Thrust Performance in Hall Thruster with Pulsating Operation

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Abstract: As a harmonized PPU with Hall thrusters, a pulsating boost chopper circuit PPU has been developed and the thrust performance was investigated using the 1 kW class magnetic layer type Hall thruster developed at Kyushu University. We call this engine system the "Volterra Engine," since it is based on the prey -predator model. The thrust performance, the thrust, the thrust efficiency, energy plume divergence, ion energy distribution function was measured. The thrust of this engine is superior to that with 150 V constant voltage operation, but ion energy distribution function is wider than that with 150 V constant voltage operation, as shown in Fig.1. Plume divergence is almost the same as that with 150 V constant voltage operation.

Nomenclature

C	=	capacitance values of capacitor
E_b	=	ion energy
F	=	Thrust
g	=	acceleration of gravity
I_d	=	discharge current
i	=	time index during navigation
L	=	induction of the coil
$\dot{m}$	=	anode mass flow rate
T	=	constant time which is longer than the oscillation period
V_d	=	discharge voltage

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I_d = discharge current

I. Introduction

HALL thruster system will be required to be as light/small as possible because of the installation limitations on a rocket payload. These limitations will require that the power processing units (PPU) be small and light with low power consumption operation. One of the solution of this is "harmonized PPU with Hall thrusters" In the Hall thruster, discharge current naturally oscillates due to the various instabilities, with the largest oscillation being prey-predator oscillation (ionization oscillation)[1-5]. "Stability" should therefore be re-defined not as "oscillation suppressed" but as "discharge maintained," with the PPU allowing natural discharge oscillation. The harmonized PPU provides power in accordance with the fluctuating (over time) impedance of the Hall thrusters. That is, it works as a constant voltage source for maintaining discharge when the discharge current is small, and it works as a constant current source during large pulsed current flows. We called this engine system as "Volterra Engine", respecting the work of Vito Volterra who evolved the predator–prey model.[6] As a harmonized PPU with Hall thrusters, a pulsating boost chopper circuit PPU has been developed. [7,8] These works show the advantage of the Volterra engine, that it is light weight and has superior thrust efficiency and the thrust to power ratio compared to DC operation. The real important finding in these works is that oscillation in Hall thrusters can be controlled by changing the voltage, or Hall thruster operation can be synchronized with PPU in some range. And the thrust performance of Hall thrusters depends on the phase angle between discharge voltage and current. In addition, we found that the dependency of the phase angle between discharge voltage and discharge current on frequency is almost the same as that of LC circuits. These results will be very helpful to understand how Hall thruster work in an electronic network and to clarify the physics in the Hall thrusters. It could be used to developed better PPU, improve filter performance or impedance matching, reduce mass and avoid instabilities.

The aim of this study is to investigate the detailed relationship between phase shift and chopping frequency and to evaluate the effect of the pulsating operation on thrust performance for understanding Hall thruster physics and development of better PPU. In our previous study, the phase angle was measured using rectangular pulse train superposition on constant voltage to the Hall thruster. For the modeling of the Hall thruster, we measure the phase angle using sine function superposition on constant voltage to the Hall thruster using frequency response analyzer.

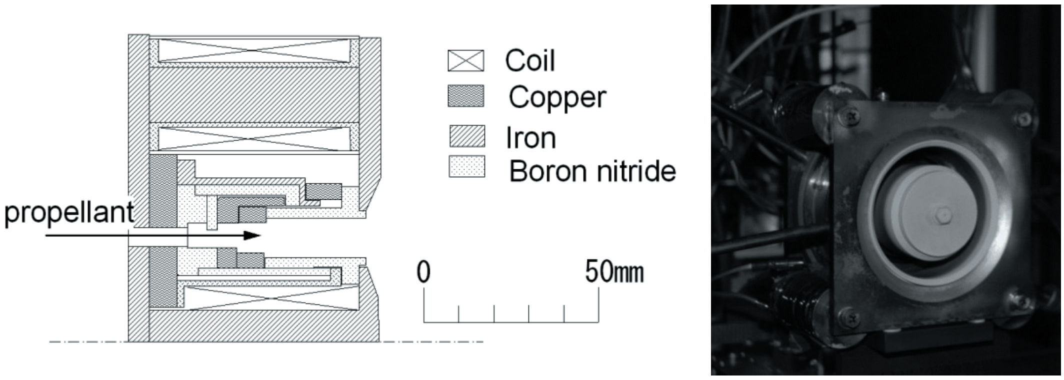
II. Experimental setup

Figure 1(a) shows a cross-section of the 1 kW class magnetic layer type Hall thruster used in the current experiments. The inner and outer diameters of the acceleration channel are 50 mm and 70 mm respectively. The acceleration channel is made of boron nitride. The anode is set at 30 mm upstream of the thruster exit. As shown in Fig. 1(b), an inner solenoid coil and four outer solenoid coils create a predominantly radial magnetic field in the acceleration channel. The magnetic flux density is varied by changing the coil current. The magnetic field distribution along the channel median is shown in Fig. 2(a) and the calculated magnetic field lines are shown in Fig. 2(b) (each coil current is 1 A, calculated using Magnum3.0, Field Precision LLC.). The origin of Fig.2(a) is the exit of the acceleration channel, and the radial magnetic flux density peaks at $z = -1$ mm. Magnetic flux density is higher on the inner wall and decreases with radius, since the magnetic flux between the poles is conserved.

High-purity 99.999% xenon gas was used as the propellant with thermal mass flow controllers. A hollow cathode is used as the electron source. A frequency response test is conducted in a vacuum chamber of 1.0 m diameter by 1.2 m length The pumping system includes a rotary pump and a turbo molecular pump (air pumping speed is 2050 *l*/s) and cryogenic pump (2300 *l*/s). The chamber baseline pressure is below 1×10^{-3} Pa. The background pressure was maintained below 1×10^{-2} Pa at a xenon mass flow rate of 1.2 mg/s (anode 1.0 mg/s and cathode 0.2 mg/s). Thrust performance tests are conducted in the space science plasma chamber in ISAS/JAXA, which is 2.5 m diameter by 5.0 m length. The pumping system includes a rotary pump and a turbo molecular pump (air pumping speed is 3400 *l*/s in nitrogen) and two cryogenic pumps (22,000×2 *l*/s in nitrogen). The chamber baseline pressure is below 1×10^{-5} Pa. The background pressure was maintained below 2×10^{-3} Pa at a xenon mass flow rate of 2.2 mg/s (anode 2.0 mg/s and cathode 0.2 mg/s).

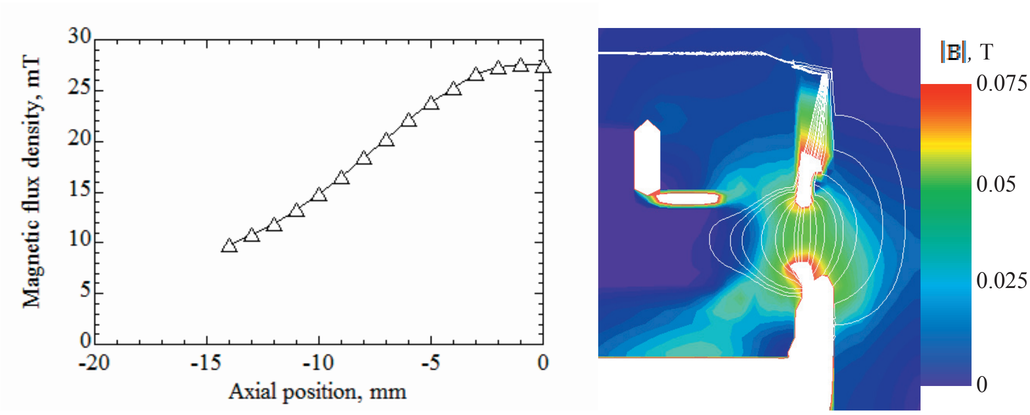
A pendulum-type thrust stand is used for the thrust measurements. To reduce the influence of thermal drift, low thermal expansion carbon/carbon composite (0.08×10^{-6} /K) is used as the leg component. Thrust stand calibration is conducted with a set of two known weights in a pulley system assembly. The overall uncertainty in thrust is conservatively estimated at ±5%.

An ion collector (9 mm diameter) is set at 1500 mm downstream of the thruster for the measurement of the ion beam current from the thruster. Retarding potential analyzer is also set at 1500 mm downstream of the thruster for the measurement of the ion beam profile and ion energy distribution function. The ion collector and RPA can be moved along the line perpendicular to the thruster axis.



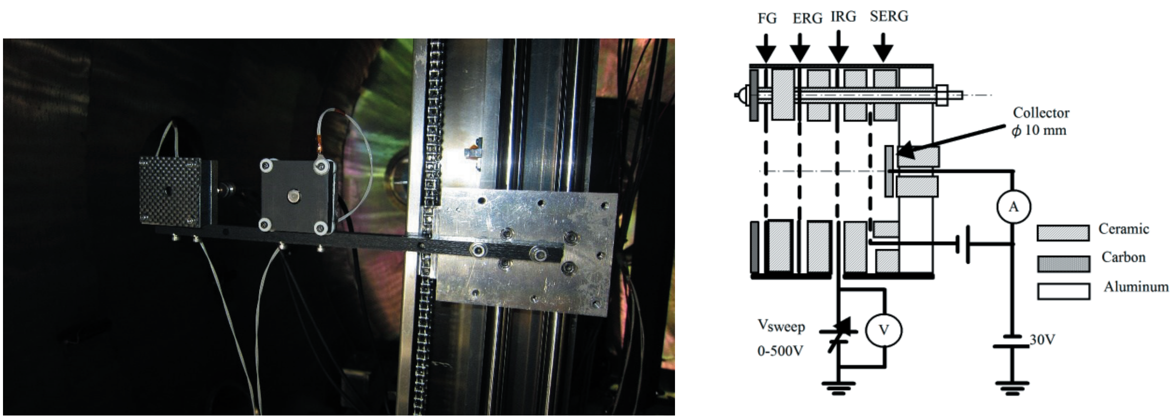
(a) (b)

Figure 1. Magnetic layer type Hall thruster developed at Kyushu University. (a) Cross section (b) photo



(a) (b)

Figure 2. Magnetic field configuration of the Hall thruster developed at Kyushu University. (a) Radial magnetic flux density profile (outer coil current = 1 A, inner coil current= 1A, r=30 mm) (b) Calculated magnetic field lines (calculated using Magnum3.0, Field Precision LLC)



(a) (b)

Figure 3. Ion collector and retarding potential analyzer. (a) front view (left: RPA, right: ion collector) (b) Schematic of RPA developed at Kyushu university

For the measurement of frequency response characteristics in Hall thrusters, a frequency response analyzer (FRA), NF Corporation, FRA5096) and a precision power amplifier (NF Corporation, NF 4520) were used. The schematic of this measurement system was shown in Fig.4. The FRA provides sign signal with scanning from 5 kHz to 20 kHz to the power amplifier, and the power amplifier amplifies the signal and provide the discharge voltage to the thruster. The discharge voltage and the current were measured using 100 MHz differential probe(Yokogawa 700924) and 100 MHz current probe(Tektronix, TCP312A), respectively, and these signals go back to the FRA. The FRA measures the amplitude, the phase angle of the discharge voltage and discharge current, impedance, etc.. We applied sine function discharge voltage (the amplitude of 50 Vp-p) superimposed on DC(150 V-225 V) as a discharge voltage.

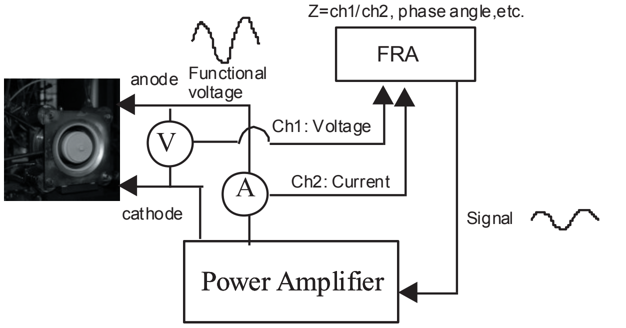


Figure 4. Schematic of frequency response characteristics measurement.

III. Results and discussion

In order to evaluate the performance of Hall thrusters, specific impulse, I_{sp}, and thrust efficiency, η_t, are defined as,

$$I_{sp} = \frac{F}{\dot{m} g}$$
$$\eta_t = \frac{F^2}{2\dot{m} \int_0^T V_d I_d dt / T} \tag{1}$$

A. Phase angle between discharge voltage and discharge current

Figure 5 shows the phase of current against discharge voltage for various frequency at discharge voltage of 150 V (DC) ±50 V (sine) and mass flow rate of 1.0 mg/s. the phase is defined as the difference between applied voltage to the anode and discharge current; subtract the phase of discharge current from the phase of discharge voltage.

The phase shift between discharge voltage and discharge current is zero at 8 kHz, which is almost the same as the natural frequency of ionization oscillation in this thruster. The phase of the current lags more with increase in frequency. These results show that the thruster can be treated as an LC circuit when the Hall thruster synchronized with applied voltage; in this case, it is from 8 kHz to 14 kHz. It is easy to see that synchronized current is large if the thruster is syncronized with applied voltage, as shown in Fig. 4.

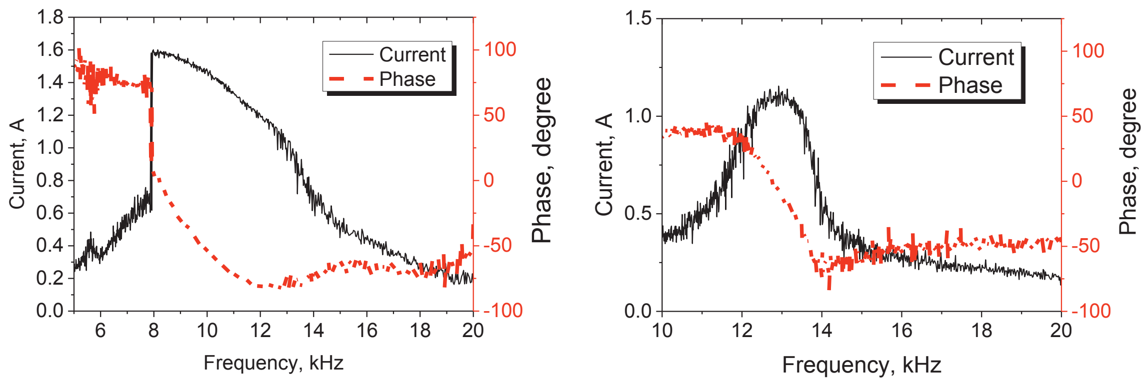


Figure 5. Phase shift between discharge voltage and discharge current. (a) *(DC 150V±25 V (sine)(b)DC 200V±25 V (sine) at xenon mass flow rate of 1.0 mg/s.*

Figure 5(b) shows the phase difference at discharge coltege is 200 V ±50 V (sine). At 200 V case, the phase shift is gradually changed and the syncronized current also changed gradually and has peak at 13 kHz. At that frequency(f=13 kHz), the phase difference is also zero. In this condition, the phase of current leads if f <13 kHz, and the phase decrease with frequency and if f>13 kHz, the phase of current lags. With increase in discharge voltage, the frequency which the phase is zero is increase, as natural ionizaition frequency increase with discharge voltage.

B. Thrust performance of Volterra engine

Figure 6 shows the pulsating boost chopper circuit using in this study as a Volterra engines power unit. The chopping frequency, duty ratio, primary supplied voltage (base voltage), capacitance of capacitor, and inductance of the coil can be changed. In this study, the capacitance changed from 0.22 to 2.2 μF, and inductance is 0.5 mH and 0.9 mH. The mimimum chopping frequency is restricted by the MOSFET ability (maximum drain current, maximum drain-source voltage), and this depends on the thruster operational condition.

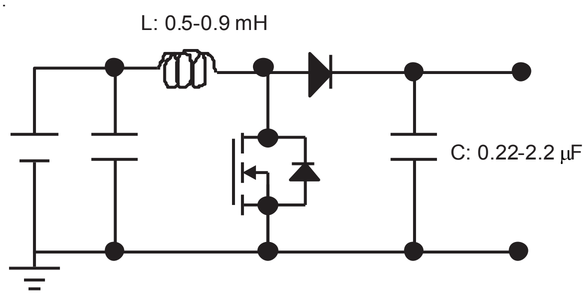


Figure 6. Pulsating boost chopper circuit.

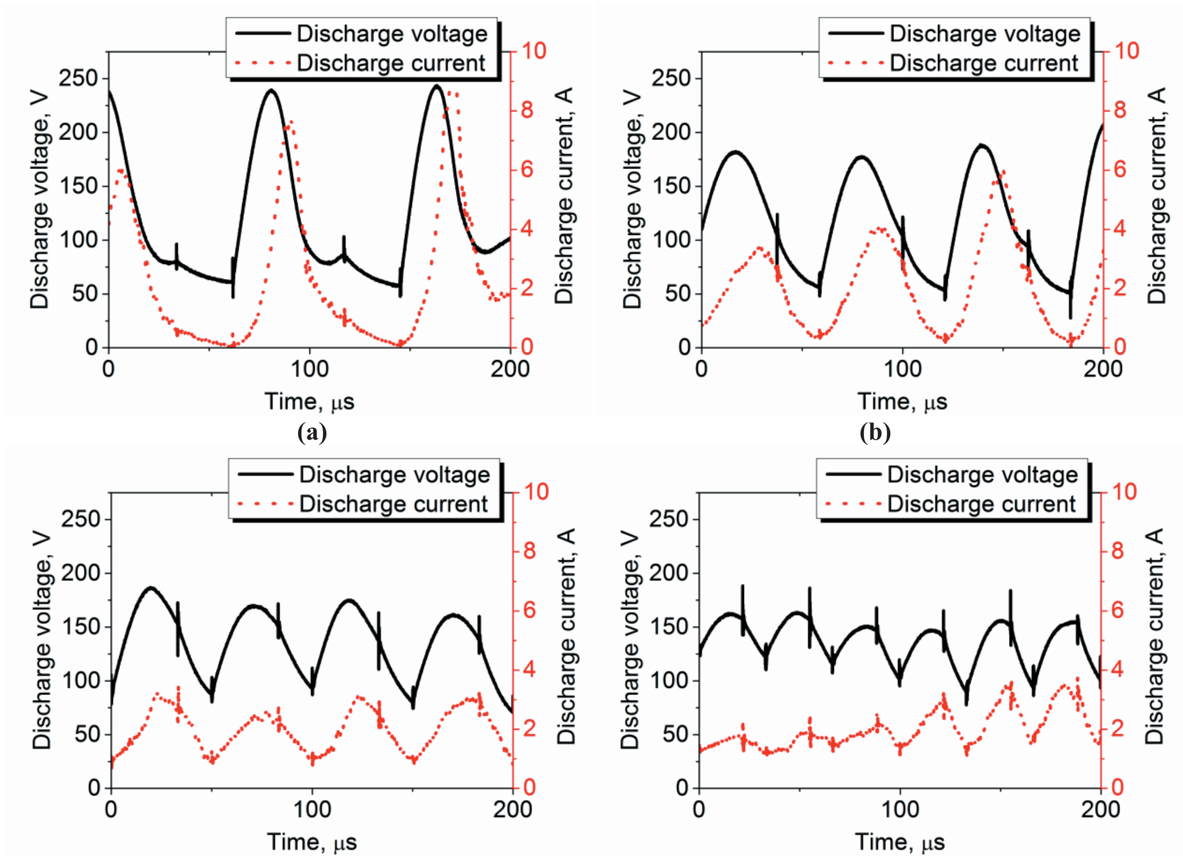


Figure 7. Discharge current trace for various chopping frequencies. (a)12 kHz(b)16 kHz(c) 20 kHz(d)30 kHz at the capacitance of the capacitor of 0.47 μF and the inductance of the coil of 0.5 mH, at xenon mass flow rate of 2.0 mg/s , the duty ratio of chopping of 0.33.

Figure 7 shows the discharge voltage and discharge current trace for four chopping frequencies, 12 kHz, 16 kHz, 20 kHz and 30 kHz at the capacitance of the capacitor of 0.47 μF and the inductance of the coil of 0.5 mH, at xenon mass flow rate of 2.0 mg/s , the duty ratio of chopping of 0.33.

Phase angle between discharge voltage and discharge current is almost the same (30-50 degree), so, the dependency of phase angle on chopping frequency differ from the simple sine function discharge voltage. As our previous study, the maximum discharge voltage (or amplitude of the discharge voltage) decrease with the increase in chopping frequency and in this condition, the voltage close to 150 V. Even the frequency of 30 kHz, thruster synchronized with PPU (chopping). The amplitude of the discharge current decrease with the increase in chopping frequency, and this is the same tendency of our precious study.

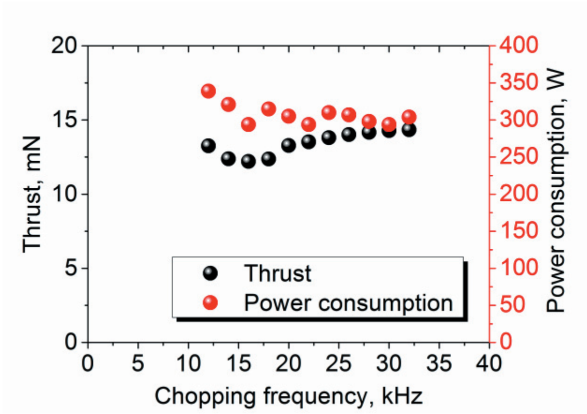


Figure 8. Thrust performance vs. chopping frequency.

Figure 8 shows the dependence of the thrust and the power consumption on the chopping frequency at the same condition. The thrust and the power consumption decrease with the increase in chopping frequency and at critical frequency (in this condition, it is 18 kHz), the thrust increase with the increase of chopping frequency. The decrease in thrust and power consumption is due to the decrease in the effective discharge voltage, as our previous study. The thrust performance of the Volterra at frequency of 30 kHz is 14.3 mN, 294 W, which is superior to the DC one: 13.6 mN, 336 W. The power consumption of Volterra engine is less than that of DC operation is the phase angle difference between the discharge voltage and the discharge current, as shown in Fig. 7.

Figure 9 shows the ion beam profile (E_b>100 eV) by means of Retarding potential analyzer for three chopping frequencies. With the increase in chopping frequency, the ion beam current increases, that is, propellant unitization improved. On the other hand, the average ion energy decreases with the increase in the chopping frequency, as shown in fig. 10. This is due to the maximum discharge voltage increase with the decrease in chopping frequency. So, ion energy distribution function becomes narrower with increase in chopping frequency and close to DC one. Anyway, the tradeoff between propellant unitization and average ion energy causes the dependency of the thrust on the chopping frequency, as shown in Fig. 8.

The beam profile of the Volterra is almost the same as DC operation, the full width of half maximum is 18.6 to 19.6 degree. This result might show that the lifetime of the Volterra is almost the same as DC operation. That is, the Volterra operation affects little on the beam divergence. The Volterra operation affects on the beam energy efficiency, the wider ion energy distribution function than that with DC operation. This degrades the total thrust efficiency, though itis negligible compared to other factors, since the thrust is almost the same (or larger) as that of DC operation.

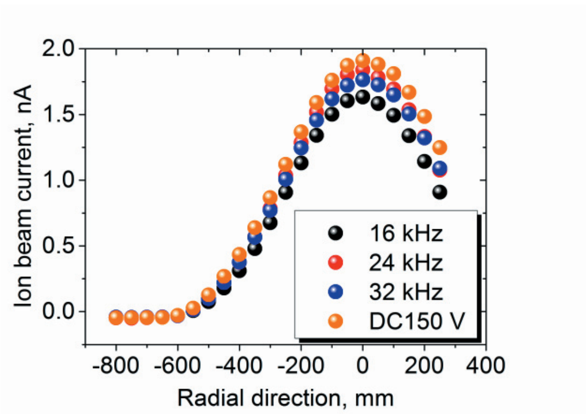


Figure 9. Ion beam profile for three chopping frequencies.

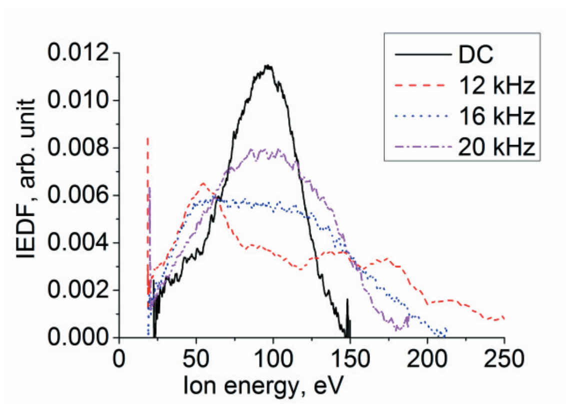


Figure 10. Ion energy distribution fuction for three chopping frequencies

IV. Conclusion

The effect of the pulsating operation on thrust performance, thrust, thrust efficiency, beam divergence in Hall thruster was investigated using 1 kW class magnetic layer type Hall thruster. Thrust and thrust performance with pulsating operation are 14.3 mN, 0.17, respectively, which are superior to of DC operation; 13.6 and 0.14. The effect on plume divergence is negligible. The ion energy distribution function with pulsating operation is wider than that with DC operation.

The frequency response characteristics in Hall thrusters was also investigated using frequency response analyzer and power amplifier. The synchronized frequency is close to natural ionization frequency and the phase angle between discharge voltage and current decrease with frequency as normal LC circuit does. The more detail study about the dependence of phase angle and thrust performance will be helpful in constructing a Hall thruster model and this should contribute the development of better power processing unit, improvement of filter performance and impedance matching, reducing mass of PPU.

Acknowledgments

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