Plasma fluctuations measurements in a Hall Thruster

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Abstract: For understanding the relation between these fluctuations and anomalous transportation in Hall thrusters, Electron number density, and fluctuation of electron number density was measured for two region, plume region and inside an acceleration channel, using 76 GHz interferometer and electric field fluctuation at thruster exit was measured using a double probe. Three oscillations, 13 kHz, 150 kHz, and 3 MHz are observed in electric field fluctuations and the same oscillations are observed in discharge current. The 76 GHz interferometer experiment results shows that electron number density fluctuation at 15 kHz depends on discharge current oscillation, that is, there are linear relation between the amplitude of the number density fluctuations and the amplitude of discharge current fluctuations. 300 kHz number density fluctuation can be observed inside the acceleration channel when strong magnetic field strength is applied, though it has not clear peak. In the MHz range, broadband spectra in number density fluctuation are observed in strong magnetic field condition.

I.Introduction

ONE of the Barriers to improvement of thrust power ratio in Hall thruster is electrons anomalous transportation. There have been wide variety of theories to describe the anomalous transportation in Hall thrusters, it still remains unresolved. Hirakawa et al. shows azimuthal electric field fluctuation leads to electrons anomalous diffusion[1)] and near wall conductivity[2,3)] and Reynolds stress[4,5)] are also the candidates to leads to anomalous transportation. Therefore, in order to improve the thrust power ratio in Hall thrusters, it is necessary to answer what causes anomalous transportation in Hall thrusters. Understanding the physics behind anomalous transport in Hall thrusters requires highly spatially and temporally resolved electron and neutral atom number density profiles and the fluctuation of the electron number density and electric field. A microwave diagnostics[6-8] is powerful tool to measure the highly spatially and temporally resolved electron number density profiles and fluctuation of electron number density. For the measurement of electric field fluctuation, Langmuir probe[9,10] can be useful and neutral atom number density measurement, Rayleigh scattering[11,12] is a powerful tool.

The aim of this study is to demonstrate the measurement of electron number density, and fluctuation of electron number density using 76 GHz interferometer and electric field fluctuation using a double probe, in order to understand the relation between these fluctuations and anomalous transportation in Hall thrusters.

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II.Experimental setup

A. Hall thruster

Figure 1(a) shows a photo of the 200 W class magnetic layer type Hall thruster developed at Kyushu University. The size is 120 mm×120 mm×72 mm, it will be a little bit large considering 200 W class thruster head.[13] The inner and outer diameters of the acceleration channel are 40 mm and 56 mm respectively. The acceleration channel is made of boron nitride (BN). The anode is set at 15 mm upstream of the thruster exit. Anode is made of pure iron, which also works as a magnetic shield for the effective space utilization. The anode has a cover, which works as a neutral atom distributer, which will provide uniform neutral atoms in the discharge chamber. 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 radial magnetic flux density has a peaks at downstream of the acceleration channel to push out the ionization region.

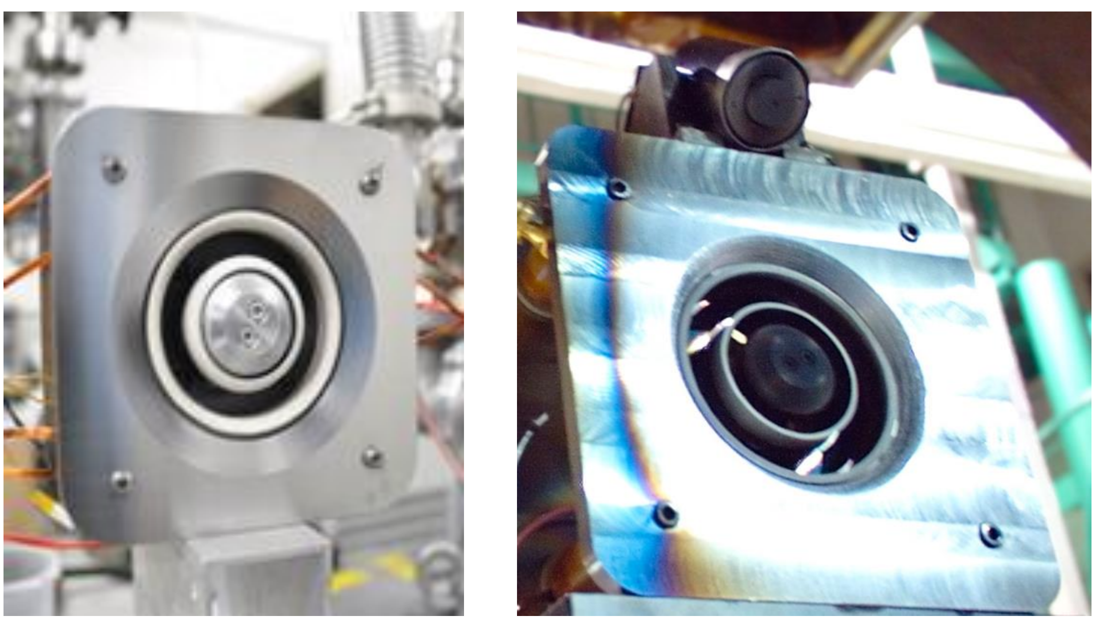
Figure 1(b) shows a photo of the 900 W class magnetic layer type Hall thruster developed at Kyushu University. The size is 200 mm×200 mm×85 mm. The inner and outer diameters of the acceleration channel are 61 mm and 91 mm respectively. The acceleration channel is made of boron nitride. The anode is set at 14 mm upstream of the thruster exit.

A hollow cathode (HC252, Veeco) was used as the electron source. High-purity 99.999% xenon gas was used as the propellant with thermal mass flow controllers.

B. Vacuum facility

The interferometer experiments 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, a mechanical booster pump and a turbo molecular pump (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 1×10^{-3} Pa at a xenon mass flow rate of 1.2 mg/s (anode 1.0 mg/s and cathode 0.2 mg/s).

The probe experiments are conducted in the chamber in Kyushu University, which is 1 m diameter by 1.2 m length. The pumping system consists a rotary pump, a mechanical booster pump, two turbo molecular pump (pumping speed is 2300 *l*/s in nitrogen) and a cryogenic pump (2000 *l*/s in nitrogen).The chamber baseline pressure is below 1×10^{-4} Pa. The background pressure was maintained below 1×10^{-2} Pa at a xenon mass flow rate of 1.0 mg/s (anode 0.7 mg/s and cathode 0.3 mg/s).



(a) (b)

Figure 1. Photo of 200 W class Hall thruster(a) and 900 W class Hall thruster(b) developed at Kyushu University.

C. Langmuir probe

For the measurement of electric field fluctuation, floating potential difference between two Langmuir probes are measured. The length of the probe is 1.5 mm and the diameter of the probe is 0.15 mm. The double probe is lined along azimuthal direction in acceleration channel and the distance between two electrodes is 1.0 mm. The probe can be moved along 45 degree direction to the thruster axis, as shown in Fig.2, and is set at 3 mm downstream of the Hall thruster, since the probe position is closer than 3 mm, the thruster operation was stopped. Each probe measurers floating potential of the electrode. The floating potentials are measured using differential data recorder, whose bandwidth is less than 20 MHz .

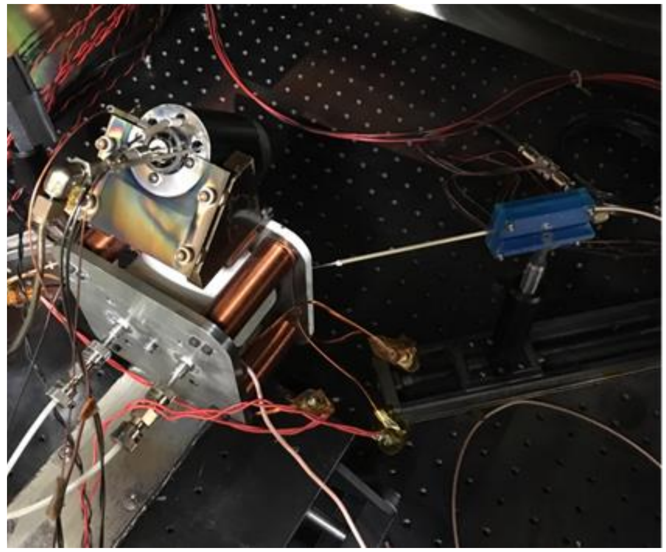


Figure 2. Electric field measurement system. *THe probe is mounted on the one-dimensional traverse system. The diameter and length of the probe are 0.15 mm and 1.5 mm, respectively. The electrodes are surrounded to the alumina tube.*

D. Microwave interferometer

The interferometer system is shown in Fig. 3. The system is based on a frequency-multiplied heterodyne scheme using two oscillators. A 19 GHz local oscillator wave, generated by a voltage controlled oscillator, is up-converted to 19.0275 GHz by mixing a 27.5 MHz signal from a temperature-compensated crystal oscillator (TCXO). This 1/4 frequency RF wave is frequency multiplied to 76.11 GHz by a quadrupler. The RF wave emitted from the antenna is converted to the parallel beam as shown in Fig.3. RF signal through plasma and the multiplied LO signal is mixed and the mixing signal is realized using microstrip line on the circuit board. This enables simple and uniform LO supply to antenna by only a 19-GHz LO source and a coaxial cable transmission line instead of using a 76-GHz source, LO optics, and a waveguide transmission line.

In 76 GHz interferometer, we measure electron number density and its fluctuation in plume region and inside the acceleration channel. Figure 4 shows the photo of this measurement system in plume region measurement. In this experiment, 200 W class Hall thruster was used, since it is compact (120 mm×120 mm×72 mm). The transmission antenna and receiving antenna is on the aluminum frame and the relative position against the 200 W class thruster can be changed. The distance between two antennas is 200 mm, which is greater than the thruster width.

Figure 5 shows the schematic diagram and photo of the antennas for inside region measurement. The transmission antenna is set inside the acceleration channel, at 3 mm upstream of the thruster exit. The transmission antenna directs at 10 o'clock direction, and the receiving antenna can be set on the line of 10 o'clock direction. The microwaves transmit through acceleration channel made of BN, which is dielectric material, and plasma and go into the receiving antenna.

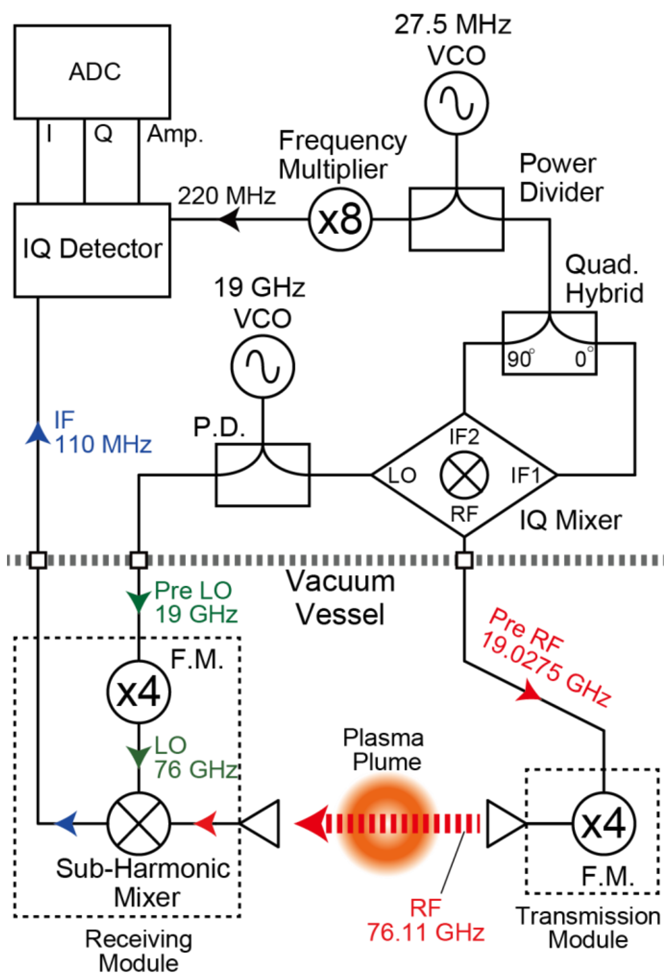
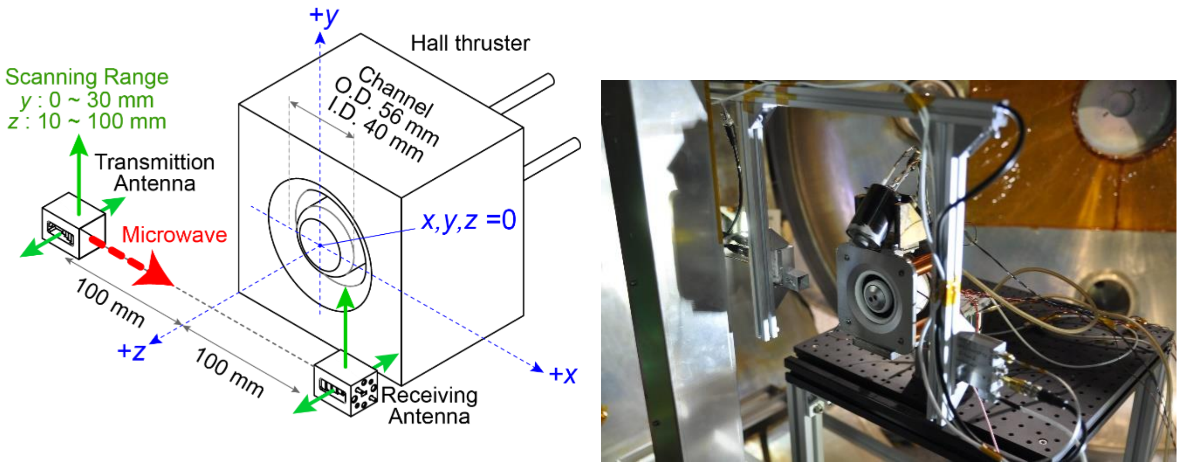
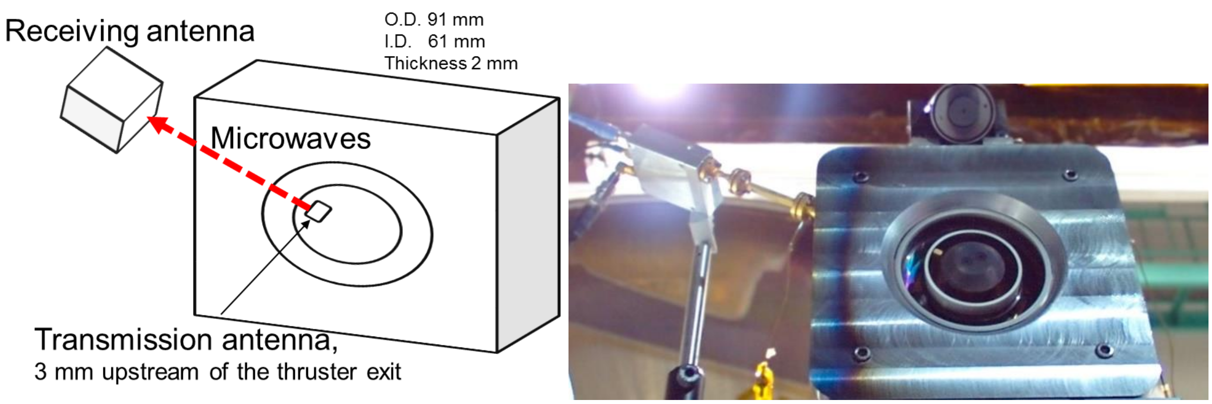


Figure 3. Block diagram of microwave interferometer system developed at Chubu University.



(a) (b)

Figure 4. Schematic diagram and photo of 76 GHz interferometer for plume region measurement. (a) Schematic diagram (b) Photo *Hall thruster is set in the middle of the transmission antenna and receiving antenna. The relative position can be changed using three dimensional travers system..*



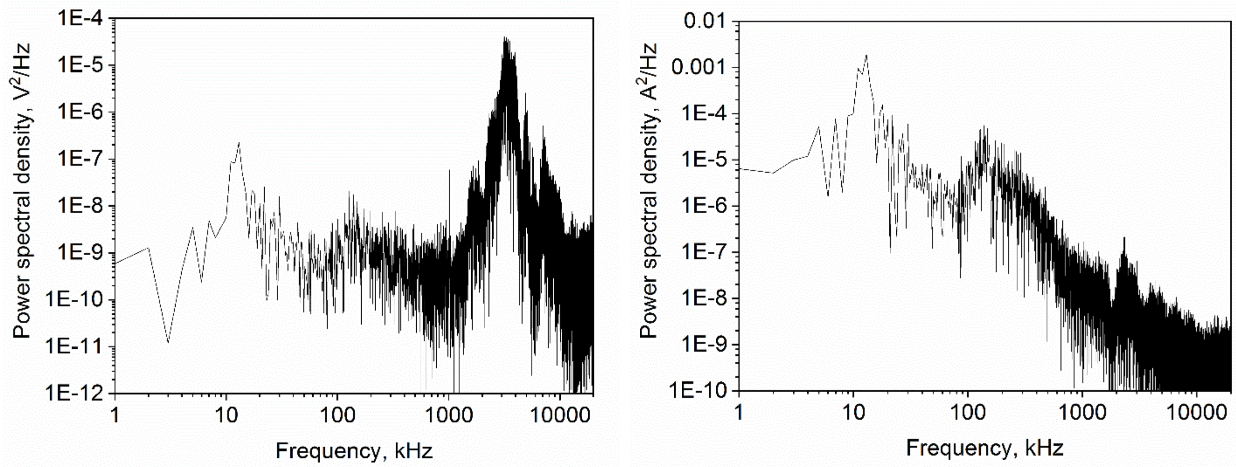
(a) (b)

Figure 5. Schematic diagram and photo of 76 GHz interferometer for inside region measurement.. (a) Schematic diagram (b)Photo. *The transmission antenna is set inside the inner acceleration channel and the receiving antenna is set at outside of the acceleration channel.*

III.Results and discussion

Figure 6 shows the power spectral density of electric field fluctuations deduced from floating potential of probes at 3mm downstream of the thruster exit using fast Fourier transform(FFT) and that of discharge current fluctuations by current probe (the bandwidth is 100 MHz) at discharge voltage of 150 V and inner coil current of 1.67 A. It is interesting that the peaks of electric field fluctuations are in good agreement with that of discharge current has same peak that is, there are three peaks, 13 kHz, 150 kHz and 3 MHz, seems to be corresponding to ionization oscillation,[14] transit-time oscillation and drift instability. In the current fluctuation, the amplitude of 13 kHz oscillation is the largest of all, and t that of MHz oscillation is the smallest among three. In the electric field oscillation, however, the amplitude of 3 MHz oscillation is the largest of all, and 13 kHz oscillation and that of 150 kHz oscillation the smallest of all.

This oscillation regime is IV defined as our previous study,[15] the amplitude of the discharge current oscillation is small, but the discharge current is increased against that in regime II or III. Indeed, the amplitude of current oscillation at 13 kHz, 150 kHz, 3 MHz is at most 60 mA, 4 mA, and 0.4 mA, respectively and discharge current is 0.68 A, not minimum(0.5 A at coil current of 1.4 A, 0.1 A) larger than the minimum current at week magnetic field. That is, anomalous transportation would be occurred in this regime.



(a) (b)

Figure 6. Power spectral density in 200 W Hall thruster. (a) electric field fluctuations deduced from the difference between two electrode floating potential (b) discharge current fluctuations using current probe.

Considering the distance between two electrodes, the amplitude of the electric field fluctuation at MHz range is at most, 8 V/m, this is small in comparison with electric field using numerical simulation.[16] This would be because the measurement position is outside the acceleration channel. In Regime II, the amplitude of this MHz fluctuations is decreased by 10 dB.[18] These results shows this MHz electric field fluctuation would affect electron anomalous transportation. There is also 150 KHz fluctuation, and this might whose amplitude is increase from regime IV to reigme III, so 150 kHz fluctuation would also affects the anomalous transportation.

Figure 7(a) shows time variation of the linear number density at y=0 mm and z=20 mm(center of the plume, at 20 mm downstream of the thruster exit) and discharge current for three oscillation regime[17] at discharge voltage of 300 V and mass flow rate of 1.0 mg/s. In regime II, The frequency of discharge current oscillation and linear density fluctuation is the same and the amplitude of discharge current oscillation is small, about 0.2 A and the amplitude of linear density fluctuation is about 10^{16} m^{-2}. In regime III, The history of discharge current is almost the same as that of linear density. The amplitude of linear density fluctuation becomes in the order of 10^{17} m^{-2}. If the symmetrical plasma with center diameter of 48 mm, which is the same as the acceleration channel, is assumed, the number density fluctuation is about 2×10^{18} m^{-3}.

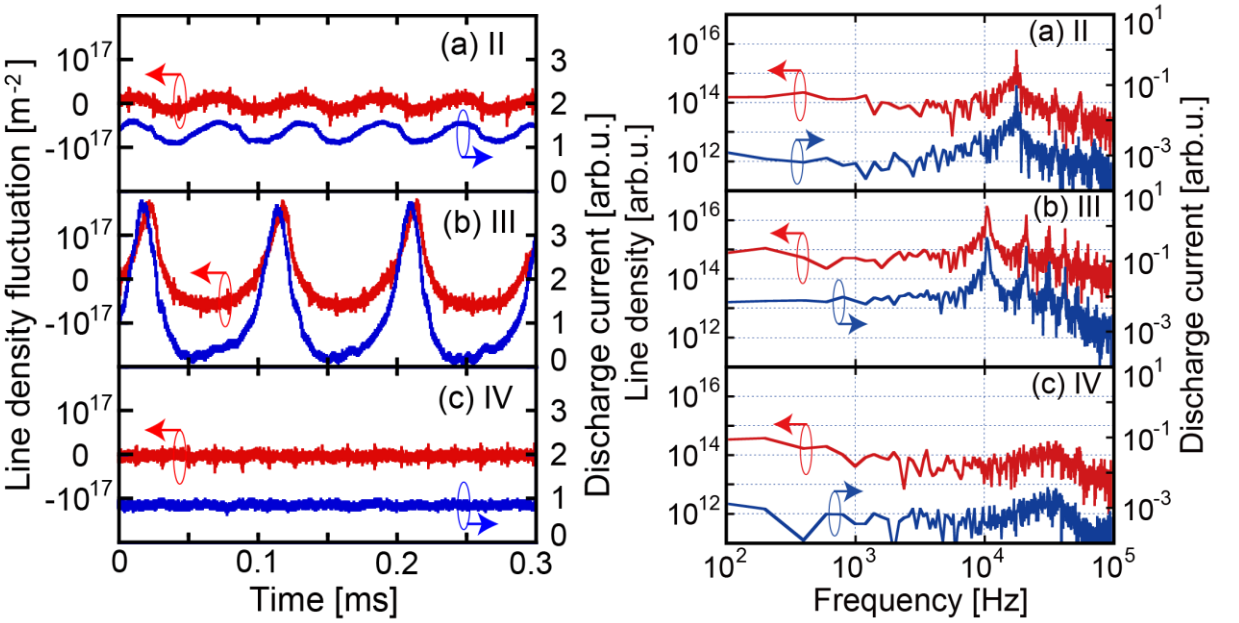


Figure 7. Power spectral density in 200 W Hall thruster. (a) small oscillation regime (b) large oscillation regime(c) calm oscillation regime. *The discharge voltage of 300 V, mass flow rate of 1.0mg/s.*

In regime IV, there is little oscillation in discharge current and linear density fluctuation. As these results show, the discharge current has strong correlation with linear number density, that is, the exhausted ion number density. This can be seen in the linear density and discharge current spectra using FFT. The peaks of linear density are in good agreement of that of discharge current.

Figure 8 shows the electron number density fluctuation inside the acceleration channel and discharge current oscillation for four magnetic field strength, coil current of 0.6 A, 0.8A , 1.0 A and 2.0 A. Inside the acceleration channel,. 10-30 kHz number density fluctuation can be observed and the linear relation between the amplitude of density fluctuation at this frequency range and that of discharge current oscillation. However, broadband peaks are observed from one hundred kHz to several MHz range, though the discharge current oscillation has shape peaks. In the strong magnetic field strength (d, coil current of 2 A), there is 300 KHz oscillation both current and density fluctuation, but the peak of density is not as sharp as that of current.

In comparison with no-plasma signal, less than 3×10^{21} above 100 kHz, each spectrum in (b), (c), (d) has wide peaks, whose center frequency is about 1 MHz, though the spectrum of discharge current oscillation in each case has clear peaks. The observed number density fluctuations is turbulence, so the power spectral density has broadband peaks.

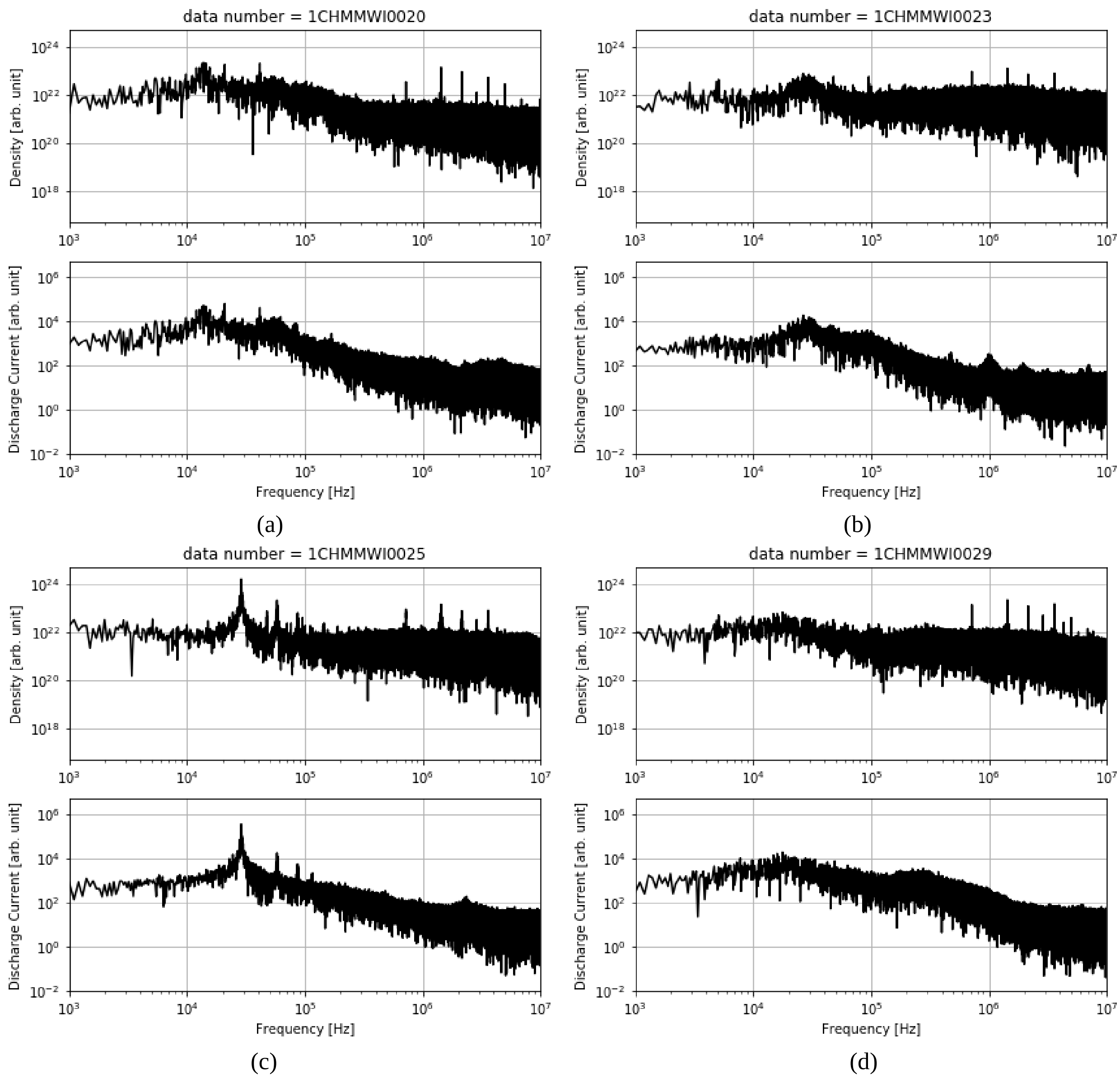


Figure 8. Power spectral density in 900 W Hall thruster. (a) coil current of 0.6A, (b) coil current of 0.8A (c) coil current of 1.0 A (d) coil current of 2A.

IV.Conclusion

Demonstration to measurer an electron number density, and fluctuation of electron number density using 76 GHz interferometer and electric field fluctuation using a double probe, in order to understand the relation between these fluctuations and anomalous transportation in Hall thrusters. There are azimuthal electric field fluctuation with frequency of 3 MHz and amplitude of 8 V/m. The electron linear number density in the plume region fluctuated at the same frequency of ionization oscillation, 10 kHz, and the amplitude of 10^{17} m^{-2}. Inside the acceleration channel, the electron number density also fluctuates, there are broadband peaks around 1oo kHz and 1 MHz, on the contrary, there are apparent peak was observed in the ionization oscillation.

Acknowledgments

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