

Benchmark of local and non-local neoclassical transport calculations in helical configurations

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Neoclassical (NC) transport analysis in stellarator / heliotron configurations has more important role than that in tokamaks, because of its large amplitude, stronger dependence on radial electric field and collisionality. Moreover, the radial electric field can be expected through the ambipolar NC flux condition. Since it is time-consuming to solve the drift-kinetic equation (DKE) in helical geometry, local and mono-energy approximation models have been adopted in the NC transport codes (DKES[1], GSRAKE[2], DGN/LHD[3], etc.). These local codes have been benchmarked in detail [4], and it has been reported that in some ion-root (negative- E_r) plasmas of which ion and electron collisionality are close, fairly good agreement was found between NC particle and energy fluxes from local codes and those analyzed from the particle and energy balance in the experiments[8].

On the other hand, according to the progress in large-scale computation method and resources, now it is possible to solve 5-dimensional DKE without relying on the local and mono-energy approximation by using FORTEC-3D code we have developed[5] in arbitrary helical configuration. It is expected that the non-local nature in NC transport, which is originated from the finite magnetic drift of guiding-center motions in both perpendicular and tangential to the flux surfaces, will change NC flux and ambipolar condition[6, 7]. In order to improve the predictability of NC transport in helical plasmas, in this paper we benchmark the local and non-local codes in several helical configurations such as LHD, TJ-II, W7-AS. Also, by comparing the non-local calculation with the experimental observations shown in [8], the impact of the non-local effect on transport analysis is investigated.

The DKE for the perturbation of distribution function $\delta f(r, \theta, \zeta, v, \xi) = f - f_M(r, v)$ is

$$\frac{\partial \delta f}{\partial t} + \left[(\mathbf{v}_{\parallel} + \mathbf{v}_{E \times B} + \mathbf{v}_B) \cdot \nabla + \dot{v} \frac{\partial}{\partial v} + \dot{\xi} \frac{\partial}{\partial \xi} \right] \delta f = - \left(\mathbf{v}_B \cdot \nabla r \frac{\partial}{\partial r} + \dot{v} \frac{\partial}{\partial v} \right) f_M(r, v) + C(\delta f), \quad (1)$$

where v is absolute velocity, $\xi = v_{\parallel}/v$, $\mathbf{v}_{E \times B}$ and \mathbf{v}_B are $E \times B$ and magnetic drift velocity, respectively, and $C(\delta f)$ represents the linearized collision operator. The local and mono-energy NC codes adopts the following approximations : (i) Collision operator is approximated by pitch-angle scattering (diffusion only in the ξ -space), (ii) Zero-orbit-width approximation : $\mathbf{v}_B \cdot \nabla r$ and $\dot{v} \partial / \partial v$ terms in the LHS of DKE is neglected. Under these approximations, r and v become mere numerical parameters which does not change along the guiding-center trajectories.

In DKES code, further approximation is used by neglecting completely the $\mathbf{v}_B \cdot \nabla$ term in the LHS. GSRAKE solves the ripple-averaged DKE with keeping the $\langle \mathbf{v}_B \cdot \nabla \theta \rangle$ term. The expression of the magnetic geometry is simplified in GSRAKE. On the other hand, FORTEC-3D solves Eq. (1) as it is by using the two-weight δf -PIC method[5]. The most important difference is that FORTEC-3D code keeps the whole $(\mathbf{v}_B \cdot \nabla + \dot{v} \partial / \partial v) \delta f$ terms. This is referred as the "non-local" treatment of DKE in this paper.

To demonstrate the difference in local and non-local calculations, we show here simulation results of a W7-AS case in [8] (shot #34313), where Figures 1 show the radial profiles of ambipolar- E_r and NC fluxes evaluated from DKES and FORTEC-3D codes. The ambipolar- E_r does not change so much inside $r < 0.6a$, but the difference becomes clearer towards the edge. The E_r profiles are determined in both codes so as to satisfy $\Gamma_i(r, E_r) = \Gamma_e(r, E_r)$. In figures 2, the dependence of $\Gamma_{i,e}$ on E_r around the ion-root is shown on two flux surface, $r = 0.56a$ (where $E_{amb}[\text{FORTEC-3D}] < E_{amb}[\text{DKES}]$) and $r = 0.96a$ (opposite). We speculate the effect of finite magnetic drift term in non-local NC simulation in two ways as follows. On $r = 0.56a$ surface, FORTEC-3D Γ_i is

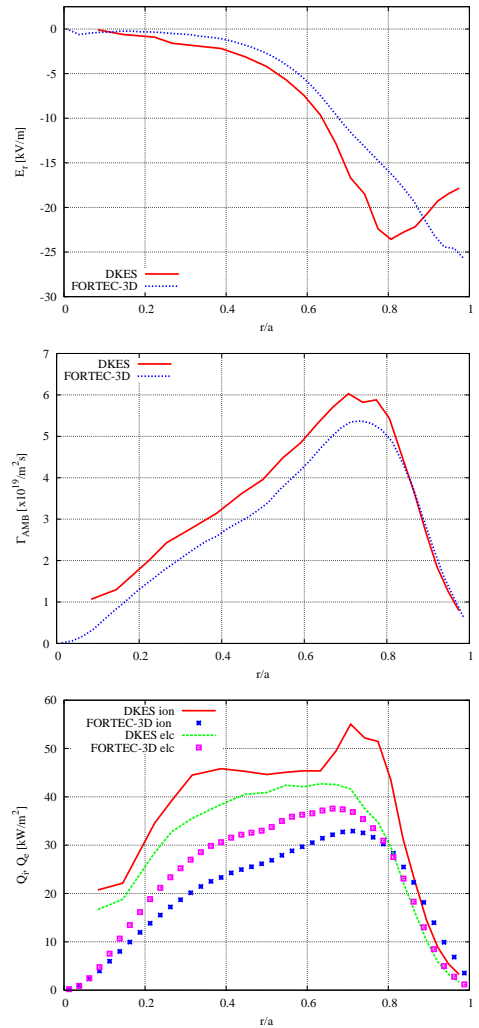


Figure 1: Comparison of NC ambipolar E_r , NC particle flux, NC ion and electron energy fluxes in a W7-AS plasma.

much smaller than DKES around the ion root. Actually, the assumption $v_{E \times B} \gg v_B$ used in DKES is not valid for ions if the E_{amb} is close to zero. Finite $\mathbf{v}_B \cdot \nabla \theta$ term in non-local calculation allows ripple-trapped particles to precess in poloidal directions even without $E \times B$ rotation and prevents large radial excursion of trapped ions. Thus the ambipolar- E_r becomes smaller in amplitude in non-local calculation on $r = 0.56a$ surface. On the other hand at the edge region $r = 0.96a$, we found FORTEC-3D Γ_i becomes larger than DKES solution. The $v_{E \times B} \gg v_B$ assumption is valid there, since ion temperature is lower while the ion-root E_r amplitude is very larger compared to the those on $0.56a$ surface. Therefore, the difference of Γ_i on this flux surface is not from the $\mathbf{v}_B \cdot \nabla \theta$ term, but it is speculated that another non-local effect on Γ_i appears here. Basically, the radial magnetic drift velocity is proportional to $\partial B / \partial \theta$ and $\partial B / \partial \zeta$ terms, and the magnetic ripple amplitude in helical devices is larger towards the edge in general. Therefore, the finite radial drift motion in non-local code, $\mathbf{v}_B \cdot \nabla r$, is considered to enhance the NC flux compared to local NC calculation. On the other hand, we can see in Fig.2 that the difference in Γ_e between local and non-local calculations is small. It is simply because the radial orbit width of trapped electrons are much smaller than ions and zero-orbit-width approximation is well satisfied. Moreover, Γ_e depends weakly on E_r . Thus the ambipolar flux Γ_{amb} does not differ so much even E_{amb} is different between two calculations, especially at $r/a > 0.8$. The small but finite difference in Γ_{amb} at $r < 0.8a$ is found to originate from the overestimation of Γ_e in DKES code if $|E_r| \sim 0$, since $v_{E \times B} \gg v_B$ assumption is not valid also for electrons in such a case.

The most clear difference between two NC calculations appears in the ion energy flux Q_i . FORTEC-3D Q_i is about half of the DKES one. The energy flux is v^3 -moment of δf and therefore more high- v particles in the distribution function contributes to Q_i compared to Γ_i . Then the non-local effect by the finite magnetic drift can be more effective on energy flux. The same tendency is found when we compared local and non-local NC simulation results for LHD(shot #109696) and TJ-II(shot #19065) in [8]. As TJ-II case is most collisional (plateau-regime) among the 3 cases, differences in E_{amb} and Q_i are smallest.

Finally, we compared the simulation results with experimental analysis. Figure 3 compares the E_r and Q_i from NC simulations with the experimental analysis

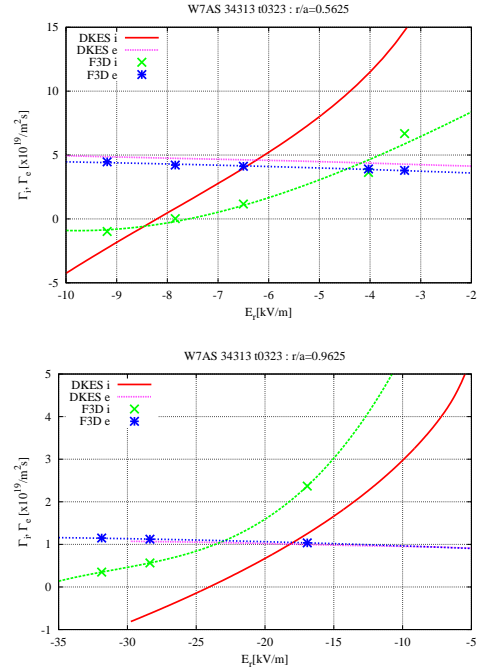


Figure 2: Dependence of NC flux on E_r a W7-AS plasma.

by TASK-3D package[9] in the LHD case. In the previous analysis[8], the E_r profile from CXRS measurement was found to more negative than local NC simulation, but the NC energy transport is comparable to that evaluated from power balance. It was expected that non-local NC simulation would explain the disagreement in E_r , but we found the difference cannot be fully compensated by non-local NC simulation. Therefore, some unconsidered mechanism of ion particle loss other than bulk NC flux is expected to explain the measured E_r . Concerning Q_i , as non-local calculation gives about 1.5 times larger Q_i at $r > 0.7a$, the difference between NC and the analyzed total energy flux becomes smaller at edge region. This suggests that the precise non-local NC calculation also affects the expectation of turbulent transport level in helical plasmas, which is considered to explain the difference $Q_{i(\text{total})} - Q_{i(\text{NC})}$. Since the difference between local and non-local NC Q_i differs as much as factor 2 at the ion-root, this difference is not negligible in analyzing energy confinement of helical devices.

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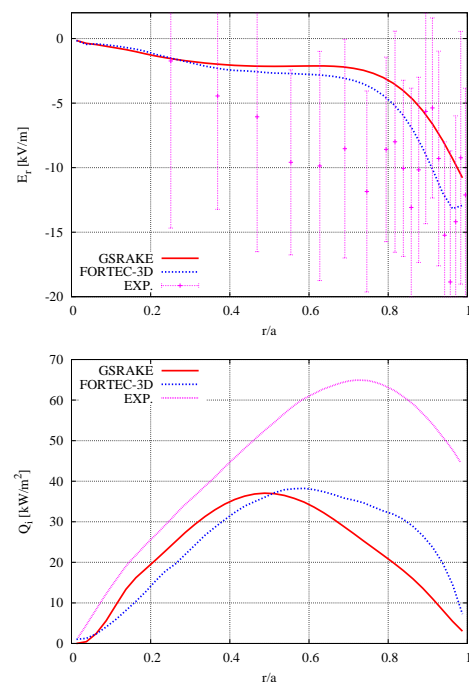


Figure 3: E_r and Q_i profiles in LHD plasma from NC simulations and experimental analysis by TASK-3D.