Contribution ID: **657** Type: **Regular Poster**

Global calculation of neoclassical impurity transport including the variation of electrostatic potential

Thursday 13 May 2021 12:10 (20 minutes)

We carried out global calculations of neoclassical (NC) impurity transport in helical plasmas including the effect of variation of electrostatic potential on the flux surface, Φ_1, for the first time. An impurity hole plasma found in LHD experiment is analysed by the global simulation. Contrary to the conventional local approximation models, which indicate negative ambipolar radial electric field (E_r) for the ambipolar condition, the global NC simulation predicts positive ambipolar-E_r and impurity particle flux is driven outwardly, which is even enhanced by Φ_1. If E_r is negative in the global simulation, on the other hand, Φ_1 enhances the inward impurity flux. Our result indicates that the global effect is the key to correctly predict the E_r profile and impurity transport in impurity hole plasmas.

In LHD, the formation of extremely hollow density profiles of impurity ions, such as carbon C^{6+}, in the core region of high T_i plasmas has been observed. This phenomenon is called "impurity hole". Local NC simulations, which neglect radial drift in the guiding-centre equations of motion, find ion-roots (negative E_r) as the ambipolar conditions for such plasmas. These results indicate that highly charged impurities are expected to be driven inwardly, which are contradicting to the observation. Gyrokinetic simulation[1] also predicts that the impurity particle flux is inwardly directed in the impurity hole plasma. In recent studies, it has been shown that the Φ_1 potential, which had commonly been neglected, has significant impact on NC impurity transport[2−4]. Yet, all of those calculations have been performed with local simulation codes, and the necessity of global calculation has been suggested[3,5]. We thus have extended a global NC code FORTEC-3D to include Φ_1.

Besides the studies of the Φ_1-effect, we find an electron-root of the ambipolar condition for the impurity hole plasma by the global simulation. In the high-T_i and low-collisionality regions in which impurity hole is usually found, E_r is relatively weak and the radially local approximation tends to be invalidated by the global effects. Thus, we have investigated the structure of Φ_1 and its impact on particle transport for two different cases, one with an ion-root (local solution) and the other with an electron-root (global solution) E_r, respectively (see Figure 1).

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In Figure 2, the radial carbon particle fluxes for the cases with and without E_r are compared. For the ion-root case, the CΦ_1 flux is driven further inwardly by $^{6+}$. This result is analogous to the local resultsΦ_1. In contrast, the radial flux is outwardly enhanced by [3,4] for the electron-root case. The reason behind the contrast between those cases can be found in the phase structure of carbon density variation. In Figure 3, the phase structure of Φ_1 and the density variation of carbon, Φ_1, on the flux surface at n_{C1} are shown, where $r/a = 0.5$ is the radial coordinate and r is the minor radius of the plasma. Comparing a and Φ_1 between positive and negative n_{C1} cases, respectively, it can be seen that the phase structures of E_r are not largely different but the structures of Φ_1 are inverted in n_{C1}-direction between the two cases. The sign of the radial particle flux driven by θ is determined by the product of the Fourier spectra of Φ_1 and the radial n_{C1}-drift generated by $E \times B$. The phase inversion of Φ_1 in n_{C1}-direction reflects the sign inversion of the leading modes in the θ spectrum. Thus, in order to avoid the negative enhancement of the flux by n_{C1} for the ion-root case, either the phase structure of Φ_1 or Φ_1 has to be strongly modified, but our analysis implies that such radial modifications are unlikely to occur unless strong particle or torque source exists. Thus, our conclusion is that it is difficult for n_{C1} to mitigate the inward CΦ_1 flux in ion-root plasmas.

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Although impurity hole has been observed in several different shots, a measurement on the core $^{6+}$ profile has been reported only for a single caseΦ_1. Plasma profiles used in our study are close to but not the same as those in the measured case. The experimental study shows that while the sign of Φ_1 is indeed negative near the magnetic axis, E_r transits to positive at some outer radius [6]. Our code can be applied to such a case in which E_r changes its sign, which is another advantage over the local codes. The sign of E_r, which is the key to predict the impurity flux, can change in the conditions which are not included in the present simulations. The result of this study suggests the necessity of extension of our code for self-consistent calculation of multi-ion-species transport and the ambipolar condition including $r/a \sim 0.5$.

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Session Classification: P5 Posters 5

Track Classification: Magnetic Fusion Theory and Modelling