§16. Development of Linearized Collision Operator for Multiple Ion Species in Gyrokinetic Simulations

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The magnetically confined plasma should consist of different ion species such as deuterium, carbon, and so on. Therefore, the collisions between different ion species should be taken into account in the turbulent transport simulations satisfying physically properties such as several conservation laws, analytically and numerically. In this work, the linearized model collision operators for multiple ion species[1)] are implemented into a local flux-tube gyrokinetic code, GKV/GKV-X[2, 3)].

The developed operator [4)] is designed for satisfying the conservation laws of particle, momentum, and energy, and the Boltzmann's H-theorem and the adjointness relations, we should estimate the numerical errors of the newly implemented collision operator for the conservation laws and the physical constraints. To estimate the numerical errors, we define an acceptable level of the errors in the local gyrokinetic simulations. Typical GKV/GKV-X simulations require a calculation duration time of $t_{\rm sim} \sim 10^2$ $(R_0/v_{\rm ti})$ to reach the turbulent saturation. If we request an acceptable error $\Delta_{\rm lim}$ of less than 1% over the whole duration, the cumulative error in the calculation with the collision term $t_{\rm sim}|\Delta_{\rm lim}|$ should not exceed 10^{-2}. Thus, we specify $|\Delta_{\rm lim}| < 10^{-4}$ as the upper-limit error. From the test calculations in multi-species plasmas with deuterium, helium and carbon, we confirmed that all the errors are within the acceptable level of the local gyrokinetic simulations. and we also confirmed that the H-theorem is satisfied[1)].

As an application of the implemented collision operator to the gyrokinetic calculations, the collisional linear response of the zonal flow potential are evaluated. The zonal flows are given by an electrostatic potential perturbation that varies in the radial direction but remains constant on the flux-surface. Hence, the zonal flow component is evaluated at $k_y = 0$, where k_y is the perpendicular wavenumber along the poloidal direction. The time evolutions of the zonal flow potential are calculated in the linear response to the Maxwellian initial perturbation solving the linear gyrokinetic equation with the implemented collision operator for single–ion species and the multi-species plasma consists of deuterium, helium and carbon. Here, we assume the electron density perturbation to be given by $\delta n_e = (n_0 e/T_e)(\delta\phi_{k_\perp} - \langle\delta\phi_{k_\perp}\rangle_{\rm ZF})$, and we employ the Cyclone base case configuration with the parameters of $r/R_0 = 0.18$ and $q = 1.42$. Figure 1 plots the linear responses of the zonal flow potential with the radial wavenumber of $k_x\rho_{\rm tp} = 0.1$. In the plots, one finds the geodesic acoustic mode (GAM) frequency is lowered by increase of the effective Z number in the multi-species ion case. For the longer-time response of zonal flows, a certain difference between both cases appears although the difference is small since we adopted a small perpendicular wavenumber, i.e., $k_\perp\rho_{\rm tp} = 0.1$, in the calculation. The results suggest that components of the multi-species plasmas may influence the turbulent transport phenomena by changing the collisionality and the zonal flow response function.

In this work, we implemented of a collision operator for multiple ion species plasma to the gyrokinetic flux-tube code. The developed operator satisfies the conservation laws, as well as the adjointness relations even for collisions among different particle specie within the acceptable error levels in local gyrokinetic turbulence simulations. The newly implemented collision operator is sufficient for practical use in the turbulent transport analysis of fusion plasmas. Therefore, we can treat the collisional effects including multiple ion species for the development of the reduced transport model[5)].

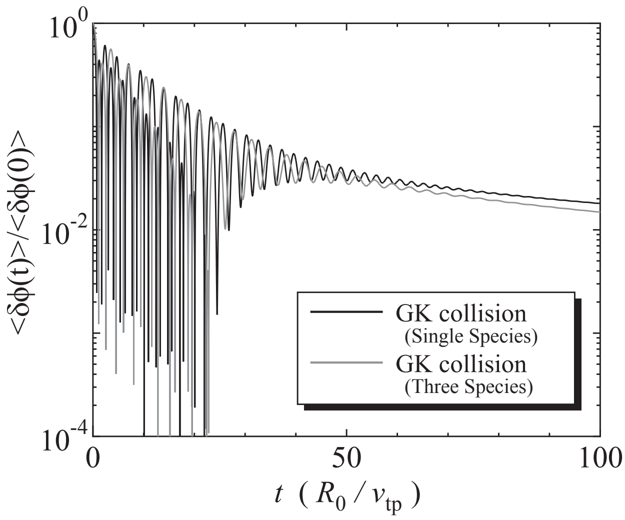

Fig. 1: Collisional linear responses of the zonal flow potentials of the multi-species plasma consists of deuterium, helium and carbon (gray curve). The black curve shows the result in the case of the single ion species. The plots are obtained in $k_x\rho_{\rm tp} = 0.1$.

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