Gyrokinetic Simulations of Neoclassical Flows Embedded in Turbulence*

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GYRO is a comprehensive nonlinear continuum (Eulerian) gyrokinetic code which can treat either gyroBohm scaled flux tubes at vanishing ρ_* or full-radius core profiles at small but finite ρ_*. It contains all the physics presently thought to be needed for physically realistic simulations of the tokamak core: toroidal ion temperature gradient (ITG) mode physics, trapped and passing electrons, electron-ion pitch angle collisions, electromagnetic effects up to the ideal beta limit, real geometry, E×B and magnetic flutter transport. GYRO operating in a nearly full radius slice at finite ρ_* and has both E×B and diamagnetic rotational shear stabilization which can effectively break gyroBohm scaling.[1] Parallel rotational shear drive from the toroidal rotation is also included. GYRO has been used to simulate the DIII-D L-mode dimensionally similar ρ_* pair with Bohm scaling.[2] Using experimental profiles, simulated power flows are within twofold of experimental flows and 10% adjustment of the ion temperature gradients can bring them into agreement. Multiple ion species have been added and impurity and plasma flow studies are underway. Recently neoclassical flows and drivers have been added.

In previous work, Wang *et al*. used a global PIC n=0 gyrokinetic code to simulate large banana orbit neoclassical flows.[3] (n is the toroidal mode number.) The present work includes all n and focuses on the interaction of $|n| \geq 0$ turbulence and n=0 neoclassical flows. Turbulent E×B and magnetic flutter radial transport flows, $\left\langle (\tilde{\upsilon}_E \cdot \nabla r)\tilde{f} \right\rangle$ and $\left\langle (\upsilon_\parallel \tilde{B}_\perp / B_0 \cdot \nabla r)\tilde{f} \right\rangle$ are driven by the ω_* terms $(\tilde{\upsilon}_E \cdot \nabla r)F_M$ and $(\upsilon_\parallel \tilde{B}_\perp / B_0 \cdot \nabla r)F_M$ in the $|n| > 0$ gyrokinetic equations. ($\langle \ \rangle$ denotes flux surface average, $\tilde{f}$ is the perturbation from the Maxwellian distribution function F_M). The neoclassical curvature drift velocity (υ_D) flows $\left\langle (\upsilon_D \cdot \nabla r)\tilde{f} \right\rangle$ are driven by $(\upsilon_D \cdot \nabla r)F_M$ in the n=0 gyrokinetic equation for $\tilde{f}$ when ion-ion collisions are included. Global simulations will approach the cyclic flux tube simulations in the limit of vanishing ρ_*. We denote perturbations by $f_{n,p}(\theta)$ where p is the radial wave number harmonic with p=0 the longest scale. The neoclassical flows and driver involve only (n,p) = (0,0) and turbulence involves all others. In the vanishing ρ_* limit where the parallel nonlinearities vanish, it is easy to show there is no interaction between turbulent and neoclassical transport. Advancing only the (n,p) = (0,0) component (normally excluded from cyclic flux tubes), GYRO can recover the standard small orbit neoclassical radial flows as well as ion parallel flows and bootstrap current. We include an electron-ion drag and test number, energy, and momentum conserving Krook as well as pitch-angle scattering ion-ion collision operators. The radial electric filed is input with density and temperature gradients. There is no perturbed electric field. These flows are then compared with those with the local radially averaged flows in simulations of finite-ρ_* (large banana orbit) global profile slices with and without interaction with the turbulence induced by the finite-n modes. Perturbed electric fields then are obtained from the (polarized) quasi-neutrality equation. We examine the effect of the neoclassical driver on the turbulent transport and n=0 zonal flows.

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