The Design and Control of Hall Thrusters Using the Dimension Scaling Law of the Operating Points

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Abstract: For the two types of different size Hall Thrusters and for the Hall Thruster with the channel erosion simulated the end of life, we performed observations of the electrical characteristics and the low-frequency discharge current oscillation by widely varying the external control parameters. Introducing the parameter "Equivalent Energy Density" which represents how much energy is injected into the ionization zone per unit area, we discovered that the stable operation condition can be normalized by the external control parameters and the thruster dimension. Moreover, as for the case that the channel shapes is greatly changed by the erosion, we found that the normalization by the "Equivalent Energy Density" is applicable. Using the dimension scaling law, we can not only know clearly the best operating point for each condition, but also make the optimum design of thruster dimension and thrust, and control the transient operation. This must be a very important guideline for the thruster design and the prediction of the characteristics at the end of life.

Nomenclature

B	=	magnetic flux density
D	=	diffusion constant
d	=	channel length
E	=	electric field intensity
I_a	=	anode current

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I_c = coil current
I_{ci} = inner coil current
I_{co} = outer coil current
k_i = reaction rate coefficient of ionization
k_m = reaction rate coefficient of the momentum transfer collision between electrons and neutral atoms
L = ionization zone length
m = electron mass
N_A = Avogadro's number
N_e = electron density number
N_n = neutral atom density number
Q = gas flux
q = electronic charge
S = cross section of the channel
V_a = anode voltage
V_e = electron velocity
V_m = volume of the ideal gas
v_n = velocity of the neutral atoms
w_{eq} = equivalent energy density
β = proportional coefficient determined by the axial distribution of the magnetic flux density
μ_e = electron mobility
σ = standard deviation, which represents the current oscillation strength
τ = velocity of the neutral atoms

Subscripts
a = anode side
x = exit side

I. Introduction

THE Hall thruster has many features such as high thrust density and a relatively simple structure. Therefore, among the various types of electric propulsion systems, Hall thruster is most suitable for next-generation large-thrust systems, and Hall thruster systems with a thrust of more than 250 mN have been developed [1) 2)]. The major problems of the Hall Thruster development are the discharge oscillation and life time.

As the development of a next-generation large-thrust electric propulsion system performed by the Institute for Unmanned Space Experiment Free Flyer (USEF), under the Advanced Satellite Engineering Research Project contract sponsored by the Ministry of Economics, Trade and Industry (METI), Mitsubishi Electric Corp. is also developing a Hall thruster whose thrust is more than 250 mN, and specific impulse is over 1500 sec [3)], and a power processing unit (PPU) to drive our Hall thruster [4)].

The PPU has a very important role in the electric propulsion system, and it is very important to simultaneously develop both the thruster and the PPU. One of the reasons for this is that, because the Hall thruster is a discharge apparatus that produces thrust by generating plasma, it has nonlinear electric characteristics and thus requires special control methods. The performance of the PPU affects the stability of the discharge. In particular, special control of the PPU is necessary to turn on the thruster.

The other reason is the electromagnetic compatibility (EMC) with other equipment in the satellite. It is known that the discharge current of the Hall thruster has many oscillation modes [5) 6)], and the low-frequency oscillations around 10 kHz may not only affect the performance of the hall thruster but also have a detrimental effect on the other equipment through the PPU and bus power lines. Therefore, the suppression of the low-frequency oscillation is essential for the development of the Hall thruster system, and we focus on the problem how to keep the Hall Thruster stable by the control of PPU.

Until now we investigated that the condition that low-frequency oscillation occurs by widely varying the external control parameters with the 250mN-Class Hall Thruster and PPU [7)]. Then we developed "Synchronous Control Method" of power conditioners, which enables oscillation-free stable operation, even for transient operations such as the thruster being turned on. It was shown that for transient operations such as turning on the thruster, changing the thrust condition, and turning off the thruster, low-frequency oscillation-free operation can be realized [8)]. Also, electromagnetic interference noise in the primary bus power lines through the PPU was shown to be sufficiently small [9)]. Applying operation parameter control by the PPU, not only during the stable operation, but also during transient operation such as start-up, low-frequency oscillation can be suppressed essentially.

However, our experimental data are obtained by 250mN-Class thruster [7], and there is no reason that another Hall Thruster has the similar oscillation property. We developed "Synchronous Control Method" of power conditioners, but it is not clear that the method is applicable to another thruster. Even if another Hall Thruster also has the similar oscillation characteristics, we cannot predict the stable operation region, and how should we control the coil current for the stable operation for the general thruster.

Furthermore, considering the long-term operation of the thruster, we have to prepare some idea for the case of channel erosion at the end of life,

In this paper, we make a report the comparison result of the characteristics for the two types of different size Hall Thrusters. We make a measurement of electrical characteristics pf 250mN-Class Hall Thruster developed in MELCO, and 20mN-Class Hall Thruster of Kyushu University. Both thrusters are so to call SPT (Stationary Plasma Thruster) type, but channel dimension and magnetic flux density distribution are different. Comparing these thrusters' characteristics, we considered that how the stable operation region depends on the channel dimension and what is the physical background. As the results, introducing the parameter "Equivalent Energy Density" which represents how much energy is injected into the ionization zone per unit area, we discovered that the stable operation condition can be normalized by the external control parameters and the thruster dimension. Moreover, as for the case that the channel shapes is greatly changed by the erosion, we found that the normalization by the "Equivalent Energy Density" is also applicable. We also discuss the effect on the electrical characteristics by the channel erosion.

Using the dimension scaling law, not only we can know clearly the best operating point for each condition, but also we can make the optimum design of thruster dimension and thrust, and control the transient operation. This must be a very important guideline for the thruster design and the prediction of the characteristics at the end of life.

Table 1. parameters of the two thrusters

	250mN Class	20mN Class
Thrust [mN]	～250	～50
Channel Cross Section [mm^2]	9425	2262
Channel Length [mm]	50	29
Anode Voltage [V]	200～325	150～300
Gas Flow [mg/s]	4.9～14.8	0.4～1.4

II. Experimental Setup

Table 1 shows the thruster channel dimension and measurement condition for the 250mN-Class and 20mN-Class thruster. Both are Magnetic Layer type, which is typified by SPT (Stationary Plasma Thruster) [10]. Both have a circular ring channel made by BN. The propellant gas is Xe.

Figure 1 shows the axial cross section of the Hall thruster, the block diagram of the power supply and the mass flow controller (MFC) for propellant gas. A hollow cathode is fitted externally because the Hall thruster requires an external electron source. The PCs are fitted with a keeper electrode and a cathode heater electrode. The MFC is used to supply Xe gas to the hollow cathode. As long as the hollow cathode operates stably, it rarely affects the oscillation. Therefore, we did not consider the operation conditions of the hollow cathode in this study. Xe gas is also supplied to the anode electrode through an MFC. Here, Q indicates the gas flux of the Hall thruster and does not include the gas flux of the hollow cathode.

A 100 V bus is supplied from a primary power supply to the PPU. The Hall thruster is equipped with PCs for the anode electrode, an inner magnetic coil, and outer magnetic coils. The currents of the inner and outer magnetic coils can be individually regulated. The operation conditions are determined by four parameters: the anode voltage V_a, propellant gas flux Q, inner magnetic coil current I_{ci} and outer magnetic coil current

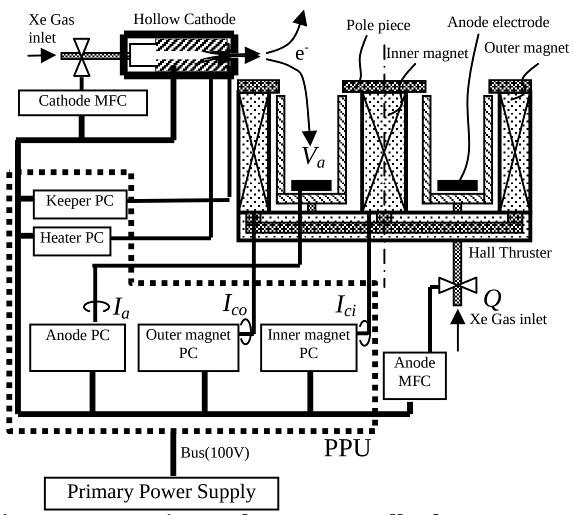


Figure 1. Experimental setup: Hall thruster, power conditioners (PCs), and mass flow controllers (MFCs). *A 100 V bus is supplied from a primary power supply to the PPU.*

I_{co}. In this measurement, we fixed both the inner magnetic coil current I_{ci} and the outer magnetic coil current I_{co} to I_c. The oscillation is detected by measuring the anode current I_a. The measured oscillation strength is estimated by the following equation using the standard deviation,

$$\sigma = \sqrt{\frac{1}{\tau}\int_0^{\tau}\left(I_a - \overline{I_a}\right)dt}\ , \quad (1)$$

where τ is the period of current measurement. In this measurement we made the above operation in electric circuit with Op-Amp and RMS-DC converter LTC1966 (Linear Technology Corp.), and took in the data logger.

III. Oscillation Mode Maps

Figure 2 shows the typical current and oscillation strength dependence of Hall Thruster on magnetic flux density [11]. As the figure shows, the current become minimum around the boundary of Classical diffusion and anomalous diffusion, and the desirable operating point is around the region. The current oscillation basically becomes weak around the region.

As the basis of the measured results, we carried out an experimental and theoretical study of the low-frequency oscillation of the Hall thruster and concluded that the oscillation mode is clearly determined by the external control parameters V_a, Q and I_c [7]. And using a diagram we call oscillation mode map, the relationship between the parameters and the oscillation mode and stable operation region are clearly figured out. The oscillation amplitude contour is plotted with the product of the anode voltage V_a and gas flux Q on the ordinate, and the magnetic flux density (or coil current) on the abscissa.

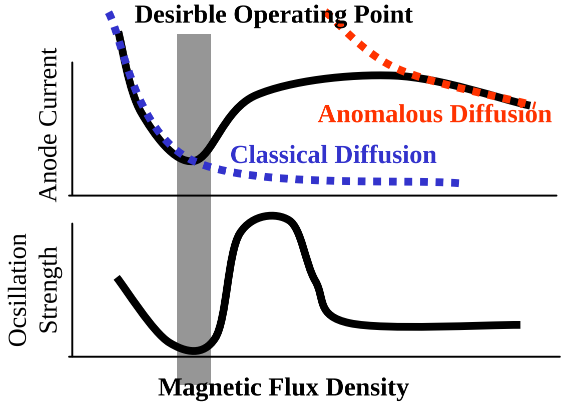


Fig. 2 Dependence of oscillation strength on magnetic flux density

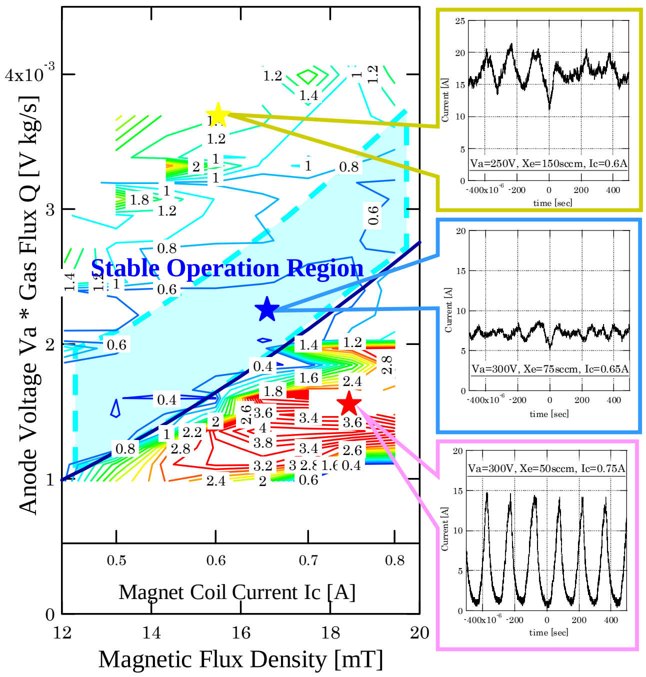


Figure 3. Oscillation Mode Map of 250mN-Class Thruster and the typical anode current waveforms.

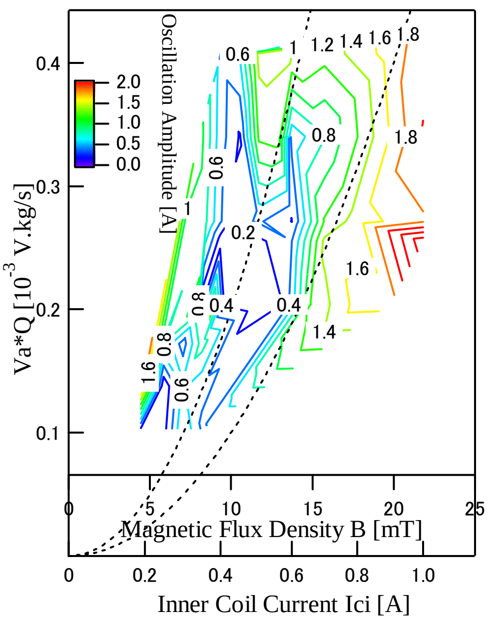


Figure 4. Oscillation Mode Map of 20mN-Class Thruster.
The dotted lines are $V_aQ[V.kg/s]=1*B[T]^2$, *and* $V_aQ=2*B^2$, *respectively.*

Figure 3 shows the oscillation mode map of 250mN-Class Hall Thruster. In the figure the typical current waveforms are also shown. The figure shows that, even for the different V_a and Q conditions, plotting with the product of the anode voltage V_a and gas flux Q on the ordinate, the oscillation mode are normalized. And we can easily find the optimum magnetic flux density for the condition to suppress the current oscillation. Also this figure shows that the boundary as the curve of $V_a{*}Q/B^2$=const. The stable operation region is agrees with the diagram of Figure 2.

Figure 4 shows the oscillation mode map of 20mN-Class Hall Thruster. The figure shows that the oscillation mode map also applicable for the 20mN-Class thruster. As we discuss later, the oscillation property is complicated compared with the 250mN-Class, and we can see two minimum values at the partial region. But the boundary is also the curve of $V_a{*}Q/B^2$=const, and it bears out our physical consideration.

Then we confirm that the idea of oscillation mode map and synchronous control method of power conditioners can be applicable to at least these two thrusters, and probably applicable to the general SPT Hall Thruster of similar configuration.

IV. Dimension Scaling Law

Here we make a theoretical consideration of current oscillation and the scaling law of channel dimension. The oscillation model presented by Yamamoto, et al. [11] is very simple and is suitable for a notional understanding of the oscillation phenomena. They derived the analytical function of the oscillation conditions, and the stable and oscillation free operational condition is expressed by the following inequality.

$$(V_{ea} - V_{ex})S - k_i \overline{N_n} \cdot SL > 0 \qquad (2)$$

where S is a cross-section of the channel, L is the ionization zone length, and V_{ea} and V_{ex} are the electron velocities at the anode side and exit side of the ionization zone, respectively. Also N_n is the nutral atom density number, and k_i is the reaction rate coefficient of the ionization. The left side of Inequality (2) shows the difference between the balance of the electron inflow and outflow at both sides of the ionization zone, and the electron yield in the ionization zone. In other words, it shows the plasma viscosity. If Inequality (2) is positive, and the electron drift and diffusion are larger than the plasma production, then oscillation does not occur. On the other hand, if the plasma production becomes comparatively large, the current begins to oscillate.

With reference to the inequality, we formulated a hypothesis in which the electron velocity has characteristic parameters for current oscillation.

The electron velocity is expressed as follows.

$$V_e = \mu_e E + \frac{D}{N_e} \nabla N_e \qquad (3)$$

where μ_e is the electron mobility, E is the electric field intensity, D is the diffusion constant, and N_e is the electron density number. In the classical diffusion region, the electron mobility can be expressed as follows.

$$\mu_e = \frac{m k_m}{q B^2} N_n \qquad (4)$$

where q is the electronic charge, B is the magnetic flux density, m is the electron mass, and k_m is the reaction rate coeffecient of the momental transfer collision between electrons and nutral atoms.

Next, we examined how the above electron mobility or electron velocity can be expressed using the external control parameters, V_a, Q and I_c.

Figure 5 shows the schematic diagram of the axial cross section of Hall Thruster, the axial distribution of the radial component of the magnetic flux density $B(z)$ and axial distribution of electric field E. Generally it is said that, when the strong magnetic flux density is applied at the exit, the thrust efficiency improves, and magnetic flux density are designed

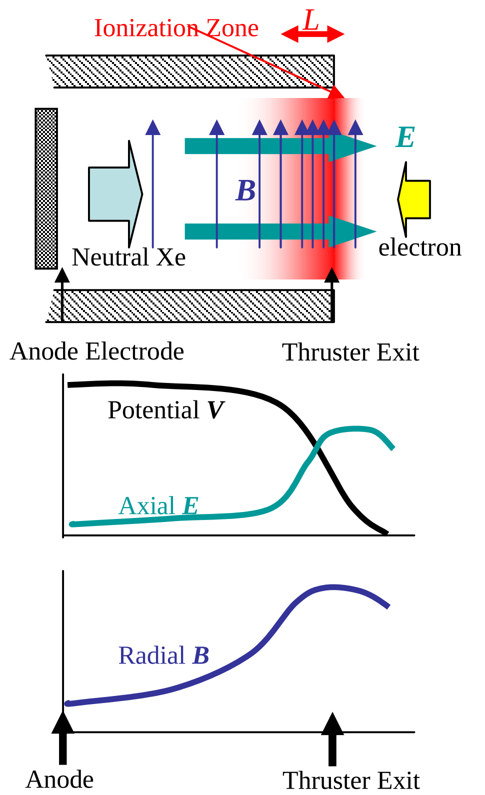


Figure 5. Ionization Zone and axial electric field and magnetic flux density distribution.

based on the idea. Then the axial distribution of magnetic flux density B designed like the figure 5. We define the B bias ratio β as the ratio of the magnetic flux density at the exit B_x and axial average of $B(z)$. d is the channel length.

$$\beta = \frac{B_x}{\frac{1}{d}\int_0^d B(z)dz} \tag{5}$$

The axial velocity of the electron becomes fast at the strong B, therefore the ionization become strong at the channel exit. The ion is accelerated mainly at this zone. Then, axial component of the electric field and potential gradient become stronger at the ionization zone. As the result, the distribution of E becomes similar with the distribution of B. That is, the electric field at the exit E_x become stronger than the average by the ratio β.

There is some distribution inside the ionization zone. When the magnetic flux density become strong, the ionization begins at the upper stream, the length of the ionization zone L will become longer. And when the neutral atom density, that is gas flux Q, increases, L will be shorter. However for the case that the discharge is maintained and the thruster operates normally, we assume that L does not change a lot. As the conclusion, in this study, we assume that the ionization zone length L is almost independent on the channel dimension, anode voltage, gas flux, and magnetic flux density.

We assume that the electric filed almost applied at the ionization zone, and because of the effect of the axial distribution of B, the electric field at the exit E_x represents as follows.

$$E_x = \frac{\beta V_a}{L} \tag{6}$$

E_x is proportional to the V_a and β, because L is constant.

Next, the neutral atom density can be expressed as follows.

$$N_n = \frac{Q \cdot N_A}{S \cdot v_n \cdot V_m} \tag{7}$$

where N_A is the Avogadro number, V_m is the volume of ideal gas, and v_n is the velocity of the neutral atoms. We assume that the velocity of neutral atom as constant. Therefore, the neutral atom density can be considered to be proportional to the gas flux Q, and inversely proportional to the channel cross section S.

The relation between the magnetic flux density B and the coil current I_c can be obtained by measurement. In particular, if B is smaller than the saturation magnetic flux density, then B is proportional to I_c. The dependence of the reaction rate coeffecient k_m in Equation (4) cannot be easily approximated, and in this study, we neglect the dependence on the external control parameters and channel dimension parameters.

Now, neglecting the diffusion term of the right side of Equation (3), and considering the dependence mentioned above, the electron velocity at the exit of channel V_{ex} can be expressed proportionally as follows.

$$V_{ex} \cong \mu_{ex} E_x \propto \frac{\beta \cdot V_a \cdot Q}{S \cdot {B_x}^2} \tag{8}$$

As the result of the above discussions, we propose the hypothesis that the state of current oscillation can be simplified by the expressions shown in Equation (8). In another words, we propose the hypothesis that the state of discharge, or the oscillation strength, changes according to the Equation (8), and to maintain the discharge condition stable, the Equation (8) should be kept constant.

Here we make a similar discussion from the another point of view. Equation (8) make a connection between discharge condition (V_{ex}), the parameter for the thruster operation and performance V_a and Q, the parameter for the stable operation B_x, and the parameter of the channel dimension S and β. For example, large thruster will consume a lot of properant gas, then Q must be normalized by S. Basen on the idea, we introduce the parameter "Equivalent Energy Density w_{eq}" which represents how much energy is injected into the ionization zone per unit area.

$$w_{eq} = \frac{\beta \cdot V_a \cdot Q}{S} \tag{9}$$

As the unit of gas flux Q, we used [kg/s] at the Figure 3 and Figure 4, which can be converted to equivalent current [A]. Then the equivalent energy density w_{eq} can be expressed by the power per unit area [W/m^2]. However, because Q is different from the practical discharge current, and β acts as a weighting factor, w_{eq} differs from the value of the actual discharge power per channel cross section.

Equivalent Energy Density w_{eq} means how much energy are injected into the ionization zone. It can be said that w_{eq} means how much thrust is needed, and it is the parameter basend on the designer's and operator's purpose.

On the other hand, B_x or the coil current I_c is mostly independent on the thruster performance. It is the parameter which maintains the discharge condition and enables the stable operation. Equation (8) make the connection between the Equivalent Energy Density w_{eq} and control parameter B_x (I_c) for the discharge condition (V_{ex}).

Based on the above considerations, we normalized the oscillation mode maps by the Equivalent Energy Density w_{eq}. The left side of the Figure 6 shows the oscillation mode map of 250mN-Class and 20mN-Class, with the Equivalent Energy Density on the ordinate. And the right side of Figure 6 shows the superposition of the left two figures. As the figure shows, using the the Equivalent Energy Density on the ordinate, the oscillation region of the different thruster are superimposed. This means that, using the Equivalent Energy Density, the oscillation mode map and the oscillation occurrence condition can be normalized by the thruster channel dimension,

The boundary of the stable and unstable region can be also normalized by Equivalent Energy Density. The boundary curves shown in Figure 6 by dotted line are expressed as follows.

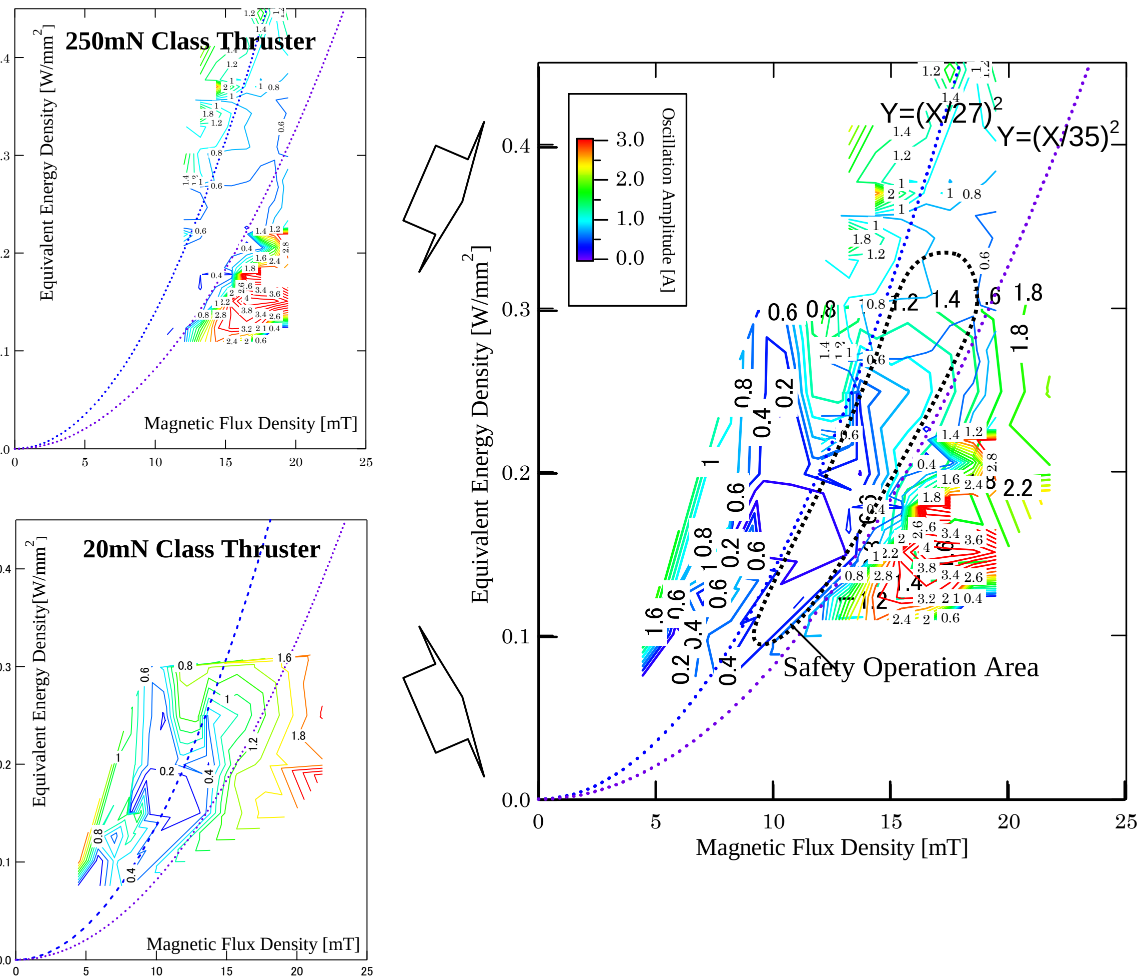


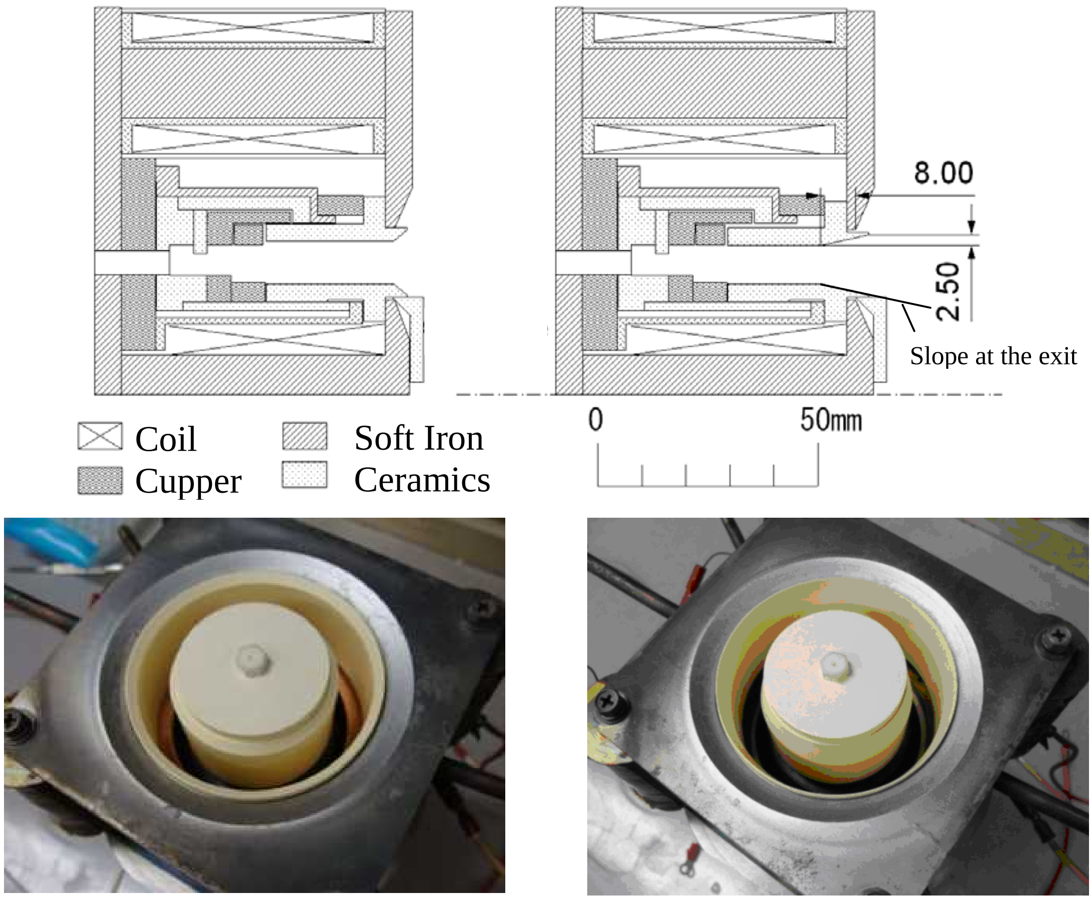
Figure 6. Oscillation Mode Map normalized by Equivalent Energy Density.
The left side of the Figure 6 shows the oscillation mode map of 250mN-Class and 20mN-Class, with the Equivalent Energy Density on the ordinate. And the right side of Figure 6 shows the superposition of the left two figures.

$$w_{eq}[W/mm^2] = \frac{\beta \cdot V_a Q}{S} = \left(\frac{B_x}{35}\right)^2 [mT] \tag{10}$$

$$w_{eq}[W/mm^2] = \frac{\beta \cdot V_a Q}{S} = \left(\frac{B_x}{27}\right)^2 [mT] \tag{11}$$

The region between these boundaries is the stable operation region. Especially, the lower boundary (Equation (10)) shows the boundary with the lower right strong oscillation region, and to operate stably, the magnetic flux density must be controlled inside the boundary.

In this study, we compared only two thrusters, and the generality of the scaling law must be examined from now. For example, the scaling law may not be valid for extremely large or very small thruster because the ionization zone length *L* cannot be assumed as similar range with the ordinary thruster. However, for the ordinary SPT hall thruster with the circular ring BN channel, we think that we can basically expect similar characteristics.



BOL (Beginning of Life) **EOL (End of Life)**

Figure 7. The cross section and outer appearances of BOL (Beginning of Life) and EOL (End of Life) thruster.

V. Effect of Channel Erosion

The life time is the very important problem of Hall Thruster. It is one of our important subjects to control the Hall Thruster stably even at the end of life. At the end of life of the thruster, the exit of the channel is subjected by erosion. To simulate the erosion effect, we compare the characteristics of two thrusters with the different shape of channel exit.

Figure 7 shows the cross section and outer appearances of BOL (Beginning of Life) and EOL (End of Life) thruster. The channel exit of EOL has a slope [12]. Comparing the characteristics of these thrusters, we think that the thruster characteristics at the end of life can be simulated. The BOL thruster is almost the same dimension with the 20mN-Class thruster in Table 1.

Figure 8 shows the measurement results of average anode current and oscillation strength for BOL and EOL thrusters. The horizontal axis is the coil current, which is almost proportional to the magnetic flux density. Figure 8 shows the result of Q=10.5sccm (standard cubic centimeters per minute). W e made a measurement at the range of Q=5 ~ 13.9 sccm, which show the similar results.

As for the anode current dependence on magnetic flux density is same property with the Figure 2. However, as for the oscillation strength, like the result of Figure 4 of 20mN thruster, two minimum values are measured.

According to the Equation (10) and (11), we can normalize the horizontal axis by the Equivalent Energy Density.

$$\frac{B_x}{\sqrt{\frac{\beta \cdot V_a Q}{S}}}[mT \cdot mm/W^{0.5}] \qquad (12)$$

BOL has a straight channel and the channel cross section S is constant. However EOL has a sloped channel and channel cross section at the exit side become larger than at the anode side. Then we assumed that the channel cross section of the EOL thruster is the mean value of that of anode side S_a and exit side S_x ($(S_a+S_x)/2$). The structure of pole piece is the same, and the magnetic flux density distribution does not change. Therefore the B bias ratio β if the same for BOL and EOL thruster.

Figure 9 shows the result of normalization by Equation (12). In the figures, two dotted lines show the Equation (10) and (11), and the gray region corresponds to the stable operation region at Figure 6. From these figures, we can see the following conclusions.

First, normalizing the horizontal axis, the properties of different V_a become the same curves. In this figure we show only the results of Q=10.5sccm, and we confirmed the same trends for another conditions of gas flux. The anode current becomes minimum at the right end of gray region, which corresponds to the desirable operating point at Figure 2 and stable operating region at Figure 6. Therefore, for the both BOL and EOL thruster, the desirable operating condition is the right end of gray region. From the results, the idea of normalization by the equivalent energy density is also applicable to the BOL and EOL thrusters.

On the other hand, the oscillation strength dependence on B has two minimum points. At the left side (lower B) the oscillation become very small, but the anode current is fairly large. At this point, because of the large anode current the input power become

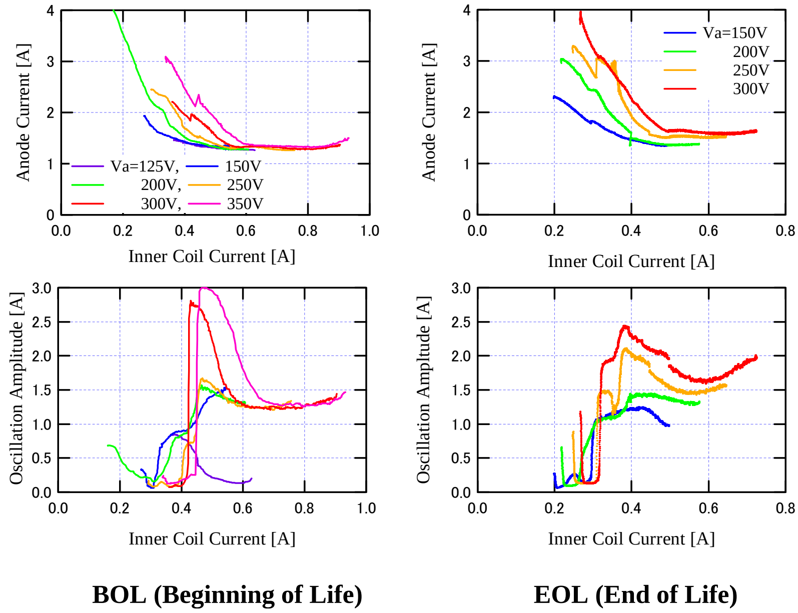
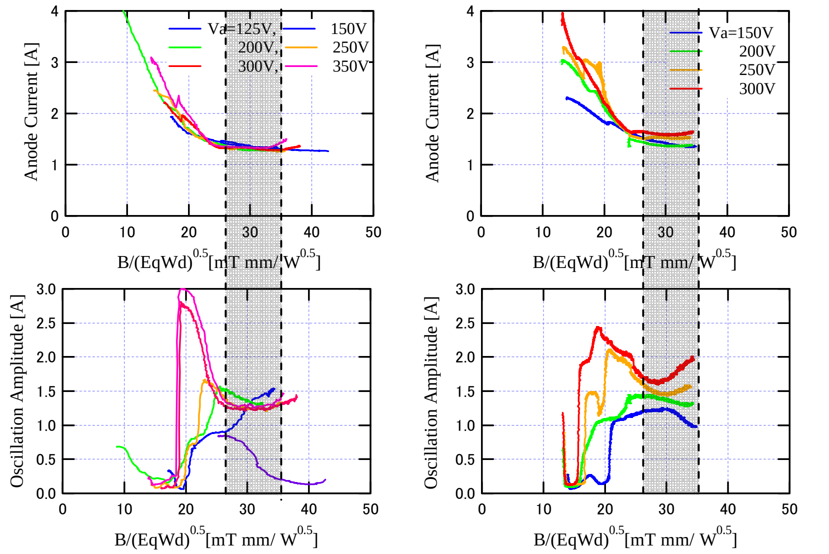


Figure 8. Average anode current and oscillation strength for BOL and EOL thrusters. Q=10.5sccm.

large, and thrust efficiency become worse which does not desirable for operation.

At the right side (high *B*), the oscillation is fairly strong, but does not extremely unstable. Therefore this region can be considered as the desirable operating point. We think that this region is the boundary region between classical diffusion and anomalous diffusion.

We have not found yet the reason of the oscillation property discussed above. For the case of the large 250mN-Class thruster, like Figure 2, the magnetic flux density for the minimum anode current and minimum oscillation strength are agreed. For the case of 20mN-Class Thruster, because of the small channel width, the unevenness of the radial component of magnetic flux density may affect the oscillation characteristics. It can be said that the oscillation characteristics may changes by the channel dimension and magnetic flux distribution at the ionization zone.



BOL (Beginning of Life) **EOL (End of Life)**

Figure 9. Average anode current and oscillation strength for BOL and EOL thrusters with the normalized horizontal axis. Q=10.5sccm. *The dotted lines and gray region are corresponds to Equation (10), (11), and the stable operation region at Figure 6.*

EOL thruster compared with the BOL, the confinement of magnetic flux density become weak, and the current at the weak *B* region become large. And the second minimum point around the desirable operating point becomes ambiguous. Therefore it is inadequate that seeking the best operating point based on the oscillation strength, and the average anode current must be the guideline for the optimum control. These characteristics can be clearly discriminate by the normalization of equivalent energy density.

VI. Conclusions

For the two types of different size Hall Thrusters of 250mN-Class and 20mN-Class, and for the Hall Thruster with the channel erosion simulated the end of life, we performed observations of the electrical characteristics and the low-frequency discharge current oscillation by widely varying the external control parameters. Introducing the parameter "Equivalent Energy Density" which represents how much energy is injected into the ionization zone per unit area, we discovered that the stable operation condition can be normalized by the external control parameters and the thruster dimension. Moreover, as for the case that the channel shapes is greatly changed by the erosion, we found that the normalization by the "Equivalent Energy Density" is applicable.

The vertical axis of the normalized oscillation mode map is "Equivalent Energy Density w_{eq}", which is the parameter based on the designer's and operator's purpose. It represents how much energy are injected into the ionization zone, and how much thrust is needed. On the other hand, B_x or the coil current I_c is the external control parameter which maintains the discharge condition and enables the stable operation. Using the normalized ocsillation mode map, we can easily know the optimum coil current for each operating condition.

Knowing the channel dimension scaling law and the property at the end of life, we can design the necessary electric characteristisc such as optimum magnetic flux density, and can also predict the characteristics of thruster operation. Moreover, we can apply the control method obtained by a laboratory size small thruster to a large size thruster. This is a very important giideline at the stage of the practical thruster development.

Using the characteristics of the EOL thruster which simulated the channel erosion at the end of life, we also can predict the property at the end of life. It is very important guideline for the development of long lifetime and stable operation at the end of life. In the future, with the guideline obtaind in this study, we will develop the stable control method of the Hall Thruster by power conditioners, especially the adoptive controol method at the end of life.

Acknowledgments

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