Density Collapse of Poloidally Rotating Plasma in TU-Heliac

Y. Tanaka, S. Kitajima, M. Sasao, H. Utoh, H. Aoyama, K. Iwazaki, H. Umetsu, K. Ishii, A. Okamoto, T. Kobuchi, S. Inagaki[b], Y. Suzuki[a], and H. Takahashi[a]

Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579, Japan
[a]National Institute for Fusion Science, Toki 509-5292, Japan
[b]Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan

The ohmic heated plasma in TU-Heliac was biased by a hot-cathode and the ***E***×***B*** poloidal rotation was driven. Coincident measurements of the line density and the ion saturation current revealed the existence of the density collapse accompanied by the fluctuation in the poloidally rotating plasma. The power spectra were calculated from the ion saturation current and the floating potential obtained by the high-speed triple probe. The density collapse frequency was 1~10 kHz. The fluctuation frequency was 100~1000 kHz. The density radial profile at the moment when the collapse occurred was estimated. The steep density gradient was vanished by the density collapse. The radial profile of the fluctuation frequency was compared to that of the ***E***×***B*** poloidal rotation frequency. Both profiles had the similar radial dependence. From this comparison, the poloidal mode number of the fluctuation was estimated to be m = 2 or 3. The collapse and the fluctuation localized in the core plasma region. This result suggested the existence of the cross-interaction between the density collapse and the fluctuation.

Keywords: heliac, stellarator, poloidal rotation, density collapse, fluctuation,

1. Introduction

H-mode was discovered in ASDEX Tokamak [1] and then the mechanism of the improvement has been studied for a long time. Recently it is considered that the plasma rotation suppresses the anomalous transport. It is also suggested that a turbulent flow can drive the poloidal rotation such as the zonal flow and that the poloidal shock is formed at a moment when the poloidal mach number exceeds unity [2]. Therefore, the understanding of the plasma rotation, especially in the super sonic regime, is important.

Spontaneous ***E***×***B*** rotation is formed in the improved plasma of the large device. An electrode biasing can drive the ***E***×***B*** rotation in the small device and the confinement improves. In Tohoku University Heliac (TU-Heliac), the negative biasing experiment has been carried out for the study of the transition phenomenon to the improved mode [3-11]. A hot-cathode made of LaB_6 was used for the electron injection to the plasma and the negative potential was formed. Typical behaviors of the improved mode were the threefold increase in the density and the formation of the radial electric field (2~4 kV/m). The ***E***×***B*** poloidal rotation frequency exceeded 100 kHz. At the same time, the density and the potential fluctuations were observed in the low frequency range (1~10 kHz) and the high frequency range (100 ~ 1000 kHz) [6, 9, 11]. The high frequency fluctuation burst and had the radial dependency. In this work, the characteristics of the poloidally rotating plasma are studied. Then the fluctuations are measured coincidently and the radial profile of the high frequency fluctuation is compared to that of the poloidal rotation.

2. Experimental Setup

TU-Heliac is a helical axis stellarator and has the bean shaped flux surface [3]. Top view of TU-Heliac is shown in Fig. 1. Major radius is 0.48 m and minor radius is 0.06 m. Toroidal period number is 4. The standard magnetic configuration was selected. The magnetic well depth at the last closed flux surface (LCFS), the rotational transform at the axis and the magnetic field were 2 %, 1.54 and 0.3 T, respectively. Working gas was He. A plasma was produced by the low frequency alternate ohmic heating. The frequency of the heating wave was 18.8 kHz. The plasma current, the loop voltage and the absorbed power to the plasma were 200 A, 200 V and 2 kW, respectively. A hot-cathode was used for the electron injection. The top position of the hot-cathode was R_{HC} = 86 mm. The origin of R_{HC} was the center of the center conductor coil. The hot-cathode was biased against the vacuum vessel. The bias voltage was -230 V and the electrode current was about 4 A. The fluctuation was one of the important plasma parameters and should be measured. In the

author's e-mail: yutaka.tanaka@ppl2.qse.tohoku.ac.jp

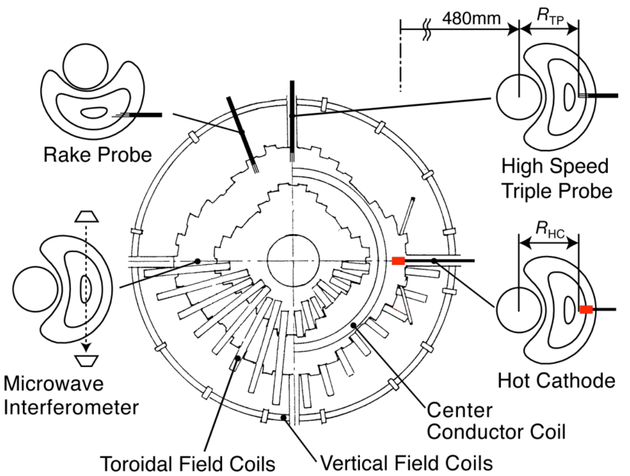

Fig. 1 Top view of TU-Heliac

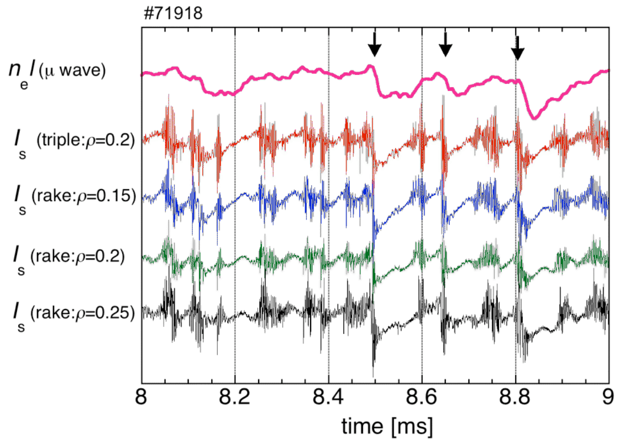

Fig. 2 Time traces of the line density $n_e l$ and the ion saturation current I_s. The positions of the triple probe and the rake probe were $\rho \sim 0.2$. The arrows indicate the time of the density collapse.

hot-cathode biased plasma, the ***E***×***B*** poloidal rotation frequency exceeded 100 kHz. The fluctuation frequency reached 400 kHz by the poloidal rotation. Langmuir probe method had the advantage of spatial and time resolutions. Therefore, the high-speed triple probe system (cutoff frequency 1 MHz) was installed to TU-Heliac [11]. It was inserted from the low field side. Its position was defined by R_{TP} as shown in Fig. 1. The magnetic axis corresponded to R_{TP} = 79 mm and the LCFS corresponded to R_{TP} = 118 mm. The 50 GHz microwave interferometer and the rake probe were also used for the coincident measurement. The rake probe had 3 tips and its tips were set radially. The length between the top and bottom tips was 6.0 mm, which was small compared to the minor radius.

3. Density Collapse Accompanied by Fluctuation

The coincident measurements at the multi-position are important to understand the plasma physics. The positions of the triple probe and the rake probe were calibrated using the electron gun. These probes were set at $\rho = 0.2$ and the biasing experiments were carried out, where ρ was the normalized minor radius defined by $\rho = \langle r \rangle / a$, $\langle r \rangle$ was the average radius of the flux surface and a was the minor radius. $\rho = 0.2$ corresponded to R_{TP} = 87 mm. Figure 2 shows the typical time traces of the line density $n_e l$ and the ion saturation current I_s. The ion saturation current suddenly decreased on the time scale of 0.01 ms (ex. time = 8.50, 8.65 and 8.81 ms). After the sudden decrease, it slowly increased on the time scale of 0.1 ms. Simultaneously the line density, which was measured along the central chord as shown in Fig. 1, had the same tendency of increase and decrease, though it did not show the sudden decrease because it was the integrated parameter. Ion saturation current is proportional to density and root of electron temperature. Increase and decrease of the ion saturation current indicate that of the density. The sudden decrease of the density was observed in different toroidal and radial positions. Therefore, this phenomenon is considered the density collapse. In the sawtooth of CHS, soft X-ray decreased at $\rho < 0.5$ and increased at $\rho > 0.5$ [12]. In the density collapse of TU-Heliac, the difference between the inside and the outside obtained by the rake probe was not observed. This reason is considered that the probe tips were close compared to the minor radius. Also the fluctuation was observed in the ion saturation current, though it was not observed in the line density because the microwave interferometer could not measure the local parameter. This fluctuation burst and had the simultaneous characteristic between all signals. It did not appear in the phase of the density increased after the density collapse (ex. time = 8.50~8.60 ms and 8.65~8.70ms). This result suggests that the growth rate of the fluctuation has the density or the density gradient dependence.

The power spectra were calculated from the ion saturation current I_s and the floating potential V_f measured by the triple probe as shown in Fig. 3. Fast Fourier Transform was used in the calculation in spite of the burst of the fluctuation. Both spectra had the similar power distribution. The density collapse frequency was 1~10 kHz. Floating potential is determined by electron temperature and space potential. The power of the floating potential indicates that the electron temperature or the space potential also collapsed with the density. The fluctuation frequency was 100~1000 kHz. The sharp peaks at 18 and 37 kHz were fundamental and second harmonic waves of the alternate ohmic heating. The peak at 3 MHz was the noise of the isolation amplifier.

The density radial profile at the moment when the collapse occurs is required for the understanding of the collapse, though it can not be measured by the present diagnostic system in TU-Heliac. The triple probe was

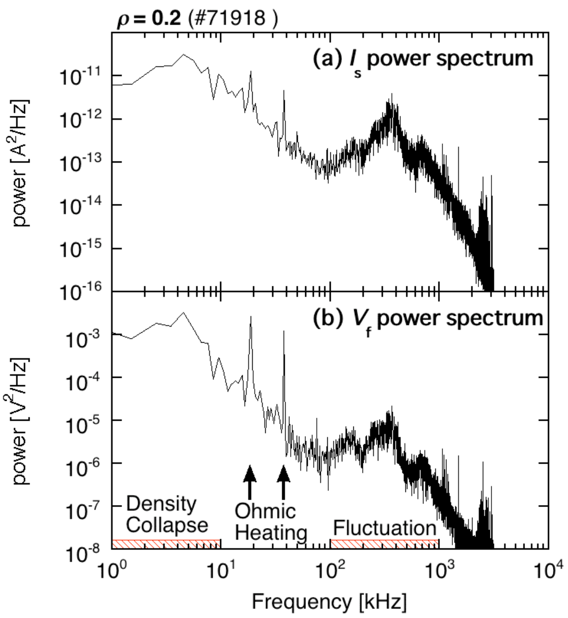

Fig. 3 Power spectra of (a) the ion saturation current I_s and (b) the floating potential V_f. Probe position was $\rho = 0.2$. The density collapse frequency was 1~10 kHz and the fluctuation frequency was 100~1000 kHz.

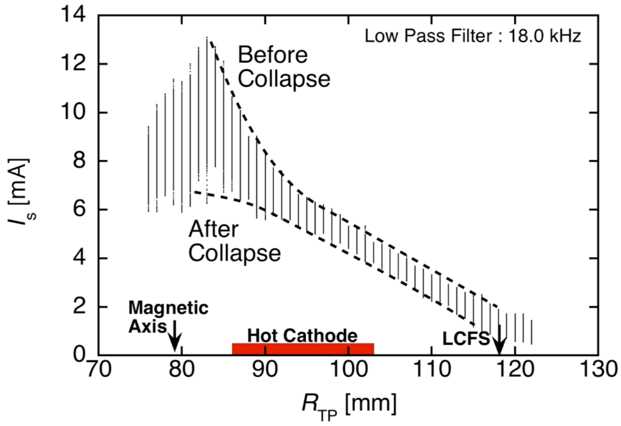

Fig. 4 Radial profile of the ion saturation current obtained by the triple probe. Low pass filter of 18.0 kHz was used to remove the 18.8 kHz ohmic heating wave. In R_{TP} = 76~87 mm, the ion saturation current decreased about 40 % after the collapse.

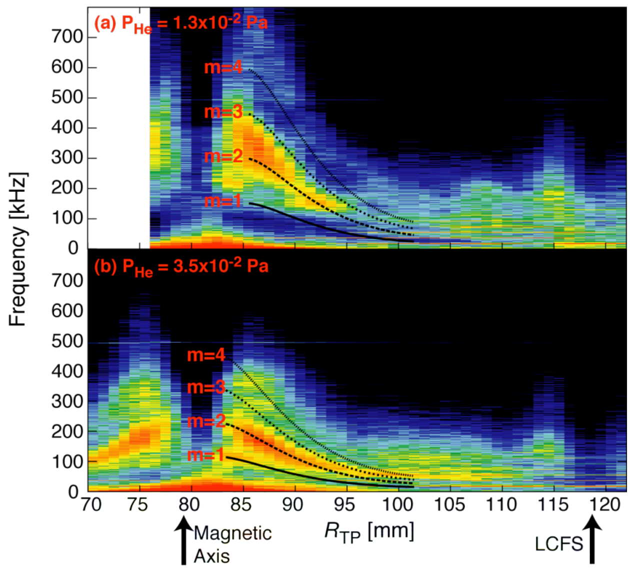

Fig. 5 Radial profile of the power spectra calculated from the ion saturation current at working gas pressure (a) p_{He}=1.3x10^{-2} Pa, (b) p_{He}=3.5x10^{-2} Pa. The lines show the poloidal rotation frequency calculated by Eq. (1). The arrows indicate the magnetic axis and LCFS.

moved its radial position shot by shot. The data of the ion saturation current was obtained moving its position every 1 mm. Digital low pass filter of 18.0 kHz was used to remove the 18.8 kHz ohmic heating wave and to pick up only the frequency corresponded to the collapse. The data obtained by 47 shots were plotted as shown in Fig. 4. The magnetic axis corresponded to R_{TP} = 79 mm and the LCFS corresponded to R_{TP} = 118 mm. The estimation of the density profile at the moment when the collapse occurred was possible from this figure. The maximum and the minimum in the ion saturation current indicated the density profiles before and after the collapse. The triple probe position in Fig. 2 was R_{TP} = 87mm. Before the collapse, steep gradient existed in R_{TP} = 83~90 mm. After the collapse, the ion saturation current decreased about 40 % in R_{TP} = 76~87 mm. The steep gradient was vanished by the collapse. This result suggests that the density gradient triggers the collapse.

The poloidal momentum balance between $\boldsymbol{J}_r\times\boldsymbol{B}$ driving force, ion viscosity and ion friction determines the poloidal rotation speed. We can control the friction term by filling the working gas because the friction results from charge exchange between ions and neutral particles. The radial profiles of the power spectra are shown in fig. 5. These were calculated from the ion saturation current obtained by the triple probe. Working gas pressure (a) 1.3x10^{-2} Pa, (b) 3.5x10^{-2} Pa were selected. Fig. 5 (a) lacks the high field side spectra. The triple probe was inserted from the low field side and the measurement of the high field side was restricted by the disturbance from the probe to the plasma. The fluctuation had the large power in R_{TP} = 85~95 mm in both pressure conditions and it had symmetry against the magnetic axis in the high-pressure condition. There was a hole on the magnetic axis, in which the fluctuation did not exist. The fluctuation had the radial dependence such as 1/r. The frequency in the low-pressure condition was 2 times higher than that in the high-pressure condition. The fluctuation frequency might be determined by the poloidal rotation frequency. Then the comparison between these frequencies is important. The $\boldsymbol{E}\times\boldsymbol{B}$ poloidal rotation frequency f_{EB} can be estimated from the radial profile of the floating potential and is written as

$$f_{EB} = \frac{dV_f / d\langle r \rangle}{2\pi \langle r \rangle B_\phi}, \qquad (1)$$

where B_ϕ is the toroidal magnetic field. Essentially the space potential should be used for the calculation of the rotation frequency though it has too large error near the magnetic axis and can not be used. This may be considered that the size of the triple probe (5 mm) is comparable to the radius of the flux surface. Eq. (1) approximately represents the correct rotation characteristic because it largely depends on $\langle r \rangle$ in the denominator. The frequency of mf_{EB} was also plotted in Fig. 5, where m was the positive integer. $m = 1$ line indicated the poloidal rotation frequency and it increased as it got close to the magnetic axis. It reached 150 kHz in the low-pressure condition. The fluctuations in both gas conditions had the similar radial dependence to $m = 2\sim3$ line. The physical meaning of m is the poloidal mode number. The fluctuation poloidal mode is estimated to be $m = 2$ or 3. It also showed the surprising result. The fluctuation burst simultaneously in the different radial positions as shown the rake probe in Fig. 2. On the other hand, the fluctuation frequency had the radial dependence.

4. Discussion

It was observed that the density profile was asymmetry against the magnetic axis as shown in Fig. 4. It may represent the plasma compressibility. To satisfy the continuity equation under the ***E***×***B*** poloidal rotation, the plasma is compressed at the certain poloidal angle. Ions try to remove the density anisotropy by the parallel thermal motion. Poloidal Mach number M_p is useful to estimate the plasma compressibility. M_p means the ratio of the parallel diffusion time by the ion thermal motion to the ***E***×***B*** poloidal rotation time. M_p is written as,

$$M_p = q\varepsilon^{-1} v_t^{-1} v_{EB}, \qquad (2)$$

where q is the safety factor, $\varepsilon = \langle r \rangle / R$ is the toroidal ripple, v_t is the ion thermal velocity and v_{EB} is the ***E***×***B*** poloidal velocity. Eq. (2) is rewritten to the convenient form as,

$$M_p = qRv_t^{-1}\omega_{EB} \ , \qquad (3)$$

where ω_{EB} is the ***E***×***B*** poloidal rotation frequency calculated by Eq. (1). Substituting ω_{EB} into Eq. (3), poloidal Mach number was calculated as $M_p \sim 10$. This result shows that the ion diffusion is not sufficient against the ion compression by the ***E***×***B*** poloidal rotation. Then the asymmetry of the ion saturation current suggests the compressibility of the plasma.

The density collapse and the fluctuation were observed in the core region of the plasma. The steep density profile was vanished by the density collapse. The fluctuation did not appear in the phase of the density increase after the collapse. These results suggest the existence of the cross-interaction between the density collapse and the fluctuation. The frequencies of the poloidal rotation and the fluctuation reached 15 % and 30~40 % of the ion cyclotron frequency. There is possibility of the electromagnetic wave such as Alfven wave. The magnetic fluctuation should be measured for the understanding of this phenomenon.

5. Summary

The hot-cathode biasing experiment was carried out in TU-Heliac. Coincident measurements of the line density and the ion saturation current revealed the existence of the density collapse accompanied by the fluctuation in the poloidally rotating plasma. The power spectra of the ion saturation current and the floating potential showed that the density collapse frequency was 1~10 kHz and that the fluctuation frequency was 100~1000 kHz. The steep density gradient was vanished by the density collapse. The radial profile of the fluctuation frequency was compared to that of the ***E***×***B*** poloidal rotation frequency. Both profiles had the similar radial dependence. From this comparison, the poloidal mode number of the fluctuation was estimated to be $m = 2$ or 3. The poloidal mach number reached 10 and suggested the plasma compressibility.

Acknowledgments

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