion beam divergence. Understanding the oscillation is essential for the future improvement of Hall thrusters, particularly of the anode layer type. Several studies have been conducted on this oscillation phenomenon, and they have revealed that the oscillation is caused by ionization instability. However, these studies did not adequately describe the oscillation, and in particular, do not determine the stability criteria for a given range of magnetic flux density. Measuring internal plasma structure in Hall thrusters is essential for describing this oscillation mechanism. It also helps the understanding the ionization and electron diffusion mechanism in the Hall thruster. Furthermore, this information will play an important role in the validation of numerical models. There have been many studies about measuring internal structure in a magnetic layer type Hall thruster. [15-17] On the other hand, there are few studies about that in an anode layer type. Comparison between the two types would give invaluable knowledge of ionization and electron diffusion mechanisms in Hall thrusters.

Therefore, the aim of this study is measuring internal plasma structure in the anode layer type Hall thruster and understanding these mechanisms in Hall thrusters.

II. Experimental Equipment

A. Anode Layer Type Hall Thruster

Figure 1 shows the cross-section of a 1 kW class, anode layer type Hall thruster.[18-22] The inner and outer diameters of the acceleration channel are 48 mm and 72 mm, respectively. A solenoidal coil is set at the center of the thruster to apply a radial magnetic field in the acceleration channel. The magnetic flux density is varied by changing the coil current. There is no outer coil because a uniform magnetic field distribution is maintained along the azimuthal direction. The magnetic field distribution along the channel median is almost uniform in the short acceleration channel, as shown in Fig.2. Magnetic flux density is maximized in the inner wall and decreases with a decrease in radius since the magnetic flux is constant. Thus, in this study, the magnetic flux density at the channel median is assumed to be representative. The guard rings are made of stainless steel (SUS304). The separation between the guard ring and the anode is 1 mm. It has a hollow annular anode, which comprises two cylindrical rings, and a propellant gas is fed through them. The position and the width of the hollow anode are varied by changing the anode components. In this study, the width of the hollow anode is 8 mm, and the gap between the tip of the anode and the exit of the acceleration channel is fixed at 3 mm.

High-purity (99.999% pure) xenon gas was used as the propellant. Thermal mass flow controllers (Kofloc, 3610) are used. A hollow cathode (Veeco-Ion Tech, HC-252) was used as the electron source.

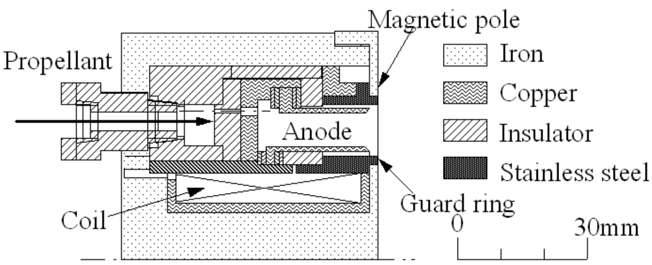


Figure 1. Cross section of the anode layer type Hall thruster developed at the University of Tokyo.

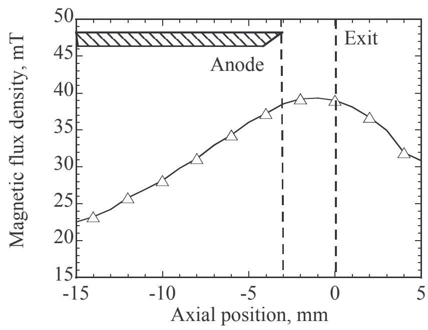


Figure 2. Magnetic field profile along z axis.

B. Electrostatic Probe

For the measurement of plasma density and electron temperature in the acceleration channel, double Langmuir probe was used. The schematic of this probe was shown in Fig. 3. The double probe consisted of two 0.15 mm in diameter and 1.8 mm in length cylindrical tungsten wire electrodes insulated from each other by two alumina insulators. The diameter of the prove, r_p and the distance between the two electrodes, d are chosen based on the standard probe theory as below.

1. The distance between two is larger than the twice of Debye length in order to avoid electrode interaction.

$$d > 2\lambda_D = 2\times\sqrt{\frac{\varepsilon_0 kT_e}{e^2 n_e}} \approx 10^{-4} \quad \text{m} \tag{1}$$

2. Collisionless plasma

$$r_p << \lambda_e, \quad \lambda_D << \lambda_e$$

$$\lambda_{en} = \frac{1}{n_n \sigma} \approx \frac{1}{10^{20}\times 10^{-19}} \approx 10^{-1}\,\text{m} \tag{2}$$

$$\lambda_{ee} \approx \lambda_{ii} \approx \lambda_{ei} = \frac{1}{n_\text{p}\sigma} = \frac{16\pi\varepsilon_0^2 m^2 v^4}{e^4 n_\text{p}} \approx 10^{-1} \text{ m}$$

3. Conventional thin sheath

$$\lambda_D < r_p \tag{3}$$

In order to minimize probe heating as much as possible in the acceleration channel, high speed linear motor reciprocating positioning system was used. This system lets the staying period in the acceleration channel be 52 ms when the most upstream position of the probe is 5.1mm upstream of the exit, as shown in Fig.4. In this study, plasma property in the channel median was measured. Applied voltage between two electrodes is swept as Sine function (the amplitude =100 V, the frequency = 400 Hz). Though the probe was moved 0.3 mm within sweeping period, this influence on the measurement is little, since 0.3 mm is less than 1.8 mm, the probe length. The error is about 20 %, which derived from the standard

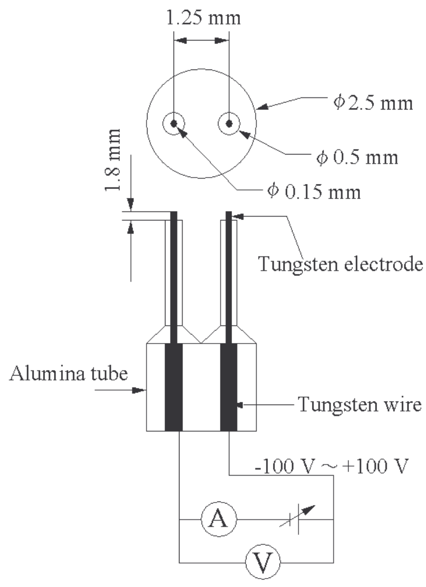


Figure 3. Schematic of double Probe.

deviation of measurement, the fitting error, and the probe processing accuracy.

The emissive probe was made of a 0.1mm in diameter 0.1% thoriated tungsten as shown in Fig. 5. A linear motor was used to insert the emissive probe into the discharge chamber. It provides linear reciprocating motion at very high motion and acceleration.

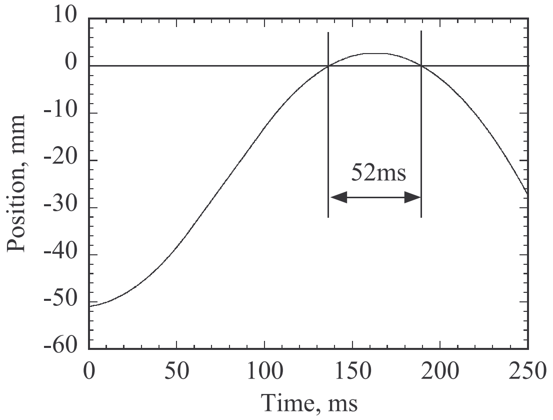


Figure 4. Probe position trace.

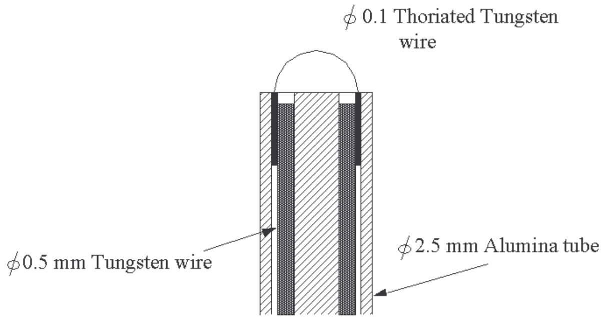


Figure 5. Schematic of emissive probe.

C. Vacuum Chamber

A vacuum chamber of 2 m diameter by 3 m length was used in the experiments. The pumping system comprised a diffusion pump, a mechanical booster pump, and two rotary pumps. The background pressure was maintained below 5.3×10^{-3} Pa for most of the operating conditions.

D. High-speed Camera

An image intensified high-speed camera (DRS Technologies Inc., Product, ULTRA 8) was used for the observation of the plasma. The maximum frame rate of this camera is 100,000,000 fps.

E. Ion Collector

An ion beam current was measured using the ion beam collector (500 mm $\times$ 500 mm nude plane collector) that was located at 250 mm downstream of the thruster. Compensation for the decay of the ion beam current by charge-exchange was performed according to the method described in Ref. 23. The charge-exchange cross section was obtained from Ref. 24. The friction of the double xenon ion was assumed to be 0.2. [25, 26] The total error of this compensation did not exceed 5%, and the largest source of error is the ionization gauge.

III. Results and Discussion

The discharge current and the amplitude of the discharge current oscillation should be a good indicator of operational condition. In order to evaluate the oscillation depth in the experimental results, the amplitude of oscillation, Δ is defined as,

$$\Delta = \frac{R.M.S}{\overline{I_d}} = \frac{1}{\overline{I_d}}\sqrt{\frac{\int_0^\tau (I_d - \overline{I_d})^2}{\tau}}, \quad (\overline{I_d} = \frac{\int_0^\tau I_d}{\tau}) \tag{4}$$

Figure 6 shows the relation between the discharge current and the amplitude of 10 kHz range oscillation against magnetic flux density. The discharge current is decreased with increase in B in B < 23 mT, and then it is increased with B. The oscillation amplitude is also decrease in B. Stable operation was observed in a

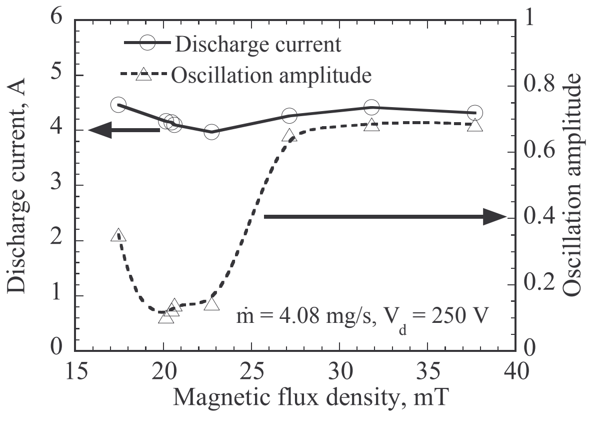


Figure 6. Operation characteristics.

narrow range near B ≈ 20 mT in this configuration. The oscillation amplitude suddenly increases at B = 24 mT. Thus, the operational condition range is narrow, and hence an extension of the stable operational condition range is required. This sensitivity to B indicates that the oscillation would be dominated by electron mobility rather than by ion mobility.

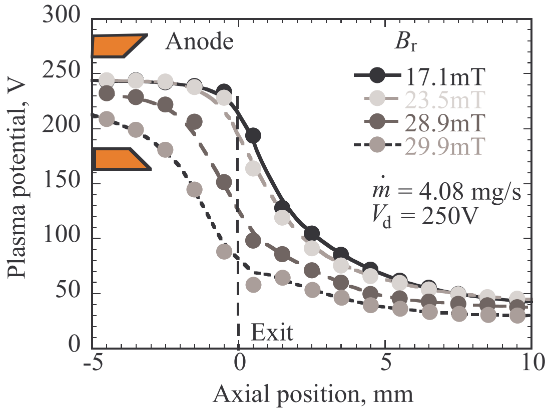
Figure 7(a), (b), and (c) show the plasma potential distribution, electron temperature distribution, and number density distribution along the axis, respectively. So-called "anode layer" was observed under low magnetic field condition. In this thin layer, ionization and acceleration would be occurred. The position that plasma potential is falling goes upstream , toward the anode, with increase in magnetic flux density. This would lead the ionization zone to go upstream with increase in magnetic flux density, as shown in Fig.5(c). On the other hand, when B > 27 mT, where the oscillation amplitude is large, the potential is falling inside the hollow anode and cannot observed anode layer. In Hall thrusters, the Lorentz force, derived from the interaction between the Hall current and magnetic field, prevents electrons from going upstream and keeps the strong electric field in the acceleration channel. Therefore, with increase in the coil current, the magnetic field inside the hollow anode is also increased and then electric field strength inside of the hollow anode is also increased. Therefore, the plasma potential is falling inside the hollow anode.

The electron temperature and number density in the ionization zone are 23 eV and 3.3x10^{18} m^{-3}, respectively, which are higher than those of magnetic layer type.[19] This high electron temperature is due to the low electron energy losses to the acceleration channel wall. There is little interaction between the wall and the electrons, since the anode layer type has a conducting wall which potential are kept in a cathode potential.

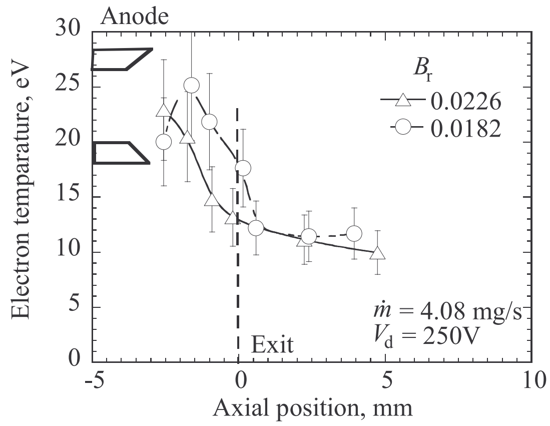
With the potential profile changing, the electron temperature profile and the electron number density profile are changed; the electron temperature has a positive correlation with downstream electric field strength, therefore, the zone, where electron temperature is high, goes upstream with the increase in magnetic coil current. The ionization zone, which exists where the potential is falling, also goes upstream with high temperature zone going upstream.

The 0D-oscillation model shows that the conditions of stable operations is written as follows:[14]

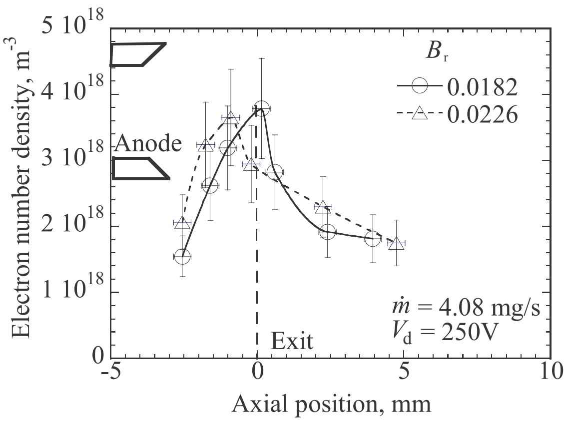
$$S_1V_{e\_1} - S_0V_{e\_0} - \overline{\langle\sigma_{di}v_e\rangle}_{T_e}\,\overline{N}_nSL > 0 \quad (5)$$



(a)



(b)



(c)

Figure 7. Plasma parameter profile.

(a) Axial profile of plasma potential.
(b) Axial profile of Electron temperature.
(c) Axial profile of Electron number density.
$\dot{m}$ = 4.08 mg/s, V_d= 250V

Table.1 Typical measurement values for estimation of diffusion coefficient.

Parameter	Classical diffusion regime	Anomalous diffusion regime
η_E	0.9	0.8
T_e, eV	16	12
E, V/m	60,000	24,000

The left hand side of Eq. (5) represents the momentum transfer corresponding to fluctuations of plasma, i.e., viscosity effects. Thus, the oscillations decay if the viscosity coefficient, i.e., the left hand side of Eq. (5), is positive.

According to the Eq.(5), the increase in plasma density in the vicinity of the anode would have operation unstable, therefore, with increase in magnetic flux density would cause the operation to be unstable.

Electron diffusion mechanism is one of the most significant mechanisms for Hall thruster, so we estimate the diffusion coefficient at the acceleration channel exit. The diffusion coefficient at the acceleration channel exit is estimated by as follows:

$$D = \frac{\Gamma_e}{S\,N_e\left(\frac{e}{kT_e}E + \frac{\nabla n_e}{N_e}\right)} \Rightarrow D_1 \approx \frac{I_d - I_i}{e\,S_1\,N_{i1}\frac{e}{kT_{e1}}E_1} \qquad (6)$$

I_i was measured by the ion collector and the number density of ions was estimated as follows:

$$N_{i1} = \frac{I_i}{eS_1 V_{i1}} \approx \frac{I_i}{e\,S_1\sqrt{\frac{2\eta_E\,eV_d}{M}}} \qquad (7)$$

The values of beam energy efficiency, [17] E, and T_e were assumed to be typical measurement values, as shown in Table. 1. η_E was measured by means of a retarding potential analyzer, [27] E was estimated to be 1.2 (300 V/250 V) times that of the above results. I_i was measured by means of the ion collector.

Figure 8 shows the estimated diffusion coefficient at the acceleration channel exit. The diffusion coefficient decreases with increase in B and suddenly increases at B = 27 mT, and then decreases with B, again. The transition at B = 27 mT is caused by the transition in electron diffusion from classical to anomalous diffusion. That is, an electron moves toward the anode via classical diffusion when B < 27 mT, and it moves via anomalous diffusion when B > 27 mT, as shown in Fig. 8. There is some transition regime at15 mT < B < 27 mT. It is noteworthy that the oscillation regime also changes at this point. This was another indication that the oscillation is sensitive to electron mobility.

Several MHz oscillations can be observed when B > 27 mT. This oscillation cannot be observed when B < 27 mT. This result shows these MHz fluctuations in the plasma would cause this anomalous diffusion. that is,

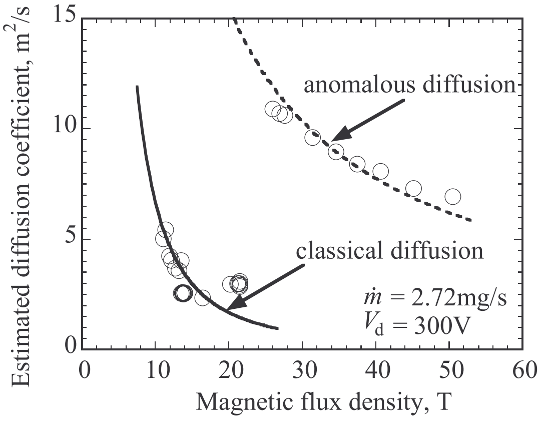


Figure 8 Estimated electron diffusion coefficient.

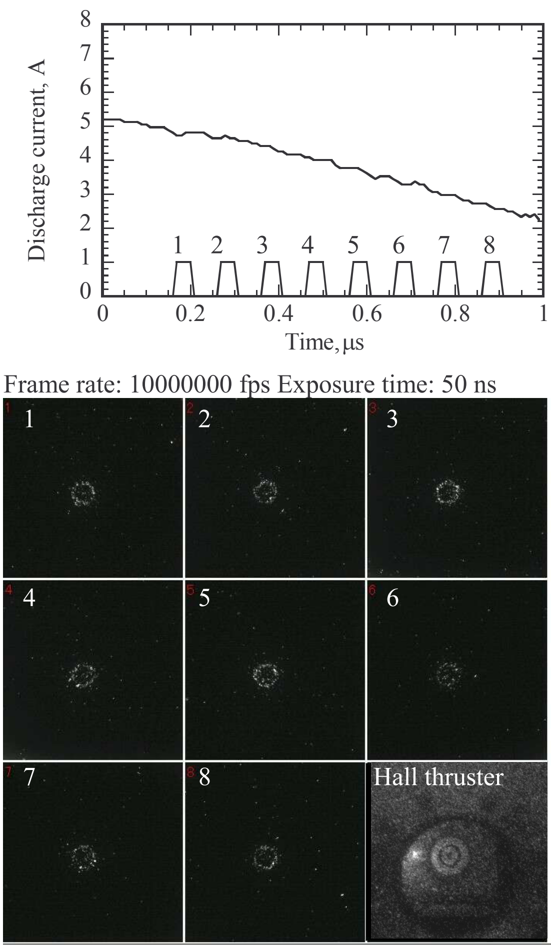


Figure 9. Plasma behavior.
$\dot{m}$ = 2.72 mg/s, V_d= 300 V B=0.046 T

with infinite small perturbation, the mobility is described as follows,

$$\mu_e = \frac{m_e}{eB^2}\left(n_n \langle \sigma v \rangle_{en} + \frac{\pi}{4}\frac{eB}{m_e}\left\langle \left(\frac{\Delta n_e}{n_e} \right)^2 \right\rangle \right) \tag{8}$$

Hirakawa et al. shows that the azimuthal plasma fluctuation lead to anomalous diffusion by numerical simulation.[28] That is, the interaction between azimuthal electric field fluctuations and radial magnetic field cause the charged particles to be drift in the *z* axial direction and the order of this is almost the same as that of the Bohm diffusion.

In order to investigate these MHz oscillations, the plasma behavior was observed by means of a high-speed camera. Figure 9 shows the plasma behavior and the discharge current trace under the unstable condition at a frame rate of 10,000,000 fps and an exposure time of 50 ns. These pictures are not distinct pictures, but it is impossible to increase the frame rate or to decrease the exposure time, since the emission of light from the plasma is weak. However, the emission in the annular acceleration channel is not uniform in the azimuthal direction and it fluctuates with the frequency of about two MHz. This azimuthal plasma fluctuation would cause anomalous diffusion in this regime.

This fluctuation would be ion plasma instability or drift instability. But this would be derived from the drift instability, since ion plasma instability would not be affect by the magnetic field strength. Azimuthal nonuniformity in the channel would be enlarged with increase in magnetic flux density, since the ionization zone in the acceleration channel expands toward anode with increase in magnetic flux density.

IV. Conclusion

Internal plasma structure in the anode layer type Hall thruster was measured by means of electrostatic probe for understanding the mechanism in Hall thrusters.

From the results of emissive probe, so-called "Anode layer" can be observed in the low magnetic flux density, and the position where potential is falling moves toward anode with increase in magnetic coil current. With this change, the ionization zone also moves toward anode with increase in *B*. The electron temperature and number density in the acceleration channel is 20 eV, and $3\text{x}10^{18}$ m^{-3}. It is confirmed that the electron temperature and electron number density in anode layer type Hall thruster is higher than that of magnetic layer, which suits the design concept of the anode layer Hall thruster.

The operational regime in the anode layer Hall thruster changes at critical magnetic flux density= 27mT at $\dot{m}$ = 2.72 mg/s, V_d = 300 V. This is because an electron moves toward the anode via classical diffusion when $B < 27$ mT, and it moves via anomalous diffusion when $B > 27$ mT. An azimuthal plasma fluctuation would cause this anomalous diffusion. That is, azimuthal electric field fluctuations caused by the azimuthal plasma fluctuation and radial magnetic field make charged particles drift in the *z* axial direction. The observation of plasma behavior by high-speed camera supports this assumption. This result implies that anomalous diffusion is caused not only by near-wall conductivity but also by the azimuthal plasma fluctuation in the magnetic layer type Hall thrusters. Therefore, more precious study about this several MHz Oscillations would be need for understanding the anomalous diffusion.

Acknowledgments

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