Impacts of External Momentum Torque on Impurity Particle Transport in LHD

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Particle transport processes of impurity ions in a multi-ion-species plasma in the Large Helical Device are investigated by neoclassical transport simulations. While the quasi-linear gyrokinetic analyses indicate that the anomalous contribution of the impurity particle transport is radially inward-directed, it is found that the external momentum sources can cause the existence of the electron root with positive radial electric field and outward-directed neoclassical particle flux of the impurity ion.

Keywords: impurity transport, Large Helical Device, neoclassical transport

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Studies on the transport processes in multi-ion-species plasmas are strongly demanded for fusion research toward burning plasma experiments in the ITER. In the Large Helical Device (LHD) [1] experiments with high ion temperature, the extremely hollow impurity density profiles, i.e., *impurity hole* [2], are often observed in the multi-ion-species plasmas heated by the neutral beam injection (NBI). Since the hollow density profiles of the impurity can avoid the impurity accumulation which deteriorates the plasma confinement performance, the understanding the mechanism of the impurity hole formation is one of the critical issues for achieving the high-performance of magnetically confined plasmas. Now, we consider the particle balance for the species s in such plasmas,

$$\frac{\partial n_s(\rho)}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho} V' \left(\Gamma_s^{(\mathrm{NC})} + \Gamma_s^{(\mathrm{Turb})}\right) = \mathcal{S}_s^{(\mathrm{Aux})}, \qquad (1)$$

and the sum of the neoclassical radial particle flux and the anomalous contribution $\Gamma_s^{(\mathrm{NC})} + \Gamma_s^{(\mathrm{Turb})}$ should vanish for each species if the system is in the steady state with negligible auxiliary particle sources and sinks, $\mathcal{S}_s^{(\mathrm{Aux})}$. Therefore, the quantitative kinetic calculations of the particle fluxes are significant for transport analyses of the multi-ion-species plasmas. For the turbulent transport in the plasmas, the linear gyrokinetic analyses were performed [3, 4]. Based on the quasi-linear estimate, using the linear growth rates of the ion temperature gradient mode which is dominant instability in the plasma, it was found that the turbulent particle fluxes including the impurity carbon are negative, i.e., radially inward-directed. On the other hand, the neoclassical particle fluxes are sensitive to the radial electric field, and the external momentum torque by NBI heating can influence the electric field and the particle fluxes [5, 6]. In this work, in order to evaluate the neoclassical particle fluxes and the impacts of the external momentum sources on the impurity transport in LHD plasmas, we perform the drift-kinetic simulations for an impurity hole plasma with the density and temperature profiles of the hydrogen, helium, and impurity carbon, which are evaluated from the experimental results.

In the drift-kinetic analyses, we employ the PENTA code [7], which can treat the mono-energetic transport coefficients to account for momentum conservation for calculation of radial electric field satisfying the ambi-polar condition, $\sum_{s\neq \mathrm{e}} Z_s\Gamma_s = \Gamma_\mathrm{e}$. Here, Z_s is the charge number of the ion species s. PENTA uses Sugama-Nishimura method [8] for deriving the viscous stress tensor in terms of transport coefficients which are calculated by DKES code [9]. To estimate the neoclassical particle fluxes in the presence of the external momentum torques by the NBI heating, we include a source term $F_{\|\mathrm{b}}$ in the parallel momentum balance equation [5] for each particle species. Employing the external torques evaluated from the experimental results based on the ratio of the input power and the densities between each particle species, the radial electric field and the particle transport fluxes are estimated. Here, we investigate the impacts of the external torques by co-injected NBI with three cases, $F_{\|\mathrm{b}} = 0, F_\|^{(\mathrm{nom.})}$, and $5F_\|^{(\mathrm{nom.})}$, where $F_\|^{(\mathrm{nom.})}$ is the nominal value of the torques in the experiment. Figure 1 shows the results in the case of the ion-root, i.e., negative radial electric field. Without the external torque, the neoclassical particle flux of the impurity carbon is quite small and its direction is negative in the inner radial region and positive in the outer region. Even if there exists the external momentum source which diminishes the electric field in the inner region, the changes of the particle fluxes are not large including the

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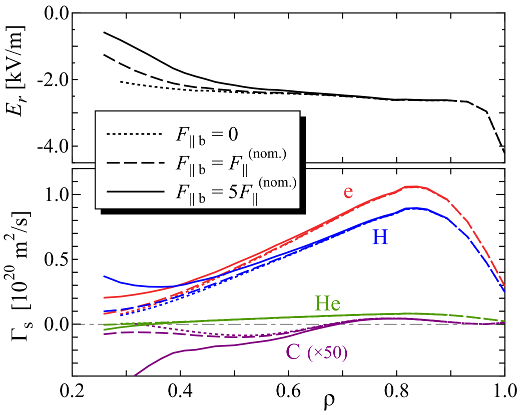

Fig. 1 Radial profiles of electric field and neoclassical particle fluxes of electron (red curves), hydrogen (blue), helium (green), and carbon (magenta, magnified 50 times) in the case of ion-root with the external momentum sources of $F_{\|b} = 0$ (dotted curves), $F_{\|}^{(\mathrm{nom.})}$ (dashed), and $5F_{\|}^{(\mathrm{nom.})}$ (solid). In the plots, the inner region ($\rho < 0.2$) is omitted since there exists large ambiguities in the density profiles.

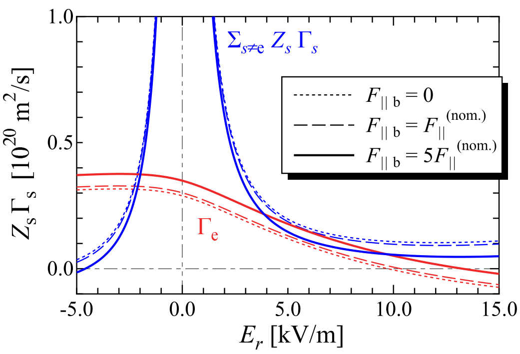

Fig. 2 Dependence of neoclassical particle fluxes of electron (red curves) and total ions (blue curves) to radial electric field with external momentum torques at $\rho = 0.44$. Dotted, dashed, and solid curves show the results for the case of external parallel momentum sources of $F_{\|b} = 0$, $F_{\|}^{(\mathrm{nom.})}$, and $5F_{\|}^{(\mathrm{nom.})}$, respectively.

carbon ion. However, the electric field can be changed further by the external momentum sources. Figure 2 shows the dependence of the neoclassical particle fluxes of electron Γ_{e} and total ions $\sum_{s\neq \mathrm{e}}\Gamma_s$ to the radial electric field changing the external momentum sources. If the external sources are increasing, there are not only the ion-root with negative radial electric field, but also the electron-root with positive radial electric field in inner and outer radial regions. In the case of the electron-root, the particle fluxes of each species can be changed and the impurity carbon flux can be outward-directed as shown in Fig. 3 in not only the outer region but also in the inner radial region where strong hollow density profile is generated. If there exists such outward-directed carbon flux, there is a possibility of existence of the neoclassical particle flux of the impurity which can be balanced with the turbulent flux.

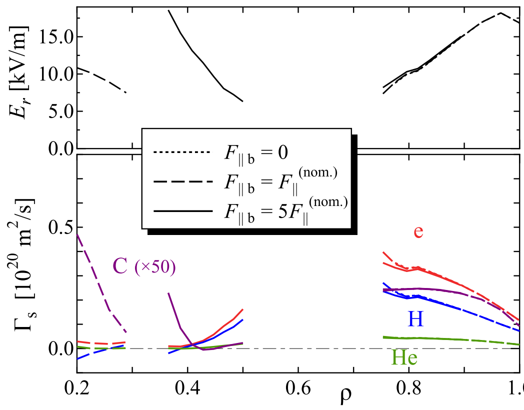

Fig. 3 The profiles of radial electric field and the neoclassical particle fluxes in the case of electron-root electric field. Here, the electron root does not exist in the mid-radial region ($\rho \lesssim 0.75$ for $F_{\|b} = 0$, $0.3 \lesssim \rho \lesssim 0.75$ for $F_{\|}^{(\mathrm{nom})}$, and $0.5 \lesssim \rho \lesssim 0.75$ for $5 \times F_{\|}^{(\mathrm{nom})}$).

In this work, we performed drift-kinetic simulations to investigate the neoclassical contributions of the particle transport and impacts of the external momentum torques on the transport fluxes in the multi-ion-species LHD plasmas including the impurity carbon. While the turbulent particle fluxes are expected to be inward-directed from the quasi-linear gyrokinetic analyses, the external torques can affect the ambi-polar radial electric field and the neoclassical particle fluxes, and the plasma can be in not only the ion-root but also in the electron-root. In the case of the electron-root, the particle flux of impurity carbon can change its direction in the inner radial region. In the neoclassical framework, the positive neoclassical impurity flux can be realized if there exists sufficient external torque by the co-injected NBI heating. On the other hand, it is experimentally expected that the electric field is in the ion-root in the high-T_{i} LHD plasmas [10] that is inconsistent with the electron-root radial electric field. However, the simulations performed here have not yet included other important effects, e.g., the poloidal variation of the electrostatic potential [11], and the direct contributions of the radial beam flux Γ_{b} to the ambi-polar condition, which may produce positive impurity flux even if the plasma is in the ion-root. Of course, the turbulent particle fluxes should be estimated by nonlinear gyrokinetic simulations beyond the quasi-linear estimate, and non-steady analyses for the profile formation due to the imbalance between the neoclassical and turbulent fluxes should be also considered. The studies regarding these points will appear elsewhere.

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