Drift-Kinetic Simulations of Neoclassical Transport*

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A new δf Eulerian kinetic code NEO-GK has been developed for numerical studies of neoclassical transport. NEO-GK serves a dual role: in addition to its practical value as a tool for high-accuracy neoclassical calculations, NEO-GK also functions as a stepping-stone (together with our nonlinear GK code GYRO) toward a full-F gyrokinetic code which integrates neoclassical transport and microturbulence. NEO-GK is based on a hierarchy of equations derived by expanding the fundamental drift-kinetic equation in powers of ρ_*, the ratio of the ion gyroradius to the system size. Thus, unlike NCLASS [1], NEO-GK represents a first-principles calculation of the neoclassical transport coefficients (particle flux, heat flux, bootstrap current, poloidal rotation, etc.) directly from the particle distribution function. NEO-GK extends previous numerical studies by including the self-consistent coupling of electrons and multiple ion species and the calculation of the first-order electrostatic potential via coupling with the Poisson equation. Fully general geometry is included, using either a full numerical equilibrium or the Miller local parameterized equilibrium model [2].

For benchmarking, comparisons of the second-order transport coefficients with various analytical theories are presented. Three model collision operators are compared in NEO-GK: the full Hirshman-Sigmar operator [3], which includes pitch-angle scattering dynamics and energy diffusion, and the reduced Hirshman-Sigmar operator [4] and the Connor model [5], both of which consist of just the sum of pitch angle scattering and momentum-restoring terms. For all three models, the ambipolar relation $\sum_s Z_s \Gamma_s=0$, which can only be maintained with complete cross-species collisional coupling, is confirmed. With the full Hirshman-Sigmar collision operator, we confirm that the widely used Chang-Hinton analytical model [6] overestimates the ion energy flux in the intermediate aspect ratio regime. Agreement with the more accurate Taguchi banana regime model [7] is shown for validation. The reduced Hirshman-Sigmar operator and the Connor model are found to consistently underestimate the ion energy flux in all collisionality regimes. Through comparisons with simulations using an adiabatic electron model, the effects of kinetic electron dynamics on the ion transport coefficients are specifically identified. The effects of heavy impurity ions are also explored and limitations of multi-species collisionally-interpolated analytical theories are discussed. Furthermore, parameterized studies of the effects of shaping are performed using the Miller model. Results using DIII-D experimental profiles are also presented.

Finally, finite orbit width effects are studied via solution of the third and fourth-order drift-kinetic equations. Neoclassical transport near the magnetic axis is explored and the implications of non-local transport on the validity of the δf formulation are discussed.

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*Supported by the US Department of Energy under DE-FG03-95ER54309.