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

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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 \( \Gamma (E_r) \) 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 \( T_{th} \) for realizing the electron root depends on \( n_e \) and also on \( B^0 \), here \( n_e \) is the electron density and \( B \) the magnetic field strength at the magnetic axis.

It is also shown that \( T_{th} \) depends strongly on \( V_T \) and only slightly on \( \nabla T \) and \( \nabla n_e \). Here, \( T_i \) is the ion temperature. In this paper, the effects of the non-axisymmetry (helicity) of a magnetic configuration on \( T_{th} \) 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 (\( \rho \)) profile of the effective helicity, \( \epsilon_{h,eff} \), for three cases with different \( R_{ax} \): 3.60 m, 3.75 m, and 3.90 m. The \( \epsilon_{h,eff} \) is calculated by the definition, \( \epsilon_{h,eff} = \left[ \frac{\left(9\sqrt{2\pi}16\left(\nu\gamma\right)\rho D\right)^{1/2}}{\nu} \right] \), with the GIOTA code [8], which is based on the bounce-averaging method. Here, \( \nu \) is the collision frequency, \( \nu \gamma \) is the drift velocity and \( D \) is the particle diffusion coefficient in the \( 1/\nu \) regime, respectively.

It is seen that \( \epsilon_{h,eff} \) increases as \( R_{ax} \) is increased, that is, as the configuration is outwardly shifted in this range of \( R_{ax} \). This \( \epsilon_{h,eff} \) 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 \( \epsilon_{h,eff} \) depending on \( R_{ax} \). The \( E_r \) is determined with the ambipolar condition, \( \Gamma_j = \Gamma_i \), where \( \Gamma_j \) 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 \( n_i \) and \( T_e \) profiles of \( n_i(\rho) = n_i(0)(1 - \rho^2) \) with \( n_i(0) = 1 \times 10^{19} \) m\(^3\) and \( T_i(\rho) = T_i(0)(1 - \rho^2) \). This diagram is obtained with varying \( T_i(0) \) while fixing \( n_i(0) \). 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 \( \epsilon_{h,eff} \) 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 \( \Gamma_{e,eff} \) 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 \( \epsilon_{h,eff} \), based on the result shown in Fig. 2 and the fact that \( \Gamma_{e,eff} \propto n_i^{1/4} \) if the temperatures are almost the same among different \( R_{ax} \) cases.

The condition for \( T_i = T_e = 1 \) 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, \( \nu_{eh}^{*} \), is plotted in Fig. 3. The \( \nu_{eh}^{*} \) is defined as \( \nu_{eh}^{*} = \nu_i [\epsilon_{h,eff}^{3/2} \nu_T^2 / 2\pi R] \) with \( \nu_i \) being the electron-ion collision frequency, \( \nu_T \) the rotational transform, and \( \nu_T \) 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 \( \nu_{eh}^{*} = 1 \) corresponds the boundary between the plateau and \( 1/\nu \) regimes. As for information, \( \epsilon_{h,eff} \) is also plotted. It is recognized that \( \nu_{eh}^{*} \) becomes effectively lower as \( \epsilon_{h,eff} \) is increased even with the same real collision frequency, that is, effectively locates deeper in the low collisional regime for larger \( \epsilon_{h,eff} \) case. This affects the behavior of neoclassical particle flux as shown in Fig. 4. As \( \nu_{eh}^{*} \) is decreased, the nonlinear dependence of \( \Gamma_e \) becomes apparent through the increase of \( \Gamma_e \) around \( E_r = 0 \) in the \( 1/\nu \) regime. Based on this fact, multiple solutions of ambipolar \( E_r \) becomes possible for cases with larger \( \epsilon_{h,eff} \) (\( R_{ax} = 3.75 \) m and 3.90 m) while the only ion root is allowed for a
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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 $\epsilon_{h,eff}$.

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 $\epsilon_{h,eff}$. 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 $0.3 \times 10^{19}$ 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 $\rho \sim 0.9$ are shown in Fig. 6(a) for three configurations. $T_e$ is in the range of 0.5 keV at $\rho \sim 0.9$ 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 $n_i$, there appear three roots (middle root is unstable), which correspond to the region of multiple solutions. Once $n_i$ 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 $\varepsilon_{h,\text{eff}}$ 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 $R_{\text{ax}} = 3.90$ m, while the ion root is predicted for a case of $R_{\text{ax}} = 3.50$ m. The experimental data for a case of $R_{\text{ax}} = 3.50$ 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 $R_{\text{ax}} = 3.75$ 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 $R_{\text{ax}}$ is qualitatively (or even quantitatively) verified in LHD experiment.

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 $R_{\text{ax}}$ 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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References