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Impurity neoclassical transport analysis in LHD Plasma

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In LHD, spontaneous expel of impurity ions such as C^{6+} from the center of the plasma is repeatedly observed in NBI-heated, relatively high-T_i discharges, which is called "impurity hole" plasma [1]. In conventional neoclassical transport theory, which is based on the radially-local approximation, could not explain the outward impurity flux. Gyrokinetic turbulence simulation predicted inward impurity flux either, when the impurity density profile becomes hollow. Therefore, some other mechanisms are expected to cancel the inward turbulent flux to make and sustain the hollow impurity density profile.

In recent years, we have developed a new neoclassical code FORTEC3D-MPS [2,3], which is non-local and applicable to multi-ion-species plasmas in 3-dimensional magnetic configurations. It also includes the effect of the potential variation on a flux surface, or the ϕ_1-effect, which is important to calculate the neoclassical transport of high-Z ions. Applying the simulation code to impurity-hole plasma analysis, some of new features have been found [2,4] as follows:

1: The ambipolar radial electric field (E_r) profile is negative near the magnetic axis but changes signs to positive at around r=0.2-0.3a, though conventional local calculation predicted all negative E_r profile.
2: The negative-to-positive E_r profile agrees with the observation by HIBP [5].
3: The carbon impurity flux directs outward even in the negative-E_r region. The ion temperature gradient is found to act as outward driving force of impurity flux.
4: The variation of ϕ_1 potential enhances the outward impurity neoclassical flux, and this enhanced outward flux balances with inward turbulent flux in the impurity-hole state.

These findings by the precise neoclassical simulation can explain the mechanism of the impurity hole. However, there are still several things that have not explained by the numerical simulation. For example, it is observed that the impurity hole is more easily created in the magnetic configuration in which magnetic axis is shifted outward, for example $R_{ax} = 3.75$m case than 3.60m case. Since neoclassical transport strongly depends on the magnetic configuration, it is expected that the formation of impurity hole is correlated with the neoclassical transport dependence on the magnetic axis position. Also, experimentally it is found that heavier ion species, such as neon, creates deeper and more clear hollow impurity density hole than lighter species as carbon. This fact also suggests the correlation between impurity hole and the ion-species dependence of neoclassical transport.

To confirm these dependences found in the impurity hole experiments by the neoclassical transport simulation, we carry out several simulations by FORTEC3D-MPS in different magnetic configurations and particle species. To validate the simulations, we also carried out impurity-hole experiments in different conditions in 2021 and 2022. In the previous impurity hole experiments, radial electric field in the core region have been measured only in a few shots. Therefore, in the series of experiments we measured the core radial electric field profile by HIBP system. We found that the negative-to-positive E_r profile found in $R_{ax} = 3.60$m case also appeared in other configuration cases. Comparing the neoclassical carbon ion fluxes simulated in different magnetic configurations, it is found that the carbon outward flux is larger for outward-shifted configuration. It is consistent with the fact that the carbon hollow density profile develops faster in the outward-shifted configuration experimentally. Also, we find that the particle flux amplitude estimated from the observed time change in density profile is the order as the simulated neoclassical flux. These findings support that the neoclassical impurity flux acts the key role in the formation of impurity hole.

In the presentation, more detailed analysis and comparisons between simulations and observation will be reported.

References

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