Experimental Study of Potential Profile Formation in Large Helical Device


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Abstract: The radial profile of potential, $\phi$, in the core region of the Large Helical Device (LHD) was measured with a Heavy Ion Beam Probe (HIBP) in wide parameter area, in which radial electric field, $E_r$, could not be measured in previous experiments. The radial profiles of $E_r$ were estimated from the differentiation of the experimental data of HIBP. These $E_r$ profiles were compared with the calculation result from neoclassical theory, and the theoretical prediction almost coincided with the experimental data of $E_r$ in the core region of LHD plasmas.

1. Introduction

In toroidal magnetized plasmas, the radial electric field $E_r$ is a very important parameter in transport phenomena. In the low collisional regime of helical devices, ripple induced diffusion loss is predicted from the neoclassical theory. This ripple-induced diffusion loss is non-ambipolar, so the radial electric field is formed. Diffusion loss in low collisional regime can be suppressed by the radial electric field, $E_r$, which is determined by the ambipolar condition. In previous experiments in LHD, charge exchange recombination spectroscopy (CXRS) was used to study $E_r$ formation. However, most of data were obtained in the outer region ($\rho>0.6$) of plasmas, in which helical ripple is large, because of insufficient emission from the impurities in the core region. In order to clarify physics of $E_r$ formation in the core region, where helical ripple is relatively small, the radial profile of plasma potential was measured with Heavy Ion Beam Probe (HIBP) [1-7]. In addition, we investigated

FIG. 1 Radial profiles of effective helical ripple of LHD are shown.

FIG. 2 Schematic view of HIBP system on LHD
$E_c$ in wider plasma-parameter space including high ion temperature ($T_i$) plasmas and high electron temperature ($T_e$) plasmas heated by ECH (no NBI), in which the electric field measurements by CXRS is difficult.

2. Experimental setup

The Large Helical Device (LHD) is a helical device, magnetic field configuration of which is characterized by the major radius of magnetic axis, $R_{ax}$, the pitch parameter $\gamma$, the quadrupole field component $B_q$. In this article, $\gamma$ and $B_q$ are fixed as the standard one, namely $\gamma = 1.254$, $B_q = 100\%$. By changing the major radius of $R_{ax}$, the amount of helical ripple is changed. In the inward shifted configuration of $R_{ax} = 3.6 m$, the helical ripple is smaller than that of the outward shifted configuration, $R_{ax} = 3.9 m$. Radial profiles of effective helical ripple are shown in Fig. 1.

HIBP [1] system was installed to LHD and has been developed in many years [2-9]. A schematic view of HIBP system in LHD is shown in Fig. 2. By using the tandem accelerator, the gold ion beam (Au$^+$), maximum energy of which is 6 MeV, is generated and it is injected to plasma as primary beam. The secondary beam (Au$^{2+}$) is formed by the collision with plasma, energy of which is analyzed by the tandem energy analyzer [10]. The three dimensional orbit of probe beam is controlled by two 8-pole electrostatic deflectors [11]. The primary and secondary beam current intensity is about a few µA and a few nA respectively. In order to detect this level of current, the sensitive current detector, micro channel plate (MCP), is used. The spatial resolution (the scale of sample volume) is about a few cm [4].

3. Experimental result

A typical shot is shown in Fig.3, when the radial profile of plasma potential was measured. The magnetic field strength, $B_t$ was 1.5 T, and the major radius of magnetic axis, $R_{ax}$ was 3.75 m. The plasma was produced by electron cyclotron heating (ECH) and sustained by neutral beam injection heating (NBI). Both of NBI#1 and NBI#3 are counter-direction. The toroidal current induced by these counter-direction NBIs is about 40 kA. The line averaged density gradually increased from $0.2 \times 10^{19} m^{-3}$ to $0.5 \times 10^{19} m^{-3}$ by gas puff control. The central electron temperature was about 2.5 keV at the line averaged density of $0.19 \times 10^{19} m^{-3}$ and $1.0 \text{ keV}$ at the line averaged density $> 0.30 \times 10^{19} m^{-3}$. In each period marked by alphabets A~E, the potential profile was measured with HIBP as shown in Fig.4. In the ECH phase (the duration A), the plasma potential at the center was positive. As the density increased, the potential decreased in the core region. In low density and high electron temperature case, the potential at the center tends to be negative or nearly zero.

By using a polynomial function of $\rho$ as a fitting function, radial electric field profile was
obtained from the experimental data. Obtained radial electric field profiles are compared with those estimated by GSRAKE code [12]. In Fig. 5 (a) and (b), the comparison in period A and C are shown respectively. In the period A ($n_e = 0.19 \times 10^{19} \text{m}^{-3}$), from the theory the positive radial electric field, so called electron root, is predicted. And this prediction roughly coincides with the experimental results. In the period C ($n_e = 0.30 \times 10^{19} \text{m}^{-3}$), the negative radial electric field, so called ion root, in the core region is predicted. And in this case, in the region $\rho > 0.26$, both roots of electron and ion roots are expected. In the core region, the ion root calculated by the neoclassical theory coincides with the experimental result. In the outer region where $\rho \sim 0.6$, the electron root of theoretical prediction coincides with the experimental result.

The dependence of the sign of measured radial electric field, $E_r$, on the electron and ion temperatures is studied and is compared with the neoclassical prediction as shown in Fig. 6. Figure shows plasma parameters in the $T_e-T_i$ space, and different symbol is used for each sign of $E_r$ at the radial position of $\rho = 0.25$. The solid curves show predicted boundaries among "Electron root" (positive $E_r$), "Ion Root" (negative $E_r$) and "Multiple Root", where parabolic

FIG.5 (a) The radial electric field profile in case A ($\bar{n}_e = 0.19 \times 10^{19} \text{m}^{-3}$). (b) $E_r$ in case C ($\bar{n}_e = 0.30 \times 10^{19} \text{m}^{-3}$) in FIG. 2. Open circle and diamond symbols are obtained from experimental data, and solid and dotted lines are theoretical predictions. Theoretical prediction roughly coincides with Experimental data.

FIG.6 The parameters of electron and ion temperature, when positive $E_r$ or negative (almost zero) $E_r$ was observed, are shown. Solid line is the theoretical boundary, which divides $T_e-T_i$ space into the regions where the electron root ($E_r > 0$), multiple root (both), and ion root ($E_r < 0$) are expected. (a) Inward shifted configuration, $R_{ax} = 3.6 \text{ m}$ (b) $R_{ax} = 3.75 \text{ m}$ (c) Outward shifted configuration, $R_{ax} = 3.9 \text{ m}$.
temperature profiles and the low density \(n \sim 0.3 - 0.5 \times 10^{19} \text{ m}^{-3}\) are assumed [13]. The major radius of magnetic axis, \(R_{\text{ax}}\), of magnetic configuration is 3.6 m for Fig. 6(a), 3.75 m for Fig. 6(b), and 3.9 m for Fig. 6(c). In the case of high \(T_e\) plasma with the electron internal transport barrier (e-ITB) [16-17], a positive radial electric field was observed. These shots are in "Electron Root" or "Multiple Root" regime in Fig. 6. The experimental parameters of the case A in Fig. 4 are in this regime. If the parameters are in the "Ion root" regime, weakly negative \(E_r\) is observed. In high \(T_i\) shots [14-15], experimental data shows small negative \(E_r\), which corresponds to "ion root" predicted by the neoclassical theory. Cases B–E in Fig. 4 correspond to discharges in the Ion root or the Multiple root regime. The theoretical prediction for the dependence of the sign of \(E_r\) on the temperatures is consistent with experimental results in three magnetic field configurations, namely wide helical ripple parameters.

4. Summary

The radial potential profile was measured with HIBP in LHD. The potential at the plasma core was positive in the case of EC heating, namely high \(T_e\), low \(n_e\). In the low \(T_e\) case, the potential in the core was almost zero or negative. The radial electric field, \(E_r\), was obtained from measured radial potential profile. Based on the condition of neoclassical ambiporarity, \(E_r\) is estimated theoretically and compared with experimental results. Theoretical predictions roughly coincide with the experimental results. The theoretical calculation of the sign of \(E_r\) (electron root and ion root) in the \(T_i - T_e\) parameter space was also done, and compared with experimental results. The theoretical calculation based on neoclassical ambipolarity is consistent with the sign of \(E_r\) observed in experiments. Thus, we clarified that physics of neoclassical context is almost dominant in \(E_r\) formation, in wide plasma parameters of advanced high temperature plasmas. The results will provide a physical basis to consider further improved confinement scenarios utilizing \(E_r\) in helical plasmas.

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