Analysis of Radial Electric Field Bifurcation in LHD Based on Neoclassical Transport Theory

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Abstract

Radial electric field (E_r) properties in LHD have been investigated based on the neoclassical transport theory and have also been applied to LHD experimental results. The effects of the helicity of the magnetic configuration on the condition required to realize the electron root are examined. The larger helicity makes the threshold temperature lower for the same electron density. A higher threshold temperature is anticipated to be required in the plasma core region based on this fact and also due to the larger density there. This high electron temperature (T_e) has been successfully obtained with a center-focused ECH. There is a threshold for the ECH power to achieve a steep gradient of T_e , and it seems to be qualitatively consistent with the transition of E_r , at least in the sense that the abrupt increase of T_e occurs after entering the anticipated electron root regime. These experimental results, consistent with those of analysis of the neoclassical ambipolar E_r , indicate that the transition phenomena of E_r in LHD are predominantly governed by neoclassical features.

Keywords:

radial electric field, neoclassical transport, electron root, helicity of magnetic configurations, ion species, LHD

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], where the neoclassical ion heat diffusivity is reduced by the large positive E_r at the edge region in neutral-beam-heated plasmas [5].

Because the ambipolar condition is local to each

flux surface, there is the possibility that multiple E_r solutions exist at one radial location, and that only one solution exists at another position. This allows the possibility of establishing an E_r domain interface [6], across which different branches of the solution (ion and electron root in this paper) touch. The formation of an E_r domain interface is effective to suppress turbulent transport, via the large radial shear of E_r [7]. An electron thermal transport barrier in CHS [8], where the density fluctuation is reduced, has been recognized as experimental evidence of an E_r domain interface.

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Thus, a comprehensive understanding of how the parameter region of the electron root and/or of multiple E_r solutions depend on plasma parameters is of vital importance for realizing improved confinement in LHD. In our previous paper [9], calculations in a wide parameter range were performed in LHD for this purpose. It was clarified that the threshold electron temperature ($T_{e(b)}$) for entering the electron root regime depends on $n_e^{0.4}$ and also on $B^{0.4}$, where 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 relevance of calculations over a wide parameter range (especially, the dependence of $T_{e(b)}$) for LHD experimental results is emphasized in Sec. 3. Prior to that, the effects of the helicity (non-axisymmetry) of the magnetic configuration and of the ion species on $T_{e(b)}$ are described in Sec. 2 for general consideration. Finally, a summary is given in Sec. 4. Basic information on neoclassical transport calculation is available in Ref. [9]. It is noted that the effective helicity ($\epsilon_{h,eff}$) is now calculated with the GIOTA code [10], which is based on the bounce-averaging method for evaluating neoclassical ripple transport. This is a more appropriate method for evaluating $\epsilon_{h,eff}$ than the estimation made solely by the poloidal averaging, used in Ref. [9].

2. Effects of the Helicity of the Magnetic Configuration and of Ion Species on the Threshold Electron Temperature for Electron Root Regime in LHD

Calculations over a wide parameter range were performed in Ref. [9], as briefly mentioned in Sec. 1. In this section, two other interesting features obtained by a wide range of calculations, the effect of the helicity of the magnetic configuration, and the effect of the ion species, are described for general considerations.

Multiple E_r solutions based on the ambipolar condition can appear due 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 [11], and findings clarified that the required temperature becomes lower as the helicity is increased as a parameter. This interesting feature is now reconsidered in LHD configurations in order to provide information vital to the experiments. Here, two approaches for varying the helicity are considered: control of the vacuum magnetic axis position (R_{ax}) and the difference of the radial position.

Fig. 1 Dependence of E_r diagram on three cases with different R_{ax} : 3.60 m, 3.75 m and 3.90 m on the (T_i, T_e) plane. The calculations are performed at $\rho = 0.8$ with $B = 1.5$ T. The H plasma is assumed. As for information, $\epsilon_{h,eff}$ is denoted in the bracket, respectively. The assumed n_e and $T_{e,i}$ profiles are $n_e(\rho) = n_e(0)(1 - \rho^8)$ with $n_e(0) = 1 \times 10^{19} \text{ m}^{-3}$ and $T_{e,i}(\rho) = T_{e,i}(0)(1 - \rho^2)$.

First, the effect of the control of R_{ax} is explained. Figure 1 shows the E_r diagram for three cases with different R_{ax} : 3.60 m, 3.75 m, and 3.90 m. The calculations are performed at $\rho = 0.8$ with $B = 1.5$ T. The hydrogen plasma is assumed. The assumed n_e and $T_{e,i}$ profiles are $n_e(\rho) = n_e(0)(1 - \rho^8)$ with $n_e(0) = 1 \times 10^{19} \text{ m}^{-3}$ and $T_{e,i}(\rho) = T_{e,i}(0)(1 - \rho^2)$. 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 is recognized that $\epsilon_{h,eff}$ varies largely depending on the control of R_{ax} . It can be clearly deduced that the $T_{e(b)}$ increases as $\epsilon_{h,eff}$ is decreased, which is consistent with the dependence reported in Ref. [11]. This result indicates that the density threshold for realizing the electron root becomes higher for a case with larger $\epsilon_{h,eff}$ (outward-shifted configuration), based on the result shown in Fig. 1 and the fact that $T_{e(b)} \propto n_e^{0.4}$ if the temperatures are almost the same among different R_{ax} cases. Experimental results in reasonable agreement with this theoretical prediction have been obtained recently in LHD, and will be reported elsewhere soon.

Second, the radial variation of E_r diagram is also investigated to clarify the difference in $T_{e(b)}$ between the plasma core and the edge regions. This is investigated by examining the E_r diagram on different radii for the case of $R_{ax} = 3.75$ m with $B = 1.5$ T. The hydrogen plasma is assumed. The assumed n_e and $T_{e,i}$ profiles are the same as those used for Fig. 1, with $n_e(0) = 1 \times 10^{19}$ m $^{-3}$ fixed. The result is shown in Fig. 2 for three different radial positions: $\rho = 0.25, 0.5$, and 0.75 . The $\epsilon_{h,eff}$ is denoted in brackets. The $T_{e(b)}$ increases from the edge towards the core region, which clearly indicates that higher T_e is required to realize the electron root in the core region. This dependence is attributed to the fact that $\epsilon_{h,eff}$ becomes smaller towards the core region and also to the basic dependences of $T_{e(b)} \propto n_e^{0.4}$ and, to the increase of $T_{e(b)}$ as ∇T_e is reduced [9].

The ion species is assumed to be hydrogen above and also in Ref. [9]. However, the effect of the ion species should also be clarified since not only hydrogen but also helium and neon discharges have been conducted in LHD. It should be noted that high T_i was achieved in Ne and recently in Ar discharges [12]. Figure 3 shows the E_r diagram for H, He, and Ne plasmas at $\rho = 0.8$ for the case of $R_{ax} = 3.75$ m with $B = 3$ T. The density and temperature profiles are assumed to be the same as those used for Fig. 1, with $n_e(0) = 1 \times 10^{19}$ m $^{-3}$ fixed. It is seen that the region of multiple E_r solutions for He plasma is shifted towards a higher T_i region than that for the case of H plasma. This feature is attributed to the fact that higher T_i is required for He to enter the low collisionality regime. On the other hand, the region of multiple E_r solutions disappears for Ne plasma, which indicates a gradual change of E_r between $E_r < 0$ and $E_r > 0$. Furthermore, $T_{e(b)}$ is sufficiently lower than those of H and He plasmas. This is due to the weakness of ion flux enhancement for Ne around a value of E_r at which the cancellation of ∇B drift and $E \times B$ drift occurs. Systematic measurement of E_r would be required to confirm this calculation result, which might be important to consider the effect of ion species on the confinement property through the different feature of E_r .

3. The Relevance of Analysis of the Threshold Electron Temperature for Electron Root Regime Based on Neoclassical Transport Theory in LHD Experimental Results

In LHD, a transition from negative E_r to positive E_r was observed in plasmas for the first time, with neutral beam injection (NBI) heating alone at a low density less

Fig. 2 Dependence of E_r diagram on different radial position ($\rho = 0.25, 0.5$ and 0.75) on the (T_i, T_e) plane. The calculations are performed for the case of $R_{ax} = 3.75$ m with $B = 1.5$ T. The H plasma is assumed. As for information, $\epsilon_{h,eff}$ is denoted in the bracket, respectively. The assumed density and temperature profiles are the same as those used for Fig. 1 with $n_e(0) = 1 \times 10^{19}$ m $^{-3}$ fixed.

Fig. 3 Dependence of E_r diagram on ion species (H, He and Ne) on the (T_i, T_e) plane. The calculations are performed at $\rho = 0.8$ for the case of $R_{ax} = 3.75$ m ($B = 3$ T) as an example. The density and temperature profiles are assumed as same as those used for Fig. 1 with $n_e(0) = 1 \times 10^{19}$ m $^{-3}$ fixed.

than $1 \times 10^{19} \text{ m}^{-3}$ [5]. In previous experiments [8,13-15], this transition was observed only in plasmas with electron cyclotron heating (ECH), in which supra-thermal electrons driven by ECH are considered to be the key ingredient for the transition [16]. The transition from ion to electron root in the edge region of NBI plasmas in LHD clearly demonstrates that supra-thermal electrons are not necessary for the transition. Systematic calculations have successfully explained the density threshold for this transition [5,9]. As anticipated from Fig. 2, the electron root can be realized in lower T_e for the edge region due to the lower n_e , larger ∇T_e , and larger helicity of the magnetic field.

On the other hand, according to Fig. 2, higher T_e is required to enter the electron root regime for the core region. This high T_e has been successfully realized with increasing center-focused ECH power [17]. A high central electron temperature has been achieved using a strongly focused Gaussian beam at the fundamental and second harmonic resonance. The microwave sources used are two 84 GHz collector potential depression (CPD)-type gyrotrons, two 82.7 GHz non-CPD gyrotrons, and three 168 GHz CPD gyrotrons. Each gyrotron provides 100–140 kW microwave power into plasmas. The magnetic field strength and the configuration are selected to have a power deposition as nearly on the axis as possible. The expected power deposition profile estimated by ray tracing, including a weakly relativistic effect, indicates that almost all of the injected power (about 1.2 MW) is concentrated within an average minor radius of $\rho \lesssim 0.2$. The electron temperature profiles are measured with a high power YAG-Thomson scattering system [18].

The central T_e is abruptly increased when the ECH injection power exceeds the threshold value, which increases with the density (cf., Fig. 2(b) in Ref. [19]). Here, this density dependence of ECH threshold power is considered from the viewpoint of the neoclassical ambipolar E_r on the (n_e, T_e) plane, as shown in Fig. 4. The magnetic configuration is $R_{ax} = 3.5 \text{ m}$ and $B = 2.854 \text{ T}$, which is relevant to ECH power scan experiments. The central T_e is re-plotted from Fig. 2(b) in Ref. [19] for reference (circles for the case with $n_e = 0.3 \times 10^{19} \text{ m}^{-3}$ and squares for that with $n_e = 0.5 \times 10^{19} \text{ m}^{-3}$). The plotted curves are the boundaries between regions with $E_r < 0$ and multiple E_r solutions (lower curve), and regions with multiple E_r solutions and $E_r > 0$ (upper curve). These boundaries are obtained from a calculation of the neoclassical ambipolar E_r at $\rho = 0.2$, around which the foot of the steep T_e gradient locates.

The $T_e(0)$ is deduced from T_e at $\rho = 0.2$ under the assumption of the parabolic profile, $T_e \propto (1 - \rho^2)$. The n_e is almost the same between $\rho = 0$ and 0.2. The temperature ratio is taken as $T_e/T_i = 2$ for the calculation. It corresponds to the condition before the steep gradient of T_e appears, since $T_i(0)$ is measured as $T_i(0) \sim 1 \text{ keV}$ by crystal spectrometer [20] and, on the other hand, $T_e(0) \sim 2 \text{ keV}$.

The $T_e(0)$ seems to increase abruptly after $T_e(0)$ exceeds a lower boundary (above which, multiple E_r solutions are possible). It is anticipated from previous results [9] that the electron root can be realized when plasma parameters enter the region where multiple E_r solutions are possible. From this expectation, this abrupt increase of $T_e(0)$ may be attributed to improvement in electron heat transport resulting from the electron root. Unfortunately, the E_r has not been sufficiently measured in such a core region of the strongly inward-shifted configuration. The E_r measurement in these circumstances will provide more information for comparison with this theoretical result. It is also recognized from Fig. 4 that $T_{e(b)}$ increases as n_e is increased, which feature seems to be consistent with the theoretical prediction of $T_{e(b)} \propto n_e^{0.4}$ [9]. Further increase of ECH power will provide results for higher n_e cases,

Fig. 4 E_r diagram in $(n_e, T_e(0))$ plane, which is relevant to ECH power scan experiments [19]. The plotted boundary is obtained from a calculation at $\rho = 0.2$ for the case of $R_{ax} = 3.5 \text{ m}$ with $B = 2.854 \text{ T}$. The temperature ratio is taken as $T_e/T_i = 2$ for the calculation. The $T_e(0)$ is re-plotted from Fig. 6(b) in Ref. [19] for reference.

which will be valuable to confirm the inter-relationships between the establishment of the steep T_e gradient and the nature of neoclassical E_r bifurcation. Extensive study in this direction should be continued.

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 temperature for the electron root lower for the same electron density. This interesting feature predicts that the threshold temperature becomes higher as the vacuum magnetic axis position is more inwardly shifted to reduce the helicity. The helicity also becomes smaller towards the core region. A higher threshold temperature is anticipated to be required to realize the electron root in the plasma core region based on this fact and also on the larger density there. This high T_e has been obtained with a center-focused ECH. The threshold of the ECH power has been observed to achieve a steep gradient of T_e , which seems to be qualitatively consistent with the transition of ambipolar E_r , at least, in the sense that significant increase of T_e occurs after entering the anticipated electron root regime.

The agreement between the results of theoretical analysis of neoclassical ambipolar E_r and experimentally clarified threshold features to realize the electron root has provided the proof that the E_r transition properties in LHD are predominantly determined based on neoclassical transport. This is a unique feature in non-axisymmetric configurations; it is not the case for an axisymmetric configuration such as tokamaks. The effect of the helicity of the magnetic field, such as dependence of the threshold ECH power on configuration variation for establishing a steep T_e gradient, is an interesting subject.

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References

- [1] H.E. Mynick *et al.*, Nucl. Fusion **23**, 1053 (1983).
- [2] M. Kovrizhnykh, Nucl. Fusion **24**, 435 (1984).
- [3] D.E. Hastings *et al.*, Nucl. Fusion **25**, 445 (1985).
- [4] A. Iiyoshi *et al.*, Nucl. Fusion **39**, 1245 (1999).
- [5] K. Ida *et al.*, Phys. Rev. Lett. **86**, 5297 (2001).
- [6] K. Itoh, H. Sanuki, S.-I. Itoh, A. Fukuyama, A. Fujisawa, M. Yagi and K. Ida, J. Plasma Fusion Res. Suppl. **74**, 282 (1998) (*in Japanese*).
- [7] K. Itoh, S.-I. Itoh and A. Fukuyama, *Transport and Structural Formation in Plasmas* (Institute of Physics Publishing, Bristol and Philadelphia, 1999).
- [8] A. Fujisawa *et al.*, Phys. Plasmas **7**, 4152 (2000).
- [9] M. Yokoyama *et al.*, Nucl. Fusion **42**, 143 (2002).
- [10] N. Nakajima, M. Okamoto and T. Amano, NIFS LHD Technical Report 1, p.288 (*in Japanese*), and K.Y. Watanabe, *private communication* (2002).
- [11] K.Y. Watanabe, Y. Nakamura and M. Wakatani, J. Phys. Soc. Jpn. **61**, 863 (1992).
- [12] S. Morita *et al.*, *19th IAEA Fusion Energy Conf.*, IAEA-CN-94/EX/P2-18 (2002).
- [13] H. Idei *et al.*, Phys. Rev. Lett. **71**, 2220 (1993).
- [14] A. Fujisawa *et al.*, Phys. Rev. Lett. **81**, 2256 (1998).
- [15] J. Baldzuhn *et al.*, Plasma Phys. Control. Fusion **40**, 967 (1998).
- [16] S. Murakami *et al.*, Nucl. Fusion **40**, 693 (2000).
- [17] S. Kubo *et al.*, J. Plasma Fusion Res. **78**, 99 (2002).
- [18] K. Narihara *et al.*, Rev. Sci. Instrum. **72**, 1122 (2001).
- [19] T. Shimozuma *et al.*, Plasma Phys. Control. Fusion **45**, 1183 (2003).
- [20] S. Morita and M. Goto, Rev. Sci. Instrum. **74**, 2375 (2003).