Numerical studies of impurity neoclassical transport in plasma edge region by global full-*f* gyrokinetic simulations

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Impurity neoclassical transport simulations for multi-species plasmas are performed using global full-*f* gyrokinetic code, GT5D, with a newly implemented improved multi-species collision operator. The improved operator is designed to recover the exact friction-flow relations, leading to the accurate prediction of the neoclassical transport. The neoclassical transport obtained with the improved operator is found to resolve the overestimates in the neoclassical transport flux, which appears when one uses the previous model operator. Neoclassical transport in the plasma edge region of a circular tokamak, in which the pressure pedestal is formed and thus the local approximations of the weak temperature/density gradients are violated, are examined by GT5D.

Control of the impurity transport is of particular importance to achieve and maintain a high confinement performance in a fusion reactor plasma, since they can have both positive and negative aspects depending on the amount of the impurity in the different regions of plasma; the seeding of impurities is necessary to increase the radiation in the peripheral region and reduce the divertor heat load; the plasma contamination with the high-Z impurities (e.g. W) from the wall will restrict the operational space of the reactor. Although the plasma transport of bulk plasmas is usually dominated by the turbulent transport, the neoclassical transport caused by the Coulomb collisions can also play a role in predicting the impurity transport and profile since it could become large due to their relatively high collisionalities.

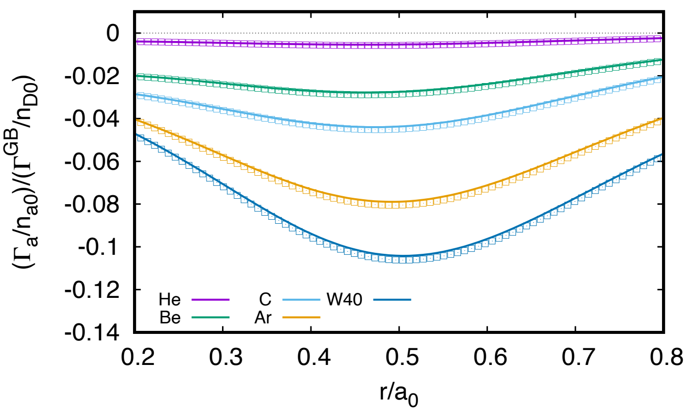

Fig. 1 Neoclassical particle fluxes of impurities (He^{2+}, Be^{4+}, C^{6+}, Ar^{18+} and W^{40+}) in a circular tokamak. Solid line represents the results obtained by Matrix Inversion with the friction coefficients of Landau operator $l_{jk}^{(exact)}$ and symbols with those of OS operator $l_{jk}^{(Sugama)}$, where $\Gamma^{\mathrm{GB}} \equiv n_{D0}\rho_{tD0}^2 v_{tD0}/a_0^2$; n_{D0}, v_{tD0} and ρ_{tD0} are the density, thermal speed, and Larmor radius of deuterium at the initial state.

To understand the behavior of the impurity neoclassical transport and obtain its exact evaluation, the choice of the collision operator is quite important. For this purpose, an improved linearized model collision operator (improved Sugama operator, IS) for multi-species plasmas [1] is recently introduced in a global full-*f* gyrokinetic code, GT5D [2]. While the IS operator retains the conservation laws of particles, momentum, and energy as well as the original model operator [3], it can reproduce the same friction-flow relations derived by the exact linearized Landau operator, which enables us to give more accurate neoclassical transport prediction compared to the original operator [4].

First, the impact of the friction-flow matrix on the impurity neoclassical transport is examined using Matrix Inversion (MI) [5] with two kinds of the friction coefficients l_{jk} (j, k = 1 and 2); one is obtained by using the exact linearized Landau operator (as usually used in the MI) denoted by $l_{jk}^{(exact)}$, and the other $l_{jk}^{(Sugama)}$ is given by the original Sugama (OS), where the friction coefficients of the IS operator $l_{jk}^{(IS)}$ are identical to $l_{jk}^{(exact)}$. The tokamak configuration parameters are based on the Cyclone Base Case (CBC) with the temperature and density gradients $R_0/L_{Ta} = 2.2$ and $R_0/L_{na} = 2.2$, respectively, where a denotes the particle species and a = D, e, He^{2+}, Be^{4+}, C^{6+}, Ar^{18+} and W^{40+}. The particle fluxes of the impurities (He^{2+}, Be^{4+}, C^{6+}, Ar^{18+} and W^{40+}) are shown in Fig.

1. From Fig. 1, we can see that MI with the OS operator predicts slightly large negative particle fluxes for all impurities compared to those obtained by MI with $l_{jk}^{(exact)}$. The differences between two operators are approximately 3-10 %; lighter impurities with the lower collisionalities show larger errors and vice versa. This is because the change in the friction coefficients only appears in $l_{22}^{(exact)} = l_{22}^{(IS)} \neq l_{22}^{(OS)}$, which mainly affects the banana-plateau component rather than the Pfirsch-Schlüter one in the particle flux of MI.

Then, as the improved operator is confirmed to improve the overestimate in the impurity particle fluxes, neoclassical simulations are performed using GT5D and MI for the same circular tokamak above with five impurities of He^{2+}, Be^{4+}, C^{6+}, Ar^{18+}, and W^{40+}. It should be noted the friction coefficients of GT5D with the IS operator, $l_{jk}^{(GT5D,IS)}$, does not agree with $l_{jk}^{(exact)}$ exactly due to the numerical resolution in the velocity space, where $(N_{v\parallel}, N_{v\perp}) = (96, 20)$ is used with $(v_{\parallel a,max}/v_{ta0}, v_{\perp a,max}/v_{ta0}) = (6, 5)$. For example, $j = k = 2$ coefficient for the W-D collision in this case is $l_{jk}^{(GT5D,IS)} = -0.79 \times 10^{-2}$ and $l_{jk}^{(exact)} = -0.74 \times 10^{-2}$. The particle fluxes of the impurities are summarized in Table 1, where the OS and IS operators are used in each code, respectively. It is found that the particle fluxes of GT5D and MI with the improved operator show smaller values than those with the OS operator, which results in the better agreement between GT5D and MI. It is also confirmed that the reduction is more (less) significant for lighter (heavier) impurities as expected from the results of Fig. 1.

Table 1 Normalized neoclassical particle fluxes of impurities $(\Gamma_a/n_{a0})/(\Gamma^{\mathrm{GB}}/n_{D0})$ evaluated at $r/a_0 = 0.5$ of the same circular tokamak as Fig. 1.

Species	MI (OS)	MI (IS)	GT5D (OS)	GT5D (IS)
He^{2+}	-0.465×10^{-2}	-0.427×10^{-2}	-0.612×10^{-2}	-0.591×10^{-2}
Be^{4+}	-0.250×10^{-1}	-0.240×10^{-1}	-0.268×10^{-1}	-0.263×10^{-1}
C^{6+}	-0.415×10^{-1}	-0.404×10^{-1}	-0.431×10^{-1}	-0.424×10^{-1}
Ar^{18+}	-0.826×10^{-1}	-0.808×10^{-1}	-0.841×10^{-1}	-0.829×10^{-1}
W^{40+}	-0.115	-0.112	-0.130	-0.129

Finally, a global transport simulation is performed for a plasma with the pressure pedestal in the edge region of a circular tokamak, where the impurities are the same as Fig. 1 and Table 1, and the IS operator is used. The temperature and density gradients at $r/a_0 = 0.8$ are set as $R_0/L_{Ta} = 2.2$ and $R_0/L_{na} = 5.0$ for all plasma species, respectively, to mimic the pedestal at the edge region. The particle fluxes of the impurities are shown in Fig. 2. In the figure, the particle fluxes of the light impurities (He, Be and C) show the good agreement with those predicted by MI, while the heavy impurities (Ar and W) by GT5D result in the smaller inward fluxes than MI. This suggests that the assumption of $\nabla \cdot \boldsymbol{q}_a = 0$ adopted in the moment approach breaks down due to the higher collisionalities of the heavy impurities, which are proportional to $Z_a^2/\sqrt{m_a}$ (for T_a fixed), where $\boldsymbol{q}_a$ denotes the heat flow. The violation of $\nabla \cdot \boldsymbol{q}_a = 0$ could be significant near the plasma edge, where the plasma becomes highly collisional. It should be noted the banana widths of the impurities $\propto m_a/\sqrt{Z_a}$ are even smaller than that of deuterium, indicating the particle orbits of the impurities are well localized on a flux surface in this case. In the presentation, the impact of $\nabla \cdot \boldsymbol{q}_a \neq 0$ in the impurity transport will be examined for a circular tokamak and JT-60SA. The effect of the plasma shape will be also discussed for the latter.

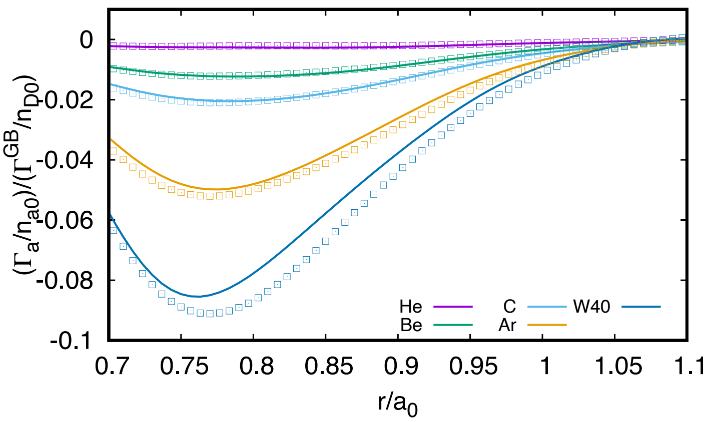

Fig. 2 Neoclassical particle fluxes of impurities (He^{2+}, Be^{4+}, C^{6+}, Ar^{18+} and W^{40+}) in the circular tokamaks with the pressure pedestal ($R_0/L_{Ta} = 2.2$ and $R_0/L_{na} = 5.0$) at the edge $r/a_0 \simeq 0.8$ obtained by GT5D (solid lines) and MI (symbols).

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