Optical diagnosis of plasma in a channel of Hall Thrusters

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Abstract

Plasma oscillations in a Hall thruster were experimentally investigated by means of optical diagnostics. A channel-length variable Hall thruster had been developed in Nagoya University. Emission lights in its acceleration channel were picked up through the optical holes aligned axially on a channel insulator wall. The measured oscillation frequency shifted from 10 to 25 kHz with the increase in discharge voltage. Furthermore, spectral analyses of the emission are presented for the study of basic plasma parameters in the acceleration channel. Emitting species were changed with the discharge current.

Introduction

A Hall thruster is thought to be an attractive propulsion system for north-south station keeping due to its optimum specific impulse. The Russian Hall thruster, SPT has been originally developed over 30 years to achieve high specific impulse in the range of 1000-3000 sec and high efficiency larger than 50%. More than 50 thrusters have been utilized for the correction of insertion trajectories and east-west station-keeping of satellites.[1] Recently, the performance of the SPT has been validated to meet Western standards. A great deal of research has focused on lifetime and performance issues of the thruster, and now the base-line operating conditions are thought to be accomplished.[2] However, there are still some phenomena not to be clearly understood though the nominal performance of the SPT has become reliable. One of these phenomena is the plasma oscillation.

Plasma oscillations have been observed in the wide range of operational conditions. They can be classified into five regions such as ionization (10^4-10^5 Hz), transit-time (10^5-10^6 Hz), electron-drift (10^6-10^7 Hz), electron-cyclotron (10^9 Hz) and Langmuir ones (10^8-10^9 Hz). The three former types of oscillations are particularly integral ones of the Hall thrusters which has a discharge channel where radial magnetic fields and axial electric fields are applied to ionize a propellant gas. These oscillations could affect on the electron conductivity and diffusion across the magnetic fields.[3] Among these types of oscillation, low frequency (10^4-10^5 Hz) ionization oscillations would be one of the main obstacles for improving its thrust efficiency. Although several discharge models are proposed, there is no adequate theory up to date, to describe these phenomena, and the relationship between oscillation and performance is still unknown.[4,5,6,7]

In our previous researches, it was found that the channel length is one of the most important design parameters which determine the thruster performance.[8] Furthermore, with the short channel-length, the efficiency went up but the discharge became unstable. The operational difficulty with the short channel-length thruster or the anode layer type Hall thruster might be overcome by understanding the plasma dynamics in the channel. In this paper, the plasma oscillation in the acceleration channel was examined by means of optical diagnosis.

Experimental Apparatus

Hall Thruster

A channel-length variable Hall thruster used in this study is schematically shown in Fig. 1. It has an acceleration channel insulated with two ceramic cylinders. The inner and outer diameter of the channel are 52 mm and 72 mm, respectively. The channel length is variable from 3 mm to 17 mm by changing anode-ring width. The anode is located at the upstream end of the channel and has twenty small apertures to uniformly feed the propellant gas into the channel. A solenoidal

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coil is set at the center of the thruster to apply magnetic fields in the radial direction in the channel. The magnetic fields are uniformly aligned in the radial direction. The magnetic induction is almost constant through the channel, and maximum induction was about 800 gauss. This uniform magnetic field distribution is different from that of the SPT-type Hall thrusters, whose magnetic fields have a peak at the channel exit. Xenon and argon are tested as a propellant gas. Propellant mass flow rate is regulated using a thermal mass-flow controller. A filament cathode, which supplies electrons to sustain the discharge and to neutralize the ions, is used instead of a hollow cathode for operational convenience. The filament is made of 2% thoriated tungsten wires coated with the triple-carbonate powder to reduce its work function for electron emission.

Test Facility

Experiments were performed in a vacuum chamber at the Nagoya University. The chamber, which has 1.0 m in diameter and 1.6 m long, is evacuated by two diffusion pumps rated at 5000 l/s each backed by a roots blower and a rotary pump. The background pressure is maintained in the order or 10^{-4} Torr during the operation. Three power supplies are used for main discharge, solenoidal-coil excitation and cathode heating. In order to stabilize the discharge, 20 Ω resistor is added to the main discharge circuit. It takes a few minutes for the main discharge to be stabilized. To test the influence of electric circuits of the power supply on the oscillation, two types of power supply are used for the main discharge.

Optical Diagnostics

As shown in Fig.2, there are three holes for optical pickup arranged in the axial direction on the outer insulator wall of the thruster. Each hale has 1.0 mm diameter. Port #1 is located at the position 9 mm from the exit of channel, and #2 and #3 are at 6 mm and 3 mm from the exit, respectively. In the case when the channel length is 11 mm, Port #1 lies in the vicinity of the anode.

A light emitted from the discharge plasma is detected by a photo-diode or a spectrometer outside the vacuum chamber through an optical fiber. A schematic of the diagnosis system is shown in Fig.3. A multi mode type optical fiber (MITSUBISHI DENSEN, Inc. STU800G-SY) with a large core diameter of 800 μm is used to minimize a transfer loss. Fibers are connected to a half depth of the pickup holes.

For the optical oscillation study, the other end of fiber is set at the entrance of a photo-diode (TOSHIBA, Inc. TPS708), which is most sensitive at a wavelength of 820 nm and the sensitivity drops to 20% of that at 450 nm. The emission intensities signals are simultaneously recorded with the discharge current and voltage oscillations using a eight-channel digital oscilloscope.

For the emission spectra analyses, the fibers are connected to a spectrometer (NIPPON BUNKOU, Inc.

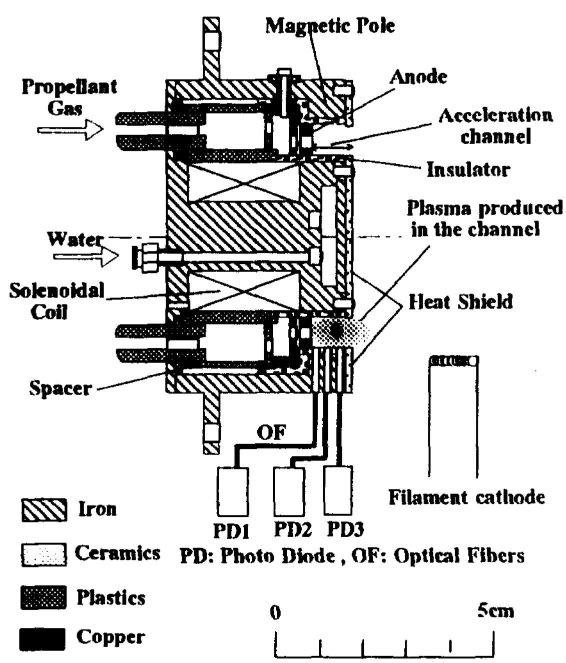

Fig.1 Nagoya University Hall thruster

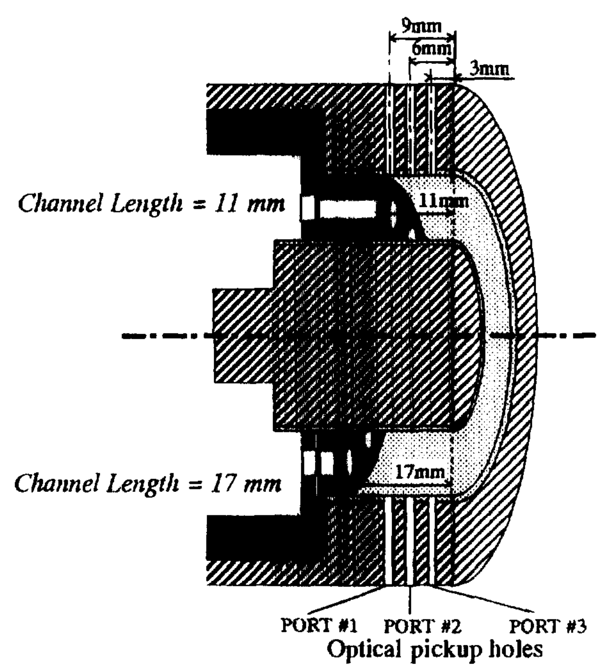

Fig. 2 Locations of optical pickup for the cases of channel length of 11 mm and 17 mm.

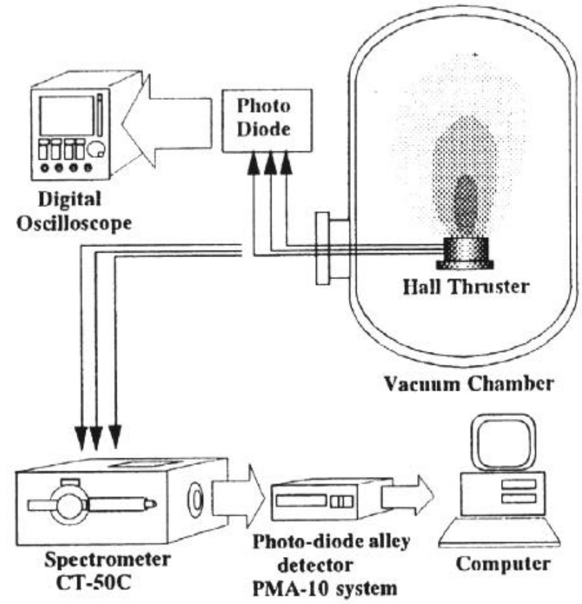

Fig.3 Diagnostics schematic

CT-50C) with a photo-diode alley detector (HAMAMATSU PMA-10). The spectral range is extended in the UV region to a wavelength of 300 nm and in the near infrared to 830 nm. The wavelength resolution was 0.01 nm.

Discharge characteristic of the Hall thruster

Figure 4 shows the current-voltage characteristic of the Nagoya University Hall thruster. As seen in this figure, the curve has a knee point at approximately 1.7 A of discharge current for xenon propellant with the mass for rate of 1.37 mg/s, corresponding to 1.0 A current equivalent. The knee point for argon propellant with the mass flow of 1.25 mg/s (3.0 A-eq.) is 4.5 A.

Oscillations of plasma emission

Oscillation frequency

Figure 5 shows the fluctuations of emission intensity simultaneously detected at the three ports. Discharge voltage was 110 V and discharge current 1.35 A ± 0.5 A with argon propellant at the mass flow rate of 1.25 mg/s. Magnetic induction is 800 gauss. The channel length was 11 mm. As seen in the figure, three signals show a similar oscillation pattern. The frequency and the phase of oscillations look same.

Figure 6 illustrates the comparison of oscillation frequencies by means of the fast Fourier transform. Each characteristic frequency of oscillation is almost equal to 15 kHz, at which typical ionization oscillation would arise. In our thruster, discharge current oscillated at a little higher frequency than optical oscillation frequency. Hence, the correlation between oscillation of light intensity and ionization oscillation is still unclear.

In the case of xenon propellant, the oscillation frequency was 10 kHz for the discharge voltage of 79 V, the discharge current of 1.0 A ± 0.5 and the magnetic induction of 800 gauss with the mass flow rate of 1.37 mg/s.

To examine the influence of electric circuits of the power supply on the oscillation, a KIKUSUI current and voltage regulated power supply and a laboratory made power supply were tested for the main discharge circuit. The resulting trends were much the same with both power supplies.

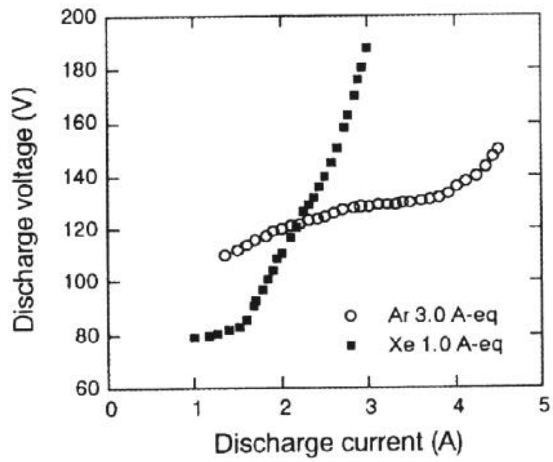

Fig.4 Current-voltage characteristic operating at the channel length = 17 mm

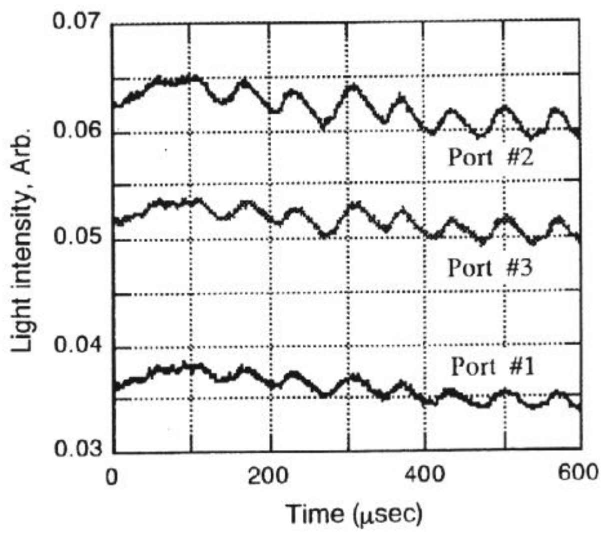

Fig. 5 Typical emission fluctuations simultaneously recorded with a digital-oscilloscope.

Dependence on a magnetic field

Figure 7 shows the emission intensities measured at the magnetic induction of 200 gauss and 800 gauss maintaining the discharge current at 1.0 A. Xenon at 1.37 mg/s is used as a propellant. At 200 gauss, emission oscillation frequency was about 10 kHz but its peak intensity was dull. At 800 gauss, the emission oscillation comes to have a clear peak frequency. (The amplitude of fluctuations at 800 gauss also becomes larger than that obtained at 200 gauss.) Peak frequency was 10 kHz for both conditions.

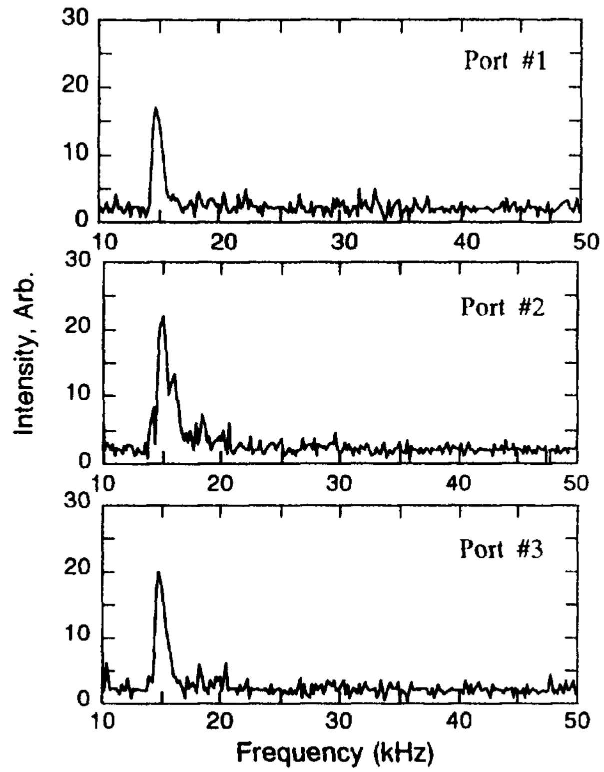

Fig. 6 Comparison of oscillation frequency of emission fluctuation for Argon discharge plasma

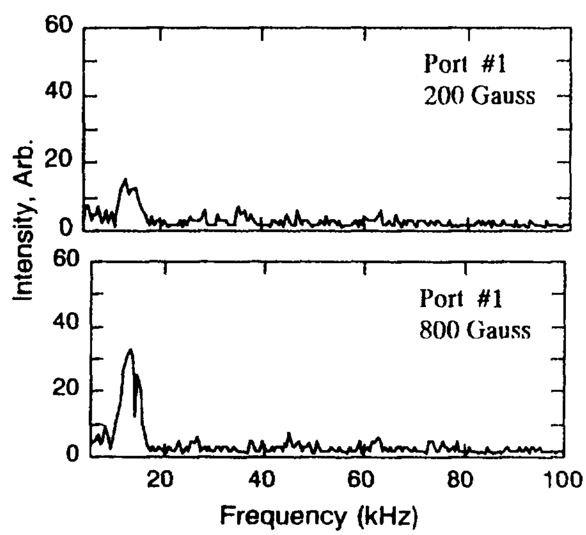

Fig. 7 Comparison of oscillation frequency of emission fluctuation at the magnetic induction of 200 gauss and 800 gauss.

Dependence on a discharge current

The correlations between the oscillation frequency and the discharge current for xenon and argon propellants are presented in Figs.8 and 9, respectively. The light is picked up from Port #1 positioned at 2 mm from the anode.

As seen in the figures, with the increase in the discharge current, the oscillation frequency shifted from 10 to 17 kHz for xenon and from 15 to 25 kHz for argon. In the case of xenon propellant, the fluctuation intensity gradually decreases with the increase in discharge current, and finally, the oscillation didn't show any characteristic peak above 1.7 A, which is the knee point of the current-voltage characteristic of the thruster as previously shown in Fig.4.

These characteristic frequency are plotted in Fig.10 with respect to the discharge current. In each case of xenon and argon, it shows an almost linear increase with the discharge current.

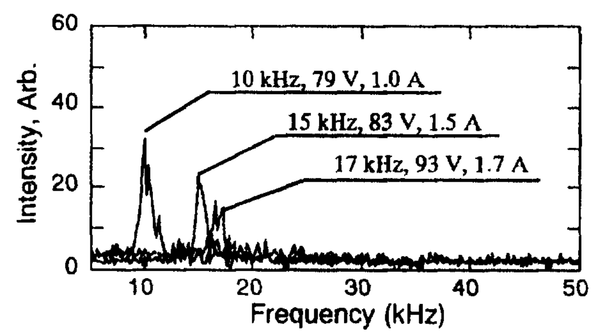

Fig.8 Frequency shift of xenon emission fluctuation at magnetic field of 800 G and 1.37 mg/s mass flow rate

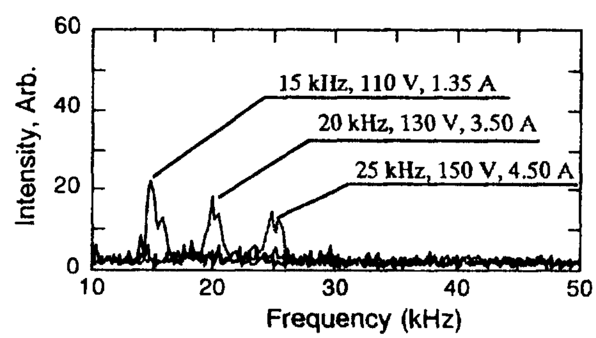

Fig.9 Frequency shift of argon emission fluctuation at magnetic field of 800 G and 1.25 mg/s mass flow rate

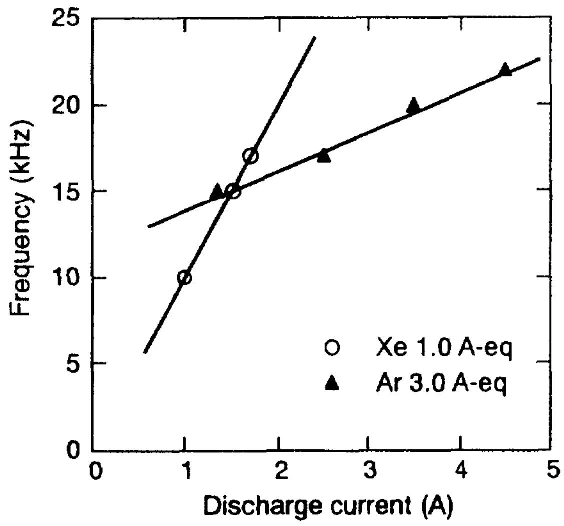

Fig. 10 Oscillation frequency characteristics

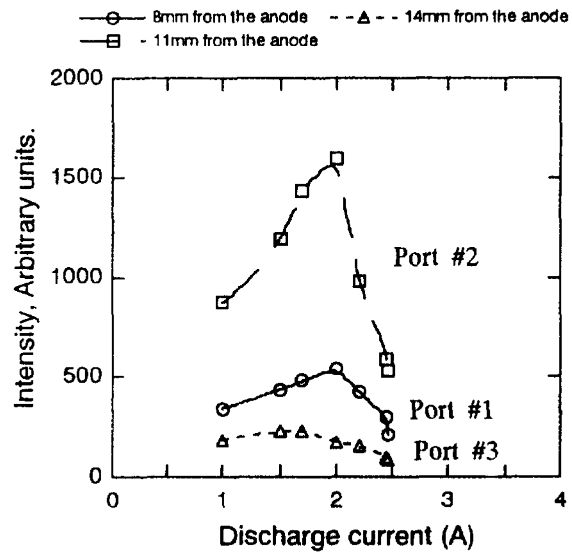

Fig.11 Light intensity variations oprating at the channel length = 17 mm. Measured lights are neutral xenon transition at 823.2 nm.

Spectral analysis

Spectral analyses using a spectrometer were done in order to identify the emitting particles in the acceleration channel. All the spectral profiles here are time-integrated for 1 msec.

The intensity of Xe I transition at 823.2 nm ($6s[3/2]^0_2$ - $6p[3/2]_2$) is plotted in Figs.11 and 12 for the different pick-up locations in the acceleration channel.

The intensity profiles at the channel length of 17 mm are shown in Fig. 11. The maximum intensity is obtained at the center of the channel (Port #2). Each curve shows an increasing trend until the discharge-current is about 2.0 A, and then decreases. Particularly, the intensity at the center of the channel shows a sudden drop by 70% above 2.0 A. This implies that the frequent excitation region of the neutral particles locates at the center of the channel upto the discharge current knee. Beyond the current knee, number density of neutral particle itself decreases due to the ionization reaction.

Figure 12 shows a result for the case at the channel length of 11 mm. The intensity curves show the same trend as those shown in Fig.11 except for the one measured in the vicinity of the anode (Port #1). It is continuously increased with the increase in the discharge current. This indicates that the main excitation zone shifts closer to the anode with the larger discharge current even beyond the current knee.

Figure 13 gives the measured intensities of Xe I, Xe II, Xe III line spectrum. Xe II intensity rapidly increases beyond 1.7 A, and then starts to decrease at 2.3 A. Although Xe III intensity increases together with the Xe II intensity, it never decreases in the range of our experiment.

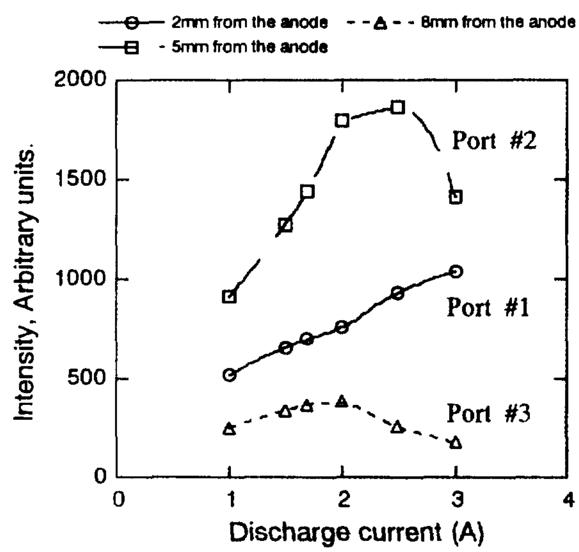

Fig.12 Light intensity variations oprating at the channel length = 11 mm. Measured lights are neutral xenon transition at 823.2 nm.

These intensity characteristics must be considered as merely an indication of the fractions of neutral excitation atoms, singly and doubly ionized ions of the plasma in the channel. In the absence of measurements of electron density and temperature, it is impossible to discuss the physics in the channel in more detailed. Measurements of such parameters by means of optical diagnosis would give a interesting time-resolved result related to the oscillation phenomena.[9,10,11]

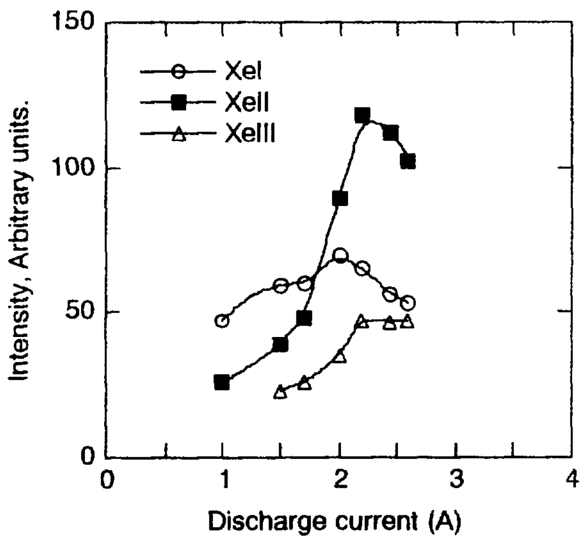

Fig. 13 Intensities of Xe I, Xe II, Xe III line spectrum

Summary

An investigation of the emission oscillation in the channel was conducted by mean of optical diagnosis. The emission intensity had a typical frequency at 10~25 kHz. The oscillation frequency was found to be strongly related to the discharge current, though it was insensitive to the magnetic induction.

Spectral analyses showed that the ratio of the Xe I, Xe II, Xe III line intensities changed with the increase in the discharge current. Further measurements of plasma parameters will give us the correlations between thruster performance and the plasma oscillation.

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