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The Effect of Non-Axisymmetry of Magnetic Configurations on Radial Electric Field Transition Properties in the LHD

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Abstract

Transition property of the radial electric field (E_r) in LHD have been theoretically investigated and also applied to explain experimental results. Especially, effects of the helicity of the magnetic configuration on the condition to realize the electron root are examined. Larger helicity makes the threshold collisionality higher. This is attributed to the nonlinear dependence of $\Gamma_e(E_r)$ in a low collisional regime. This interesting feature predicts that the threshold temperature becomes higher for a case of smaller helicity. The variation of the threshold density anticipated from the analysis for cases with different magnetic axis position is qualitatively verified in the density scan experiment.

Keywords:

LHD, radial electric field (E_r), ion and electron root, effective helicity, magnetic configuration

1. Introduction

It has been theoretically predicted that plasma confinement can be improved in non-axisymmetric helical systems by utilizing the electron root of the ambipolar radial electric field, E_r, for example [1-3]. Recently, the validity of this concept was also demonstrated experimentally in LHD [4], in which the neoclassical ion heat diffusivity reduces by the large positive E_r at the edge region of neutral-beam-heated plasmas [5].

A comprehensive understanding of how the parameter region of the electron root depends on plasma parameters is of vital importance for realizing improved confinement in LHD. In ref. [6], calculations in a wide parameter range were performed for this purpose. It was clarified that the threshold electron temperature $T_{e(b)}$ for realizing the electron root depends on $n_e^{0.4}$ and also on $B^{0.4}$, here n_e is the electron density and B the magnetic field strength at the magnetic axis. It is also shown that $T_{e(b)}$ depends strongly on ∇T_e and only slightly on ∇T_i and ∇n_e. Here, T_i is the ion temperature. In this paper, the effects of the non-axisymmetry (helicity) of a magnetic configuration on $T_{e(b)}$ is focused in Sec. **2** for LHD by utilizing the configuration flexibility to change the helicity in LHD. The density threshold is predicted to vary depending on the helicity based on the analysis of the neoclassical ambipolar E_r. The density scan experiment was conducted motivated by this prediction and predicted feature has been successfully verified as described in Sec. **3**. Finally, a summary is given in Sec. **4**. Basic information on neoclassical transport calculation is available in ref. [6].

2. Effects of the helicity of a magnetic configuration on the threshold electron temperature for electron root regime in LHD

Calculations over a wide parameter range were performed in ref. [6], as briefly mentioned in Sec. **1**. In this section, the effect of the helicity of the magnetic configuration is explained. Possibility of multiple E_r solutions and the transition from ion root to electron root based on the ambipolar condition is attributed to the helicity of the magnetic configuration (for example, [1-3]). The effect of the helicity on realizing the electron root has been already investigated [7], and findings clarified that the required temperature becomes lower as the helicity is increased as a parameter. This interesting feature is now re-considered in LHD configurations in order to provide information regarding to experiments. Here, control of the vacuum magnetic axis

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position R_{ax} is considered for varying the helicity of magnetic configurations. Figure 1 shows the radial (ρ) profile of the effective helicity, $\varepsilon_{h,eff}$, for three cases with different R_{ax}: 3.60 m, 3.75 m, and 3.90 m. The $\varepsilon_{h,eff}$ is calculated by the definition, $\varepsilon_{h,eff} = [(9\sqrt{2}\pi/16)(\nu/v_d^2)D]^{3/2}$ with the GIOTA code [8], which is based on the bounce-averaging method. Here, ν is the collision frequency, v_d is the drift velocity and D is the particle diffusion coefficient in the $1/\nu$ regime, respectively.

It is seen that $\varepsilon_{h,eff}$ increases as R_{ax} is increased, that is, as the configuration is outwardly shifted in this range of R_{ax}. This $\varepsilon_{h,eff}$ is utilized for the calculation of neoclassical particle fluxes based on the analytical formulae using the single helicity model of a magnetic field (such as in ref. [2]). Thus, the effect of the helicity of a magnetic field is taken into account through the different value of $\varepsilon_{h,eff}$ depending on R_{ax}. The E_r is determined with the ambipolar condition, $\Gamma_e = \Gamma_i$, where Γ_j denotes the particle flux of plasma species with $j = e$ for electron and $j = i$ for ion.

The E_r diagrams for these three cases are shown in Fig. 2 on (T_i, T_e) plane. Calculations are performed at $\rho = 0.8$ with $B = 1.5$ T with assumed n_e and $T_{e,i}$ profiles of $n_e(\rho) = n_e(0)(1 - \rho^8)$ with $n_e(0) = 1 \times 10^{19}$ m^{-3} and $T_{e,i}(\rho) = T_{e,i}(0)(1 - \rho^2)$. This diagram is obtained with varying $T_{e,i}(0)$ while fixing $n_e(0)$. The hydrogen plasma is assumed. The E_r is positive above the upper boundary and negative below the lower boundary. The surrounded region corresponds to the region of multiple E_r solutions. The $\varepsilon_{h,eff}$ is estimated to be about 0.05, 0.14, and 0.27 for R_{ax} = 3.60 m, 3.75 m, and 3.90 m, respectively. It can be clearly recognized from Fig. 2 that $T_{e(b)}$ (T_e for lower boundary) increases as $\varepsilon_{h,eff}$ is decreased, which is consistent with the dependence reported in ref. [7]. This result indicates that the density threshold for realizing the electron root becomes higher for a case with larger $\varepsilon_{h,eff}$, based on the result shown in Fig. 2 and the fact that $T_{e(b)} \propto n_e^{0.4}$ if the temperatures are almost the same among different R_{ax} cases.

The condition for $T_e = T_i = 1$ keV is now considered as an example (shown by the dot in Fig. 2). This condition locates in the region of multiple solutions for the case of R_{ax} = 3.90 m, marginally enters to the region of multiple solutions for the case of R_{ax} = 3.75 m, and still locates in the region of ion root for the case of R_{ax} = 3.60 m. The normalized collisionality, $\nu_{h,e}$* is plotted in Fig. 3. The $\nu_{h,e}$* is defined as $\nu_{h,e}^* = \nu_e/[\varepsilon_{h,eff}^{3/2} v_T \iota/2\pi R]$ with ν_e being the electron-ion collision frequency, $\iota/2\pi$ the rotational transform, and v_T the electron thermal velocity. This definition is introduced just by replacing the value of the single helicity to the value of the effective helicity on the collision frequency separating the plateau and $1/\nu$ regimes [9]. The $\nu_{h,e}^* = 1$ corresponds the boundary between the plateau and $1/\nu$ regimes. As for information, $\varepsilon_{h,eff}$ is also plotted. It is recognized that $\nu_{h,e}$* becomes effectively lower as $\varepsilon_{h,eff}$ is increased even with the same real collision frequency, that is, effectively locates deeper in the low collisional regime for larger $\varepsilon_{h,eff}$ case. This affects the behavior of neoclassical particle flux as shown in Fig. 4. As $\nu_{h,e}$* is decreased, the nonlinear dependence of Γ_e becomes apparent through the increase of Γ_e around $E_r \approx 0$ in the $1/\nu$ regime. Based on this fact, multiple solutions of ambipolar E_r becomes possible for cases with larger $\varepsilon_{h,eff}$ (R_{ax} = 3.75 m and 3.90 m) while the only ion root is allowed for a

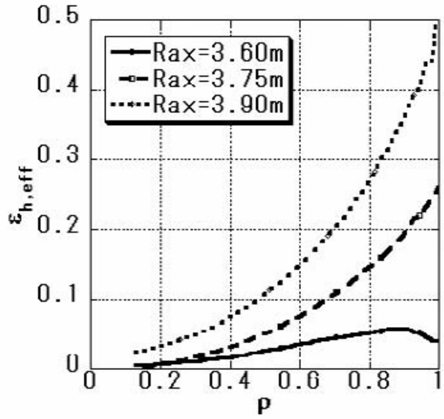

Fig. 1 Radial profile of $\varepsilon_{h,eff}$ for R_{ax} = 3.60 m, 3.75 m and 3.90 m.

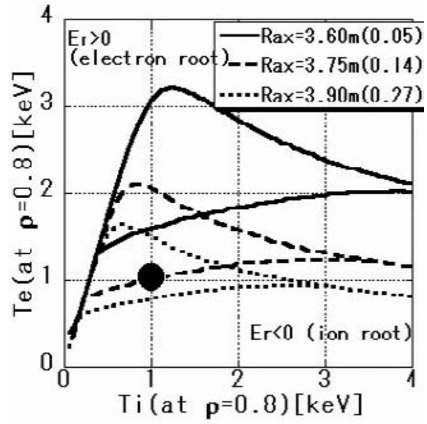

Fig. 2 Dependence of E_r diagram for R_{ax} = 3.60 m, 3.75 m and 3.90 m on (T_i, T_e) plane (at ρ = 0.8 with B = 1.5 T). As for information, $\varepsilon_{h,eff}$, is denoted in the bracket, respectively.

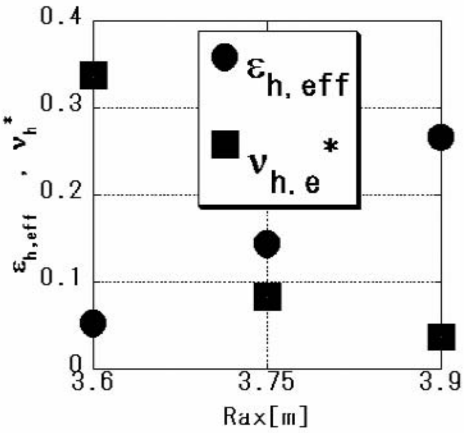

Fig. 3 The $\nu_{h,e}$* and $\varepsilon_{h,eff}$ at ρ = 0.8 with $T_e = T_i$ = 1 keV for R_{ax} = 3.60 m, 3.75 m and 3.90 m.

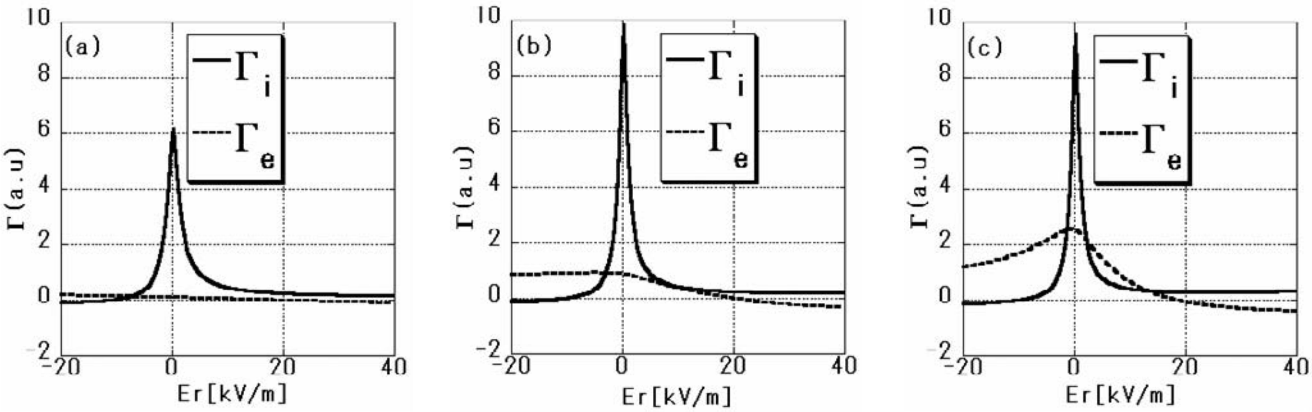

Fig. 4 The neoclassical particle fluxes, Γ_e and Γ_i, as a function of E_r for R_{ax} of (a) 3.60 m, (b) 3.75 m, and (c) 3.90 m. The calculations are based on the same conditions as those for Fig. 3.

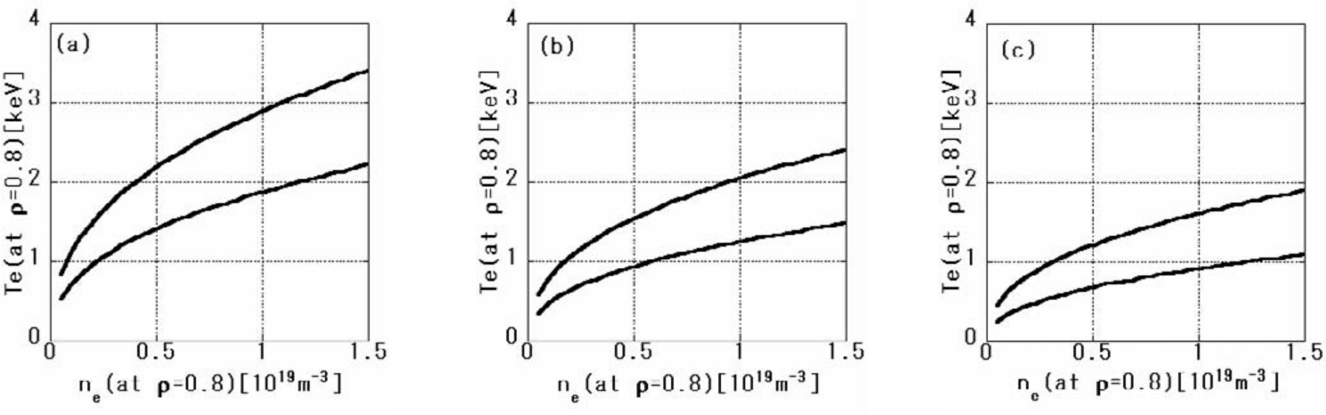

Fig. 5 Dependence of E_r diagram for R_{ax} of (a) 3.60 m, (b) 3.75 m and (c) 3.90 m on (n_e, T_e) plane. The calculations are based on the same conditions as those for Fig. 3 except fixing $T_e = T_i$.

case of smaller $\varepsilon_{h,eff}$ (R_{ax} = 3.60 m). The enhancement of the non-linearity of $\Gamma_e(E_r)$ by enlarging the helicity of a magnetic configuration plays the key role for this mechanism. This fact suggests that the realization of the electron root (or entering the region of multiple solutions) becomes easily possible for lower T_e for a case with larger $\varepsilon_{h,eff}$.

Now, the E_r diagram is considered based on the different aspect, that is, the density dependence on (n_e, T_e) plane. Figure 5 shows E_r diagrams for cases with R_{ax} = 3.60 m, 3.75 m, and 3.90 m. The density scan calculations are performed by assuming $T_e = T_i$. Other conditions are same as those utilized for Fig. 3. The dependence of $T_{e(b)}$ on n_e can be recognized as $T_{e(b)} \propto n_e^{0.4}$, which reproduces the dependence already been derived in ref. [6]. These E_r diagram also suggests that the density threshold for entering region of multiple solutions and/or electron root becomes higher for cases with larger $\varepsilon_{h,eff}$. For example, in the case of $T_e(0.8)$ = 1 keV, it is possible to enter region of multiple solutions is possible above $n_e(0.8) > 1 \times 10^{19}$ m^{-3} for a case of R_{ax} = 3.90 m, while the density has to be as low as around 0.3×10^{19} m^{-3} for a case of R_{ax} = 3.60 m.

These density and temperature dependence of threshold to enter the regime of multiple solutions and electron root can be summarized as follows. The higher helicity makes the threshold collisionality larger (higher n_e and lower temperature, especially T_e). This feature is attributed to the nonlinear dependence of $\Gamma_e(E_r)$ in a low collisional regime induced by the helicity of a magnetic configuration.

3. Experimental verification in LHD

Motivated by the neoclassical analysis described in Sec. **2**, verification experiment was conducted in LHD in a manner of the density scan for three magnetic configurations with R_{ax} = 3.50 m, 3.75 m, and 3.90 m. The E_r is evaluated through the measurement of the poloidal velocity of Ne by the 'fast' charge exchange recombination spectroscopy [10]. The deduced values of E_r for $\rho \approx 0.9$ are shown in Fig. 6(a) for three configurations. T_e is in the range of 0.5 keV at $\rho \approx 0.9$ for these discharges. It is observed that, for the same density range of $n_e \approx 1 \times 10^{19}$ m^{-3}, E_r is already positive for a case of R_{ax} = 3.90 m, while still negative for a case of R_{ax} = 3.50 m. It is interesting to see that transition from ion to electron root is observed for a case of R_{ax} = 3.75 m, between R_{ax} = 3.50 m and 3.90 m.

Corresponding density scan analysis of neoclassical ambipolar E_r is also carried out. Figure 6(b) shows solutions of E_r as a function of n_e. The calculation is performed by assuming the temperature ratio, T_e/T_i, as same as that at the plasma center, since the radial profile of T_i is not available, unfortunately. The ratio is in the range of 1~1.25 for these discharges. Below a particular value of n_e, there appear three roots (middle root is unstable), which correspond to the region of multiple solutions. Once n_e becomes as low as this threshold value, the electron root seems to be realized among three roots [5,6]. Thus, this threshold density could be considered as the threshold to realize the electron root. As generally explained in Sec. **2**, this threshold density becomes smaller as $\varepsilon_{h,eff}$ is decreased (corresponding to more inward shift of a configuration).

Comparing to experimental results shown in Fig. 6(a), for the density range scanned in the experiment, the multiple and/or electron root is anticipated for a case of R_{ax} = 3.90 m, while the ion root is predicted for a case of R_{ax} = 3.50 m. The experimental data for a case of R_{ax} = 3.50 m shows the tendency of the gradual increase of $|E_r|$ as the density is decreased on the contrary to the behaviour of the calculation result. This might be due to the change of the temperature (especially, T_e [6]) and/or the density profiles, which are assumed to be unchanged for the calculation. For a case of R_{ax} = 3.75 m, scanned range of density rather well match the threshold density anticipated from Fig. 6(b). Thus, the variation of the threshold density anticipated from the analysis of the neoclassical ambipolar E_r for cases with different R_{ax} is qualitatively (or even quantitatively) verified in LHD experiment.

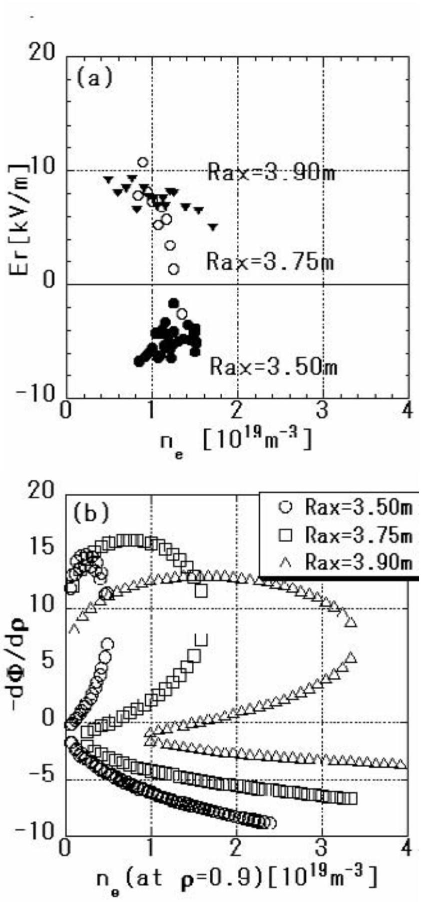

Fig. 6 (a) The deduced E_r for ρ ~ 0.9 for density scan experiment conducted in R_{ax} = 3.50 m, 3.75 m, and 3.90 m and (b) the neoclassical ambipolar E_r for ρ ~ 0.9 for density scan calculation for R_{ax} = 3.50 m, 3.75 m, and 3.90 m.

4. Summary

Radial electric field (E_r) properties in LHD have been theoretically investigated and also applied to LHD experimental results. The ambipolar E_r is calculated based on the ambipolar condition in the framework of a neoclassical transport theory. The effects of the helicity of the magnetic configuration on the condition to realize the electron root are examined. Larger helicity makes the threshold collisionality higher. This is attributed to the nonlinear dependence of $\Gamma_e(E_r)$ in a low collisional regime induced by the helicity of a magnetic configuration. This interesting feature predicts that the threshold temperature becomes higher for a case of smaller helicity, for example, by shifting the vacuum magnetic axis position inward. The variation of the threshold density anticipated from the analysis for cases with different R_{ax} is qualitatively (or even quantitatively) verified in density scan experiment conducted in LHD. This is a unique feature in non-axisymmetric configurations; it is not the case for an axisymmetric configuration such as tokamaks. The comparison between different devices with different magnetic field structure will be of vital importance for more comprehensive understanding [11].

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