Drift-Kinetic Simulations of Neoclassical Transport *

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A new δf Eulerian kinetic code NEO has been developed for numerical studies of neoclassical transport. NEO serves a dual role: in addition to its practical value as a tool for high-accuracy neoclassical calculations, NEO 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 solves a hierarchy of equations derived by expanding the drift-kinetic equation in powers of ρ_{*i}, the ratio of the ion gyroradius to the system size, and thus provides a first-principles calculation of the neoclassical transport coefficients (particle and heat fluxes, plasma flows, bootstrap current, etc.) for general plasma shape directly from solution of the distribution function. NEO 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.

For benchmarking, comparisons of the second-order transport coefficients with various analytical theories are presented. Three model collision operators are compared in NEO: the full Hirshman-Sigmar operator[1], which includes pitch-angle scattering dynamics and energy diffusion, and the reduced Hirshman-Sigmar operator[2] and the Connor model[3], 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 requires complete cross-species collisional coupling, is confirmed. With the full Hirshman-Sigmar collision operator, we confirm that the widely-used Chang-Hinton analytical model[4] overestimates the ion energy flux in the intermediate aspect ratio regime. Agreement with the more accurate Taguchi banana regime model[5] 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. For pure plasmas, finite mass-ratio corrections due to the collisional coupling are 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 local equilibrium model[6]. Results using DIII-D experimental profiles and including the effects of strong rotation are also presented.

Finally, finite orbit width effects are studied via solution of the second and third-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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