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# Analytical Study of Ambipolar Radial Electric Field in LHD

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**Abstract**

The ambipolar radial electric field ($E_r$) properties in LHD have been investigated. The $E_r$ is obtained with the neoclassical flux based on the analytical formulae. This approach is appropriate to clarify $E_r$ properties in a wide parameter range in a more transparent way. The comparison between calculated $E_r$ and experimentally measured one has shown qualitative agreement. Based on this assurance of this approach for LHD, wide range calculations have been performed to clarify the parameter region ($R_M$) where multiple $E_r$ solutions can exist. This is the region where $E_r$ domain interface can be established to realize improved confinement as experimentally confirmed in CHS.

**Keywords:**

ambipolar radial electric field ($E_r$), LHD, neoclassical flux, multiple $E_r$ solutions, $E_r$ domain interface

## 1. Introduction

Recently, significant roles of radial electric field ($E_r$) in toroidal plasmas have been widely recognized to achieve improved confinement modes [1]. The potential pulsation has also been experimentally observed in CHS [2]. This phenomenon is physically interpreted as the transition between two stable states of $E_r$ with negative (ion root) and positive (electron root) values. The electron thermal transport barrier has also been identified in CHS [3], which contributes to the reduction of the density fluctuation associated with the structural variation of the $E_r$ profile. This gives the experimental evidence of the $E_r$ domain interface as theoretically predicted [4]. The predicted parameter (density and temperatures) region for establishing $E_r$ domain interface, where multiple $E_r$ solutions can exist for the ambipolar condition are in semi-quantitative good agreement with experimental results [5]. This gives the experimental validation to consider the possibility of improved confinement based on clarifying the plasma parameter region where multiple $E_r$ solutions can exist ($R_M$). Based on these experimental confirmation, parameter regions of $R_M$ are clarified for LHD [6] towards improved confinement.

The analytical model for calculations is explained briefly in Sec. 2. In Sec. 3, calculated $E_r$ is compared with experimental ones for LHD. The qualitative (or even semi-quantitative) good agreement between those validates the use of analytical calculation to clarify the parameter region of $R_M$. Finally, a summary is given in Sec. 4.

## 2. Model Description

Neoclassical particle fluxes are calculated based on the analytical formulae [7]. The $E_r$ is then determined with the ambipolar condition, $\Gamma_e = \Gamma_i$, where $\Gamma_j$ denotes the flux of plasma species with $j = e$ for electron and $j = i$ for ion. The use of analytical formulae stimulates to clarify $E_r$ properties in a wide parameter range in a more transparent way.

The magnetic configuration control is possible in LHD with the shift of the magnetic axis position ($R_{ax}$) in vacuum. For the $R_{ax}$ = 3.75 m case, the poloidal inhomogeneity of $B$ ($|\varepsilon_{1,0}|$) is almost equal to the geometrical inverse aspect ratio. On the other hand, for

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the $R_{ax}$ = 3.60 m case, it is about 2/3 times smaller. The contribution of satellite helicity, $\varepsilon_{1,0}$, becomes larger for $R_{ax}$ = 3.60 m case even for inner region. Another satellite helicity, $\varepsilon_{3,10}$, also becomes apparent for the $R_{ax}$ =3.60 m case with the amplitude almost equal to that of $\varepsilon_{1,0}$ at the plasma edge. Thus, the magnetic field structure of LHD in vacuum - low beta conditions for this range of $R_{ax}$ can be approximately expressed as

$$B = B_0[1 + \varepsilon_{1,0}\cos\theta + \varepsilon_{2,10}\cos(2\theta - 10\zeta) + \varepsilon_{1,0}\cos(\theta - 10\zeta) + \varepsilon_{3,10}\cos(3\theta - 10\zeta)], \tag{1}$$

where ($\theta$, $\zeta$) are (poloidal, toroidal) angles, respectively.

In the original formulae, the poloidal inhomogeneity of $B$ (denoted by $\delta$ in ref. [7]) is simply defined by the geometrical inverse aspect ratio, which is no longer valid. Thus, this $\delta$ is replaced by $|\varepsilon_{1,0}|$. The helicity is defined there (denoted by $\hat{\varepsilon}$) through the modified Bessel function based on the magnetic potential analysis [8], which is also replaced by the effective helicity, $\varepsilon_H$, as

$$\varepsilon_H = \int_0^{2\pi} \sqrt{\varepsilon_{2,10}^2 + \varepsilon_{1,10}^2 + \varepsilon_{3,10}^2 + 2[\varepsilon_{2,10}(\varepsilon_{1,10} + \varepsilon_{3,10})\cos\theta + \varepsilon_{1,10}\,\varepsilon_{3,10}\cos 2\theta]}\; d\theta/2\pi\,. \tag{2}$$

The rotational transform is also given by equilibrium calculation.

The neoclassical particle fluxes (and then the ambipolar $E_r$) are calculated by determining the coefficients, $\varepsilon$, in eq. (1) for the model magnetic field (such as the effective helicity, $\varepsilon_H$) and equilibrium quantities obtained from equilbrium calculations.

## 3. Comparison with Experimental Results and Existence Region of $R_M$ in LHD

Some dependencies of $E_r$ on plasma parameters have been identified on LHD such as (1) higher temperature ($T$) is required to realize electron root $E_r$ for higher density ($n$), (2) $E_r$ becomes negative for higher $n$ (by gas-puffing and/or pellet injection) and becomes positive for lower $n$ [9]. The tendency (2) is firstly examined. During the $n$ scan experiment, $n$ is varied with gas-puffing with keeping electron and ion temperatures ($T_e$ and $T_i$) almost unchanged both in values and profiles. Thus, calculations are performed by taking electron density ($n_e$) as a parameter based on $n$ and $T$ profiles measured during this series of experiments (at 2.2 s of the discharge 13935, 13935-2.2 s with $R_{ax}$ = 3.75 m and $B$ = 1.5 T). The $n_e$ profile shape is fixed in the calculations to clearly see the dependence of $E_r$ on the $n_e$ value itself. Figure 1 shows $E_r$ solutions as a function of $n_e$ on three flux surfaces, $\rho$ = 0.85 (○), 0.90 (△) and 0.95 (x) associated with Fig. 1(a) in ref. [9]. Here $\rho$ is the normalized minor radius. The calculated $E_r$ is only one negative soultion for $n_e \geq 0.7 \times 10^{19} \equiv n_{e(c)}$ and solutions become multiple (three) for $n_e \leq n_{e(c)}$. The middle solution is unstable and one of the other two solutions is considered to be realized. As compared with Fig. 1(a) in ref. [9], $n_{e(c)}$ agrees rather well and maximum $E_r$ values in the electron root and values for ion root in a wide range of $n_e$ are also well reproduced. This indicates that these calculations can qualitatively or even semi-quantitatively explain the tendency (2), which assures the analysis utilized in this paper. It is noted that the difference of ion root values for different flux surfaces is relatively smaller than that of electron root. This implies that the response of the $E_r$ value on plasma parameters is more sensitive in the electron root. It is also recognized that the maximum positive $E_r$ for each flux surface increases as $\rho$

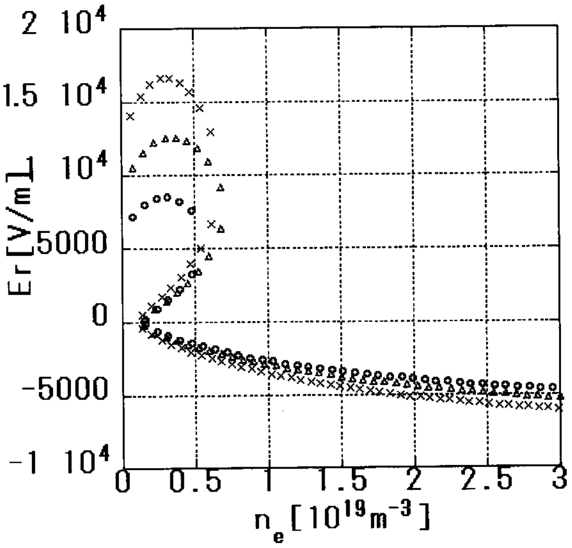


Fig. 1 Calculated $E_r$ at $\rho$ = 0.85 (○), 0.9 (△) and 0.95 (x) based on density and temparature profiles for 13935-2.2 s by varying only the density as a parameter.

increases. The increase of $\nabla T_e$ is effective to realize the electron root even for lower $T_e$ as will be reported in a separate paper. The $\nabla T_e$ increases towards the plasma edge in this case (13935-2.2 s) associated with edge pedestal fromation [10]. This gives enhanced (maximum) positive $E_r$ for outer radii even with lower $T_e$.

The difference of $n_{e(c)}$ between cases of $R_{ax}$ = 3.75 m and $R_{ax}$ = 3.60 m is explained in ref. [9] as the result of the difference of temperature ratio ($T_e/T_i$). One may consider that this difference can be explained by the difference of the magnetic configuration. However, this is less influential to vary $n_{e(c)}$. Figure 2 shows calculated $E_r$ solutions as a function of $n_e$ for three cases: solutions for original data of temperatures ($T_e/T_i \sim 1.5$) at $\rho = 0.9$ of 13935-2.2 s with $R_{ax}$ = 3.75 m (○), modified temperature values ($T_e/T_i$ = 1.0, $T_e$ is decreased artificially) with temperature gradients being kept the same as those at $\rho = 0.9$ of 13935-2.2 s (△), and temperatures (values and profiles) are kept the same as those at $\rho = 0.9$ of 13935-2.2 s but with magnetic field data of $R_{ax}$ = 3.60 m (×). The $n_{e(c)}$ does not vary for different magnetic field data ($R_{ax}$ = 3.60 m and 3.75 m) with the same temperature values and gradients. On the other hand, it reduces for a case with $T_e/T_i$ =1.0 even with the magnetic field data of $R_{ax}$ = 3.75 m. Thus, it is understood that the density threshold for transitions from ion root to electron root is influenced by the temperature ratio ($T_e/T_i$) rather than by the difference of magnetic configuration, which verifies the statement in ref. [9]. Results for neoclassical calculation shown in Fig. 1(b) in ref. [9] are obtained with temperature profiles with $T_e/T_i \sim 1$ with almost same gradients as those of 13935-2.2 s. Actually, if one performs calculations with $T_e/T_i > 1$, $n_{e(c)}$ becomes larger than that shown in that figure.

Now, the dependence of $E_r$ on temperature values is investigated to consider the above mentioned tendency (1). The tendency (1) can be expressed in other words as "electron root is possible even for higher $n_e$ when temperatures are increased". Thus, extensive calculations are performed in a wide temperature space, ($T_i$, $T_e$), taking $n_e$ as a parameter. Temperatures are amplified with keeping profiles to explore temperatures up to 3 keV (at $\rho = 0.9$) both for $T_i$ and $T_e$. Figure 3 shows the dependence of $R_M$ on $n_e$. The $E_r$ is singly negative below the lower boundary and singly positive beyond the upper boundary. The region between two boundaries for each case corresponds to $R_M$. The original value of $n_e$ is about 0.75 × $10^{19}$ m$^{-3}$, which is multiplied with the amplification parameter (*namp*, *namp* = 0.5, 1, 2, 5) with keeping its profile unchanged.

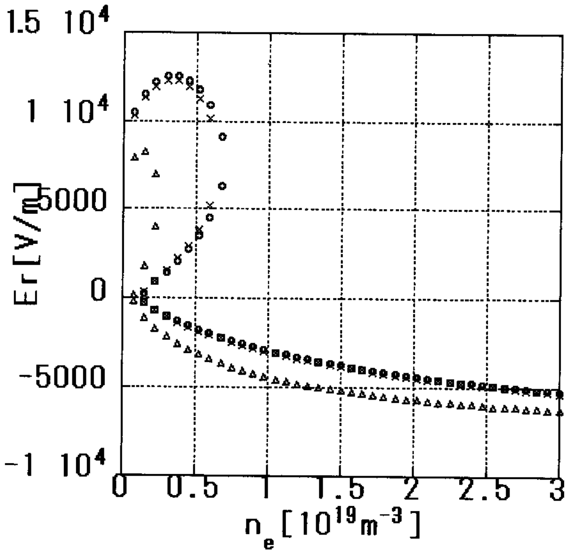


Fig. 2 Calculated $E_r$ as a function of $n_e$ for three cases: solutions for original data of temparatures ($T_e/T_i \sim$ 1.5) at $\rho = 0.9$ of 13935-2.2 s with $R_{ax}$ = 3.75 m (○), modified temperature values ($T_e/T_i$ = 1.0, $T_e$ is decreased artificially) with temperature gradients being kept the same as those at $\rho = 0.9$ of 13935-2.2 s (△), and temperatures (values and profiles) are kept the same as those at $\rho = 0.9$ of 13935-2.2 s but with magnetic field data of $R_{ax}$ = 3.60 m (×).

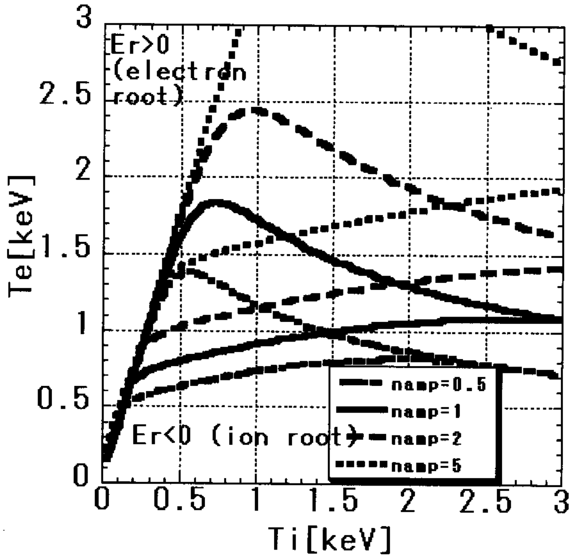


Fig. 3 Dependence of $R_M$ on $n$ parameterized by *namp* (*namp* = 0.5, 1, 2, 5) based on experimental data at $\rho = 0.9$ of 13935-2.2 s.

It is seen that higher temperatures (especially $T_e$) are required to reach $R_M$ and to realize the electron root for higher $n$. This indicates that $E_r$ tends to become positive as $n$ is decreased with keeping temperatures. This tendency well describes the experimentally observed one (tendency (1)). It can also demonstrate that $E_r$ shows transitions from negative to positive as $n_e$ is decreased for fixed temperatures (tendency (2)). The density scan calculations for Figs. 1 and 2 are regarded as a slice cut of this diagram (Fig. 3) for fixed temperatures. Thus, this diagram is valuable to grasp general tendencies of $E_r$ on a wide range in ($T_i$, $T_e$) space with density dependence. It should be noted that the calculations have been carried out in the density and temperature space so as to be easily referenced in the experiments. Theoretically, the key parameter is the electron collisionality which is changed by $n_e$ and $T_e$. The weak $T_i$-dependence of lower boundaries in Fig. 3 implies that the ion collisionality is of lesser important. The above mentioned conditions to reach $R_M$ and/or to realize electron root correspond to decrease electron collisionality.

As described above, ambipolar $E_r$ determined based on extended analytical formulae for neoclassical particle fluxes can be regarded to explain qualitative dependence of $E_r$ on temperatures and density observed in LHD. This qualitative agreement with experimental observations can assure this approach to examine the possibility of $E_r$ domain interface in LHD towards improved confinement.

## 4. Summary

The ambipolar $E_r$ properties have been examined for LHD as a first step to explore the possibility of $E_r$ domain interface towards improved confinement. The $E_r$ is obtained based on the ambipolar condition with the neoclassical flux calculated by the analytical formulae. This approach is appropriate to clarify $E_r$ properties in a wide parameter range in a more transparent way.

The calculated $E_r$ is compared with experimentally measured ones to check the validity of this approach. The experimentally observed tendencies are qualitatively well reproduced. The threshold value of $n$ for the transition from ion root to electron root is also demonstrated.

Based on this assurance of this approach for LHD, wide range calculations have been performed to clarify the parameter region for $R_M$, which is the region where an $E_r$ domain interface can be established. As $n$ is increased, $R_M$ shifts towards higher temperature (especially $T_e$), which is consistent with above mentioned experimental results for the transition from ion root to electron root below the threshold $n$ value. This systematic wide range calculations can give comprehensive understandings of experimentally observed tendencies of $E_r$ properties, which can give an appropriate guidance towards improved confinement. Further calculations for a guidance and its experimental test will appear in a separate paper.

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