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Time Evolution of Spatial Structure of Radial Electric Field in Tohoku University Heliac

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Radial electric field is closely related with the confinement of plasma. In Tohoku University Heliac (TU-Heliac), the electrode biasing experiments were carried out to control the radial electric field actively by ramping up/down the electrode current. An emissive probe array consisting of three filaments was designed as new measurement equipment. With this probe, time evolutions of the spatial structure of the radial electric field were measured in the biasing experiments. There was the tendency for the radial electric field to extend from the inner region to the outer region while the electrode current was ramping up. In the plasma inner region, the radial electric field was maintained the longer time compared with the outer region while the electrode current was ramping down. The radial electric field, poloidal flow of plasma and fluctuation level of the ion saturation current changed appreciably in the period when the electrode voltage showed nonlinearity against the electrode current. Therefore, the plasma nonlinearity period was the transition region to the improved mode.

Keywords: radial electric field, emissive probe, electrode biasing experiment, LH transition, fluctuation

1. Introduction

The neoclassical theory describes that the ion viscosity has a local maximal value against the poloidal rotation velocity [1]. The rapid increase of the poloidal rotation arises when the driving force in the poloidal direction exceeds a critical value. At that moment, it is considered that the plasma transits into the improved mode. One of the characteristics of the transition into the improved mode is sudden growth of the radial electric field [2]. Therefore, it is important to investigate the time evolution of the spatial structure of the radial electric field to comprehend the detailed transition mechanism. The radial electric field can be controlled actively by the electrode biasing experiments. In fact, the electrode biasing experiments have been done in various devices [3, 4]. In addition, the shear of the radial electric field plays an important role in the improvement of the plasma confinement with suppression of fluctuation level [5, 6].

In TU-Heliac, the electrode biasing experiments using a hot cathode made of $\mathrm{LaB_6}$ have been carried out to control the transition into the improved mode [7, 8]. We tried the forward/reverse transition experiments by ramping up/down the electrode current. In those experiments, the negative plasma resistance and the hysteresis between the radial electric field and the stored energy were observed in the transition region [9]. The nonlinear change of the electrode voltage against the electrode current is one of the characteristics of the transition. To understand the behavior of the radial electric field in the transition region, it is important to measure the time evolution of the spatial structure of the radial electric field around the period when the electrode voltage shows nonlinearity against the electrode current. For this purpose, we developed the emissive probe array to define the radial electric field. Using this probe, we measured the distributions of the radial electric field and compared them with the results of a mach probe and the fluctuation level of the ion saturation current.

2. Experimental Setup

TU-Heliac is a small heliac device with three sets of magnetic field coils. Top view of TU-Heliac is shown in Fig. 1. The size of this device is as follows: major radius R = 0.48 m, and average plasma radius $a \sim 0.07$ m. In electrode biasing experiments, the target plasma was He plasma produced by alternative ohmic heating with f = 18.8 kHz, $P \sim 35$ kW and the discharge time was 10 ms. Electron temperature T_e, electron density n_e, floating potential V_f and their fluctuation level were measured by the triple probe placed at toroidal angle $\phi = 0$ °.

The hot cathode made of $\mathrm{LaB_6}$ was used as an electrode in the electrode biasing experiments. The hot cathode was a cylindrical shape with a length of 17 mm and a diameter of 10 mm. This cathode was inserted into

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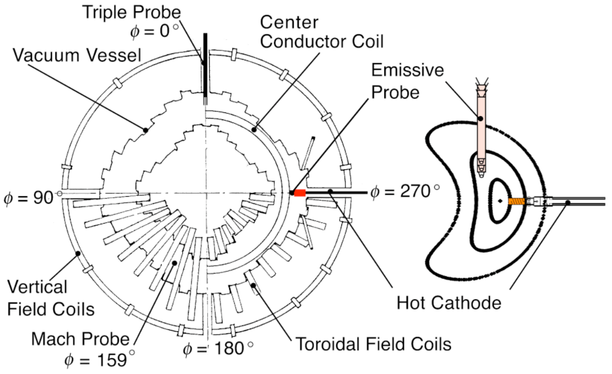

Fig. 1 Top view of TU-Heliac and cross section of magnetic surface at $\phi = 270°$.

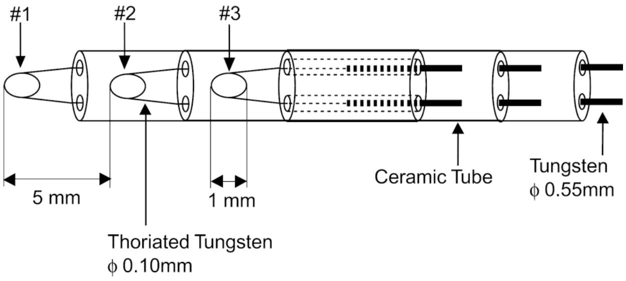

Fig. 2 Schematic of the emissive probe array

the plasma horizontally at $\phi = 270°$. In the electrode biasing experiments, the electrode was negatively biased against the vacuum vessel by a current control power supply.

The plasma poloidal flow relates closely to the radial electric field E_r. The mach probe was used to compare the E_r with the plasma poloidal flow. It was inserted vertically into the plasma from the upper port at $\phi = 159°$.

We designed the emissive probe array shown in Fig. 2. It had three filaments made of 1% thoriated tungsten (Th-W) with a diameter of 0.1 mm. Th-W is very useful material to emit the electron at low temperature compared with pure tungsten. The intervals of each filament were 5 mm. The Th-W wires were 30 mm in length and bent into a circle with a diameter of 1 mm. The both ends of the wires were connected with the tungsten wires with a diameter of 0.55 mm in a doubly drilled ceramic tube. This probe was inserted vertically into the plasma from the upper port at $\phi = 270°$. The all filaments were set facing toward the magnetic axis. This setting was adopted not to intersect the plasma flow and the magnetic field line. When the filaments are heated, they start to emit electrons and the floating potential measured by the emissive probe shifts to the plasma space potential V_s. The advantage of emissive probe is the direct measurement of the V_s compared with other Langmuir probe methods. In this experiment, the electron density was $n_e \sim 10^{12}$ cm^{-3}, the filaments were heated to 2000 K or less by the heating current about 2 A to 2.5 A, and the floating potential was almost saturated in this condition. This probe is able to measure the V_s in three points at the same time. Therefore, the coincident measurements of the E_r at three points can be carried out.

3. Experimental Results

Figure 3 shows the typical time evolution of the electrode voltage V_E and the current I_E. The I_E was controlled such that (a) the I_E was ramped up to -4 A for 6 ms starting from 4 ms or (b) the I_E was maintained at -4 A at first, and was ramped down to 0 A for 6 ms. In these experiments, the hot cathode was located at $\rho = 0.18 \sim 0.62$, where ρ is the normalized minor radius defined by $\rho = \langle r \rangle / a$, $\langle r \rangle$ is the average radius of the flux surface. The V_E shows nonlinearity against the I_E in the period surrounded by broken lines.

The radial profiles of the V_s measured by the #1 filament in the emissive probe array are shown in Fig. 4. The each profile was obtained from the results of 18 discharges. The broken lines in Fig. 4 are corresponding to that drawn in Fig. 3, and the solid line indicates the start time of ramping up/down. As can be seen in Fig. 4 (a), the V_s became deeper negatively, starting from the

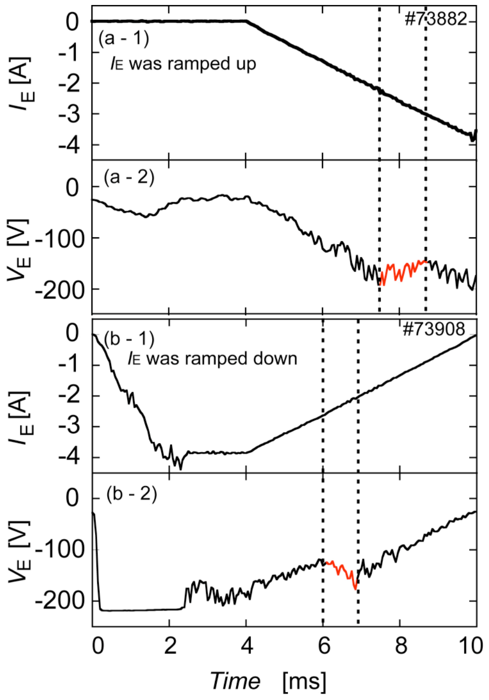

Fig. 3 Typical time evolution of V_E and I_E; (a) in the discharge of the I_E was ramped up, (b) in the discharge of the I_E was ramped down.

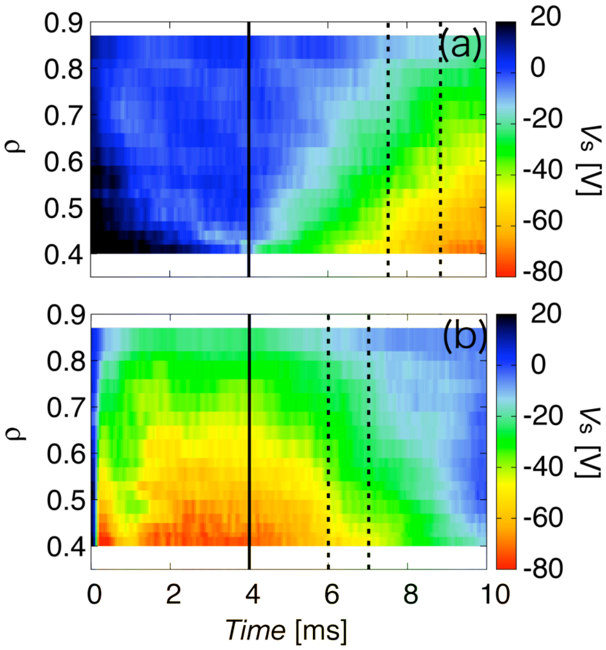

Fig. 4 The plasma space potential V_s measured with the emissive probe array in the discharge of (a) I_E ramped up and (b) I_E ramped down.

plasma inner region when the I_E was ramped up. In Fig.4 (b), when the I_E was ramped down, the V_s changed into shallow level from the plasma outer region. The similar results were also obtained with the other two filaments #2 and #3. The V_s near the magnetic axis ($\rho < 0.35$) could not be measured with the emissive probe array, because the probe scanned the plasma along the code that was off-center to the magnetic axis.

Figure 5 shows the time evolution of the spatial structure of (a) the E_r, (b) the current ratio of the mach probe and (c) the fluctuation level of the ion saturation current in the discharges of I_E ramped up, which is corresponding to Fig.3 (a). The E_r was calculated from the differential of the V_s measured with filaments of #1 and #3. In Fig. 5 (b), I_up and I_down indicate the ion saturation currents, which flowed into pins at upstream side and downstream side. It can be considered that the current ratio of the mach probe shows the plasma flow, which has a close connection to the E_r. Moreover, the suppression of fluctuation level also relates to the E_r and its shear. In this experiment, the fluctuation level was the integral of power spectrum from 0 to 100 kHz. As can be seen in Fig. 5 (a), the strong E_r arose in the plasma inner region, and diffused to the plasma outer region. Figure 5 (b) indicates the poloidal plasma flow in the electron diamagnetic direction, which is the same direction as the ***E***x***B*** poloidal flow. The high-speed flow spread from inside to outside. Figure 5 (c) shows that the fluctuation level was suppressed after the second broken line ($t > 8.7$ ms), especially in the inner region ($\rho < 0.65$). In the region of $\rho < 0.7$ and $t > 8$ ms, the region where the strong E_r was formed was corresponding to the high current ratio region of the mach probe and the low fluctuation region. In the period surrounded by broken line in Fig. 5, the E_r and the current ratio were significantly increased. And after the second broken line, both of them were saturated at higher values. On the contrary, the fluctuation level changed gradually in this period and was suppressed remarkably after this period.

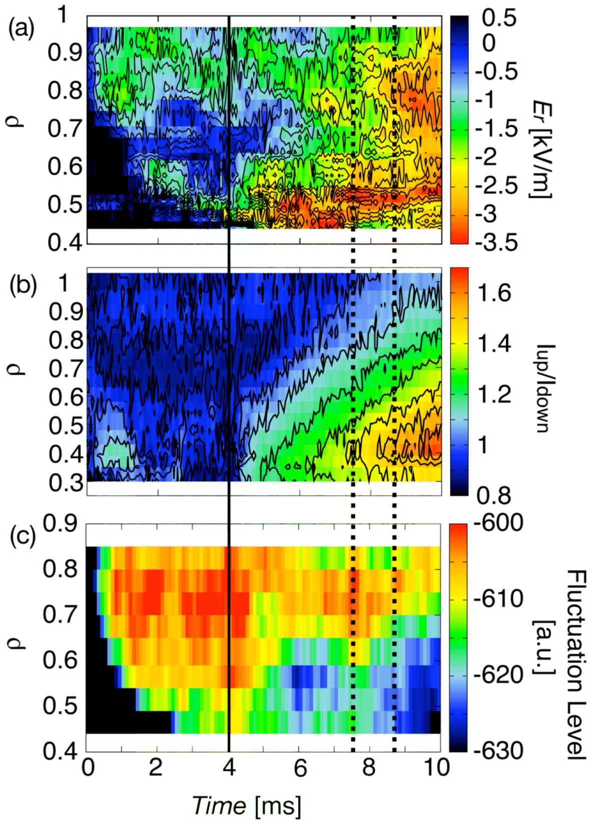

Fig. 5 The time evolution of the spatial structure of (a) the E_r, (b) the current ratio of the mach probe, (c) the fluctuation level of ion saturation current. All of them show the data in the discharges of the I_E ramped up. Solid line indicates the start time of ramping up. Broken lines are indicator of nonlinear period.

The results in the discharges of the I_E ramped down are shown in Fig. 6. In the plasma inner region the strong E_r was maintained the longer time compared to the outer region. The plasma flow gradually weakened from the plasma outer region. The fluctuation level was compressed at the low level during $2 < t < 6$ ms. This period was corresponding to that with the strong E_r and the large current ratio shown in Fig. 6 (a) and (b). This

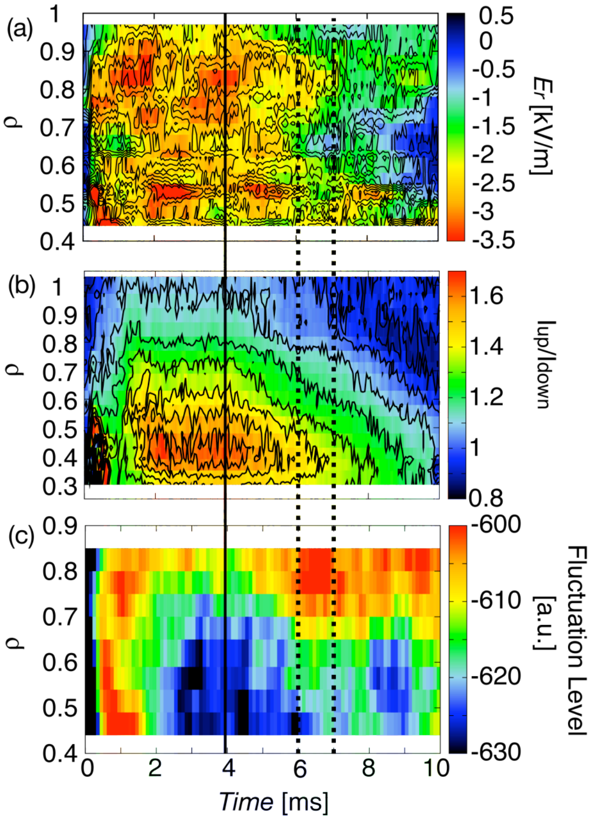

Fig. 6 The time evolution of the spatial structure of (a) the E_r, (b) current ratio of the mach probe, (c) the fluctuation level of the ion saturation current. All of them show the data in the discharge of the I_E ramped down. Solid line indicates the start time of ramping up. Broken lines are indicator of nonlinear period.

indicates that the E_r suppressed the fluctuation level. In the period surrounded by broken lines, the E_r decreased appreciably, and the fluctuation level had the maximum value in the plasma outer region. Although the current ratio did not change greatly in the outer region, the large change was seen in the inner region ($\rho < 0.6$). After the second broken line ($t > 8$ ms), the E_r became strong again and the fluctuation level became lower. It is suggested that the E_r was connected with the suppression of the fluctuation.

In both of the discharges of the I_E ramped up and down (shown in Fig. 5 and Fig. 6), the E_r was sustained at high level although the current ratio was very small in the part of outer region.

The strong E_r, the high-speed flow and the suppression of the fluctuation were observed at the period of $t > 8.7$ ms in Fig. 5 and $t < 6$ ms in Fig.6. These results suggested characteristics of the improved mode. Therefore the plasma nonlinearity region surrounded by broken lines was the transition region to the improved mode.

4. Summary

It was demonstrated that the emissive probe array had enough capability to measure the time evolution of the spatial structure of the plasma space potential in the electrode bias experiments in TU-Heliac. The estimation of the spatial profile of the radial electric field from the results of the plasma space potential was carried out. It was confirmed that the strong radial electric field spread from the inner region to the outer region in the discharge of the I_E ramped up, and was maintained for the longer time in the inner region in the discharge of the I_E ramped down. The characteristic region of the spatial and time profile of the radial electric field was corresponding to those of the current ratio of the mach probe and the fluctuation level of the ion saturation current, although the radial electric field had weak correspondence to the plasma poloidal flow at the part of the plasma outer region.

The E_r, the flow and the fluctuation level changed appreciably in the period when the bias electrode voltage shows nonlinearity against the bias electrode current. Therefore the plasma nonlinearity region was the transition region to the improved mode.

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