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 δf 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.

Keywords: drift kinetic equation, neoclassical transport, radial electric field, δf Monte Carlo method, CERC plasma

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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 ∇B and curvature reduces peaked flux around $E_\mathrm{r} = 0$ 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 δf Monte Carlo method following particles without local assumptions, and then, one can obtain particle and energy flux as velocity moments of δf 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 Γ_e self-consistently with electron drift effect taken into account. The time evolution of E_r is obtained as follows;

$$\epsilon_0 \epsilon_\perp \frac{\partial E_\mathrm{r}}{\partial t} = -\left(Z_\mathrm{i} e \Gamma_\mathrm{i} - e \Gamma_\mathrm{e} \right), \tag{1}$$

where, Z, e are the ion charge number, the electric charge, respectively, and Γ_a is a-th particle flux, ϵ_0 is the permittivity and $\epsilon_\perp \equiv (\langle |\nabla\rho|^2 \rangle + \langle \frac{c^2}{v_\mathrm{A}^2} |\nabla\rho|^2 \rangle)$ denotes the permittivity which arises from the classical polarization current. Ambipolar E_r is obtained as the steady state solution of Eq. (1), namely, $Z_\mathrm{i}\Gamma_\mathrm{i} - \Gamma_\mathrm{e} = 0$, when Γ_i and Γ_e are balanced to vanish the radial current.

To carry out this simulation, we referred to $\Gamma_\mathrm{i} = \Gamma_\mathrm{i}(\rho, E_\mathrm{r})$ data base from DCOM/NNW [7] results as ion particle flux, which is based on the conventional NC assumptions, to reduce computational burden, while Γ_e and E_r are simultaneously calculated as an initial value problem in FORTEC-3D according to Ref. [6]. The adoption of Γ_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 δf 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 Γ_e and E_r averaged over 0.01 τ_ei at $\rho = 0.25$ are shown in Fig. 2. It is shown that Γ_e balances with Γ_i at the steady state after $t/\tau_\mathrm{ei} \simeq 1.0$, where τ_ei denotes the electron-ion collision time. It is noted that an inevitable numerical noise of

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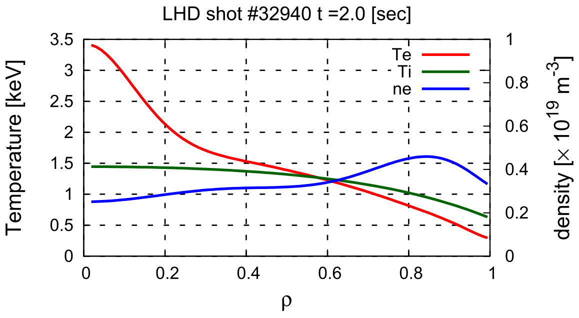

Fig. 1 Plasma profiles of a LHD CERC shot (#32940, 2.0 [sec]).

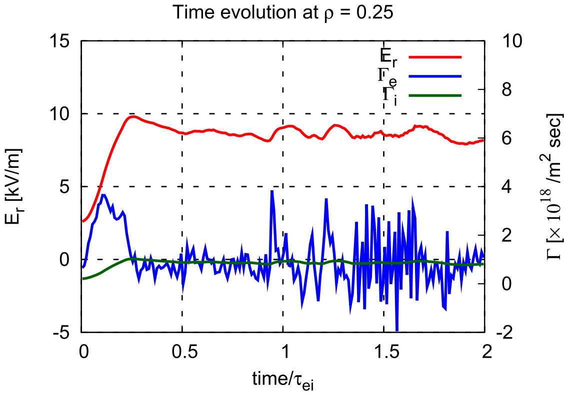

Fig. 2 Time evolution of Γ_e (blue line) and E_r (red line) at $\rho = 0.25$, each of which is averaged over 0.01 τ_{ei}. Γ_i calculated by DCOM/NNW, which is referred at each time step in the simulation, is also shown by green line. It is shown that $\Gamma_e = \Gamma_i$ is almost accomplished at the steady state after $t/\tau_{ei} \simeq 1.0$.

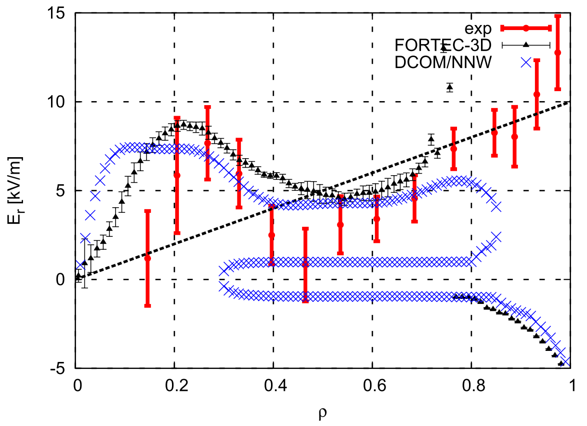

Fig. 3 Radial profile of E_r in steady state. The ambipolar E_r obtained by FORTEC-3D (black triangle symbol with error bar) and DCOM/NNW (blue cross symbol) are shown respectively. The FORTEC-3D result is averaged over 0.6 τ_{ei}. Experimental observation of E_r in the LHD experiment is represented by red circle with error bar. An initial E_r profile used in the FORTEC-3D simulation is also represented by dashed black line.

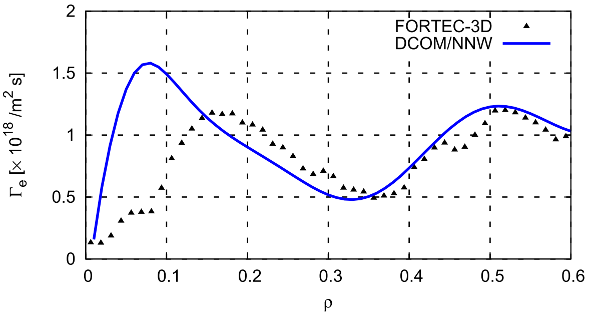

Fig. 4 Radial profile of Γ_e obtained by FORTEC-3D in steady state (black triangle symbol), averaged over 0.6 τ_{ei}. The ambipolar particle flux by DCOM/NNW corresponding to the electron-root E_r is also shown by blue line.

Γ_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 τ_{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 τ_{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 Γ_e is shown in Fig. 4. It is shown in this figure that the difference of Γ_e becomes larger in the core region especially inside $\rho \simeq 0.15$ than that at the intermediate region of $\rho > 0.2$. The reason why the difference of Γ_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 length 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 ∇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 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 Γ_e interpolation is included in FORTEC-3D simulation. It is inferred that E_r rapidly increases at the $\rho \simeq 0.75$ 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 Γ_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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