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


Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579, Japan
National Institute for Fusion Science, 322-6 Orosi-cho, Toki 509-5292, Japan

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 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 $a$ = 0.07 m. In electrode biasing experiments, the target plasma was He plasma produced by alternative ohmic heating with $f = 18.8$ kHz, $P = 35$ 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 $\phi = 0^\circ$.

The hot cathode made of 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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The plasma horizontally at $\phi = 270^\circ$. 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 $\phi = 159^\circ$.

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 $\phi = 270^\circ$. 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 $n_e \sim 10^{12} \text{cm}^{-3}$, 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 $\rho$ 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
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, (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.

In the 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.

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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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References