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Development of a global neoclassical transport simulation for multi species plasmas in helical configuration

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For the realization of steady-state operation of the burning plasma in future fusion reactor, it is crucial to understand and control the transport process of impurity ions in the core plasma. In a fusion reactor, there are several source of impurity ions: He ash born in the core by D-T reaction, W and Fe from divertor and vacuum vessel wall, etc. Accumulation of heavy impurity ions to the core region should be avoided, since they cool down the core plasma by radiation loss.

In ASDEX-U tokamak, it was observed that the central W accumulation was mitigated when a saturated m/n=1/1 kink mode presented in the core [1]. In RFX-mod RFP, plasmas with m/n=1/7 quasi-signle- helicity (QSH) core deformation was found to prevent accumulation of impurities [2]. The helically-deformed state of MHD equilibrium in originally axisymmetric devices appears either as a self-organization process or driven by external magnetic perturbation. It is demonstrated by numerical simulation that such an MHD equilibrium with 3D helical core is possible in tokamak and RFP [3].

Similar mitigation of impurity accumulation is also found in a helical device, LHD. Hollow density profile, or “impurity hole” of carbon impurity, was observed in high-T_i core plasma [4]. Therefore, it is considered that the 3D equilibrium and the transport process in it has some relation with the observed outward impurity transport, of which mechanism is still unknown yet.

Concerning the transport process in 3D MHD equilibrium, neoclassical transport has a relatively large impact compared to that in tokamak. Since ion and electron neoclassical particle fluxes in helical plasma are NOT intrinsic ambipolar, spontaneous formation of the ambipolar radial electric field so that the total radial current vanishes is also an important characteristic of the neoclassical transport in a helical plasma. Neoclassical transport theory and numerical simulations have been used to explain the impurity hole phenomenon. However, neoclassical impurity transport in the condition in which impurity hole appears usually opposes to the observation: inward impurity flux is predicted from neoclassical simulations [4]. Therefore, several models have been proposed to explain the impurity hole, such as the contribution of the turbulent transport [6], extended neoclassical transport model which includes the potential variation on flux surface, or the ϕ_1 potential effect [5], etc. However, even such extended models still have not successfully explained the impurity hole theoretically.

Drift-kinetic equation for multi-ion species plasmas, especially in 3D configuration, requires large computation resource to evaluate the neoclassical transport. Therefore, to our knowledge, previous studies on the impurity transport in helical plasmas have been carried out using a radially-local approximation model of drift-kinetic equation solver. A possible missing piece to explain the impurity hole is a consideration of the finite radial drift of guiding-center motion by using a global drift-kinetic model. From this point of view, FORTEC-3D [7], which solves the global drift-kinetic equation for single ion species plasma in 3D magnetic configuration, is extended for multi-ion species plasmas. Here, we report the first benchmark of the new code.

To treat a multi-ion species plasma, the collision operator in FORTEC-3D is extended for unlike-species collisions. We implement the model of linearized test-particle and field-particle operator proposed by Sugama[8], which possess the adjointness nature of the operator as well as the conservation low in the unlike-species collision, even if the temperature of two species are different. Firstly, these characteristics of the new collision operator is verified. It is demonstrated that the conservation property of particle number, momentum, and energy are satisfied to a rounding error level by using the adaptive field-particle operator and the weight-spreading reduction method, which are also used in the single-species version of FORTEC-3D. Relations between the weight-spreading and Boltzmann’s H-theorem is explained in the presentation.

Secondly, we will demonstrate a multi-ion species neoclassical transport simulation in a LHD configuration. Here, the ϕ_1 potential effect is neglected for simplicity. Comparison with DKES/PENTA[9] code, which can solve a radially-local drift-kinetic equation for multi-species plasmas, are shown. Difference in the ambipolar electric field and impurity transport between local and global neoclassical calculations is examined. Since DKES/PENTA can switch the treatment of the parallel momentum transfer in Coulomb collisions, we investigate the impact of momentum balance property on the impurity transport calculation. Benchmark with another global code for helical plasma, GT5D[10], in a LHD configuration will also be presented.

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