Radial Electric Field Formation Including Electron Radial Drift for a Core Electron-Root Confinement (CERC) Plasma in LHD

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Electron neoclassical transport is calculated taking non-local electron radial drift into account by using FORTEC-3D code which is based on $\delta f$ Monte Carlo method with time evolution of radial electric field, $E_r$. This simulation is implemented as the first global analysis for high-electron-temperature discharges in LHD. The simulation result of $E_r$ is compared with the experimental observation and previous calculation results.

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Core Electron-Root Confinement (CERC) plasmas are widely obtained in recent experiments in many helical devices [1,2]. These plasmas are characterized by their high electron temperature ($T_e$), steep $T_e$ gradient in the core region, and strong positive radial electric field ($E_r$) called electron root. In such high $T_e$ plasmas, electron drift, or electron finite orbit width (FOW) effect, which is conventionally neglected in the neoclassical (NC) transport theory and calculation, needs to be taken into account to accurately evaluate electron NC particle and energy flux [3], since electron drift due to $\nabla B$ and curvature reduces peaked flux around $E_r = 0$ and also shifts its position compared to that observed in conventional NC calculations. This qualitative change may in turn affect $E_r$ formation through NC ambipolar condition. While ion particle flux with ion FOW effect and its influence to the $E_r$ formation have been investigated intensively in recent years (see, for example, [4,5]), electron drift effect on $E_r$ has not been studied so much. However, to understand the $E_r$ property in CERC plasmas, it is of importance to evaluate $E_r$ more accurately with electron FOW effect.

Recently, we have extended FORTEC-3D [6] for this purpose [3]. FORTEC-3D solves drift kinetic equation based on $\delta f$ Monte Carlo method following particles without local assumptions, and then, one can obtain particle and energy flux as velocity moments of $\delta f$ part of distribution function $f_a$, where $a$ denotes particle species, that is $a = e$ for electron, $a = i$ for ion. This enables one to evaluate $E_r$ and $\Gamma_e$ self-consistently with electron drift effect taken into account. The time evolution of $E_r$ is obtained as follows;

$$\epsilon_0 \epsilon_r \frac{\partial E_r}{\partial t} = -(Z_e \Gamma_i - e \Gamma_e),$$

(1)

where, $Z$, $e$ are the ion charge number, the electric charge, respectively, and $\Gamma_e$ is $a$-th particle flux, $\epsilon_0$ is the permittivity and $\epsilon_r \equiv (\langle (\nabla \rho)^2 \rangle + \langle \nabla \rho \rho \nabla \rho \rangle)$ denotes the permittivity which arises from the classical polarization current. Ambipolar $E_r$ is obtained as the steady state solution of Eq. (1), namely, $Z \Gamma_i - \Gamma_e = 0$, when $\Gamma_i$ and $\Gamma_e$ are balanced to vanish the radial current.

To carry out this simulation, we referred to $\Gamma_i = \Gamma_i(\rho, E_r)$ data base from DCOM/NNW [7] results as ion particle flux, which is based on the conventional NC assumptions, to reduce computational burden, while $\Gamma_i$ and $E_r$ are simultaneously calculated as an initial value problem in FORTEC-3D according to Ref. [6]. The adoption of $\Gamma_i$ based on DCOM/NNW results is justified due to low $T_i$ and thus small ion FOW effect. It is noted that although DCOM/NNW calculates the NC transport based on the $\delta f$ approach with the particle motion, it regards particles as virtually located at specific (local) magnetic surfaces assuming the radial drift as small enough to be neglected. Therefore, it is considered that DCOM/NNW adopts the conventional local NC assumptions and does not involves the radial drift of the particle.

In this paper, we apply FORTEC-3D for electrons at the first time to a CERC plasma in LHD to examine the $E_r$. Plasma profiles used in this calculation are shown in Fig. 1. Equilibrium magnetic field for this particular case is obtained by VMEC code [8]. Time evolution of $\Gamma_e$ and $E_r$ averaged over 0.01 $\tau_{ei}$ at $\rho = 0.25$ are shown in Fig. 2. It is shown that $\Gamma_e$ balances with $\Gamma_i$ at the steady state after $t/\tau_{ei} \simeq 1.0$, where $\tau_{ei}$ denotes the electron-ion collision time. It is noted that an inevitable numerical noise of
\( \Gamma_e \) from Monte Carlo method using the motion of many marker particles and their random collisions exists. It is also shown that \( E_r \) reaches the steady state value approximately after 1.0 \( \tau_{ei} \).

Radial profile of \( E_r \) in steady state is shown in Fig. 3. The ambipolar \( E_r \) from DCOM/NNW steady state particle flux, which is determined by the condition of \( \Gamma_i = \Gamma_e \) is also shown in this figure. It is noted that \( E_r \) shown in Fig. 3 is the averaged one over 0.6 \( \tau_{ei} \) after the steady state. Error bars for \( E_r \) which is evaluated as its standard deviation from the averaged value at each radial position is also shown in this figure. In this figure, \( E_r \) and its shear at the steady state obtained by FORTEC-3D shows relatively good agreement with electron-root one calculated by DCOM/NNW at 0.3 < \( \rho < 0.6 \).

However, \( E_r \) by FORTEC-3D differs largely from that by DCOM/NNW at the core of \( \rho < 0.2 \). The radial profile of \( E_r \) is shown in Fig. 4. It is shown in this figure that the difference of \( \Gamma_e \) becomes larger in the core region especially inside \( \rho > 0.15 \) than that at the intermediate region of \( \rho > 0.2 \). The reason why the difference of \( \Gamma_e \) and \( E_r \) becomes larger in the core region than in the intermediate region is considered as follows. In CERC plasmas, typical radial drift width becomes larger as the temperature increases, and steep \( T_e \) gradient, or the small scale of \( T_e \) arises in the core region. Thus the local assumption that the orbit width is small enough compared to the plasma scale length, would be inappropriate. Since \( \nabla B \) and the curvature drifts, which are assumed to be small enough as the consequence of the local assumptions, become large as \( T_e \) increases, they change the NC transport qualitatively through the particle poloidal precession and the collisionless detrapping as shown in Ref. [3]. The FOW effect included in FORTEC-3D affects NC transport more in the core region where \( T_e \) of the CERC plasma is high and steep \( T_e \) gradient forms. On the other hand, as stated above, DCOM/NNW evaluates the NC transport flux based on the local assumptions. This suggests that the electron drift effect plays an important role in determining \( E_r \) at the diamagnetic region.
core region.

In the edge region of \( \rho > 0.75 \), the ion-root \( E_r \) results in and it agrees well with the ion-root \( E_r \) obtained by DCOM/NNW in contrast to the experimental observation of the electron-root \( E_r \). One can find that the electron-root \( E_r \) cannot appear as the steady state solution of ambipolar condition, thus, this electron-root feature at the edge region may result from other physical mechanisms such as heating, charge exchange with neutral particles, etc., which is not taken into account in both FORTEC-3D and DCOM/NNW. It is noted that no diffusive terms on \( E_r \) except that arises numerically from \( \Gamma_e \) interpolation is included in FORTEC simulation. It is inferred that \( E_r \) rapidly increases at the \( \rho \approx 0.75 \) since the omission of diffusivity on \( E_r \) results in numerical divergence at the interface of \( E_r \) bifurcation which changes into ion root at the edge region from electron root at the inner region.

In summary, the radial electric field \( E_r \) is simultaneously calculated with neoclassical particle flux taking the electron radial drift into account for a CERC plasma in LHD. FORTEC-3D, which includes the electron radial drift and resulting finite orbit width effect, is applied to the CERC plasma for the first time. One can obtain the NC ambipolar \( E_r \) by FORTEC-3D with less assumptions compared to that in the previous local treatment. As a result, the difference of \( \Gamma_e \) and \( E_r \) between FORTEC-3D and DCOM/NNW becomes large in the core region. Since the principal difference between these codes is the additional FOW effect included in FORTEC-3D, this suggests that it is necessary to evaluate the NC transport flux and the resultant \( E_r \) formation with FOW effect. It has been found that in tokamaks the FOW effect either reduce or increase neoclassical heat flux near the magnetic axis depending on the plasma temperature profile [4]. In LHD, the FOW effect is more complicated due to such features as collisionless detrapping and the strong dependence on radial electric field, which are not seen in tokamak cases. Since it is difficult to treat such problems analytically, the direct simulation of the radial flux and ambipolar \( E_r \) with the FOW effect taken into account is useful. The ion-root \( E_r \) is obtained by FORTEC-3D at the edge region as that by DCOM/NNW, which is in contrast to the experimental observation. Since FORTEC-3D enables one to simulate the particle flux and the \( E_r \) evolution with time in addition to the steady state values, more detailed analyses on the difference between NC \( E_r \) and experimental observations will be carried out in the future work.

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