Advances in Comprehensive Gyrokinetic Simulations of Transport in Tokamaks*

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This paper exemplifies recent advances in gyrokinetic simulations of tokamak transport and notes future challenges. GYRO development began in 1999 and reached its major design milestones in 2002 [1]. It is presently the most advanced gyrokinetic code. GYRO is a comprehensive nonlinear continuum (Eulerian) gyrokinetic code which can treat either (i) gyroBohm scaled flux tubes at vanishing ρ_* or (ii) full-radius core profiles at small but finite ρ_*. It contains the physics needed for physically realistic simulations of the tokamak core: toroidal ITG 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. These features are in common with the similar predecessor flux tube continuum gyrokinetic code GS2 [2] and the more recent PIC flux tube code GEM [3] against which GYRO has been successfully benchmarked. Uniquely, GYRO operating in a nearly full radius slice at finite ρ_* has both E×B and diamagnetic rotational shear stabilization which can effectively break gyroBohm scaling [4], as well as parallel rotational shear drive. The versatility of GYRO with either artificial or experimental profile input, and with either flux-tube or global operation, allows many applications, some of which we review here.

The most important finite ρ_* global application and motivation for GYRO development has been the simulations of Bohm-scaled DIII-D L-mode dimensionally similar ρ_* pairs [5] shown in Fig. 1. The simulations use the deuterium mass ratio $m_i/m_e = 3600$. Simulations of varying radial domain sizes (80 ρ_s, 160 ρ_s, 240 ρ_s) show little dependence on domain size at $r/a = 0.6$. The 240 ρ_s domain covered $0.2 < r/a < 0.8$. Using the experimental profiles, the simulated ion energy transport with the full physics activated is about 2x larger than the experimental flows, yet clearly shows the Bohm scaling of the experiment, i.e. the

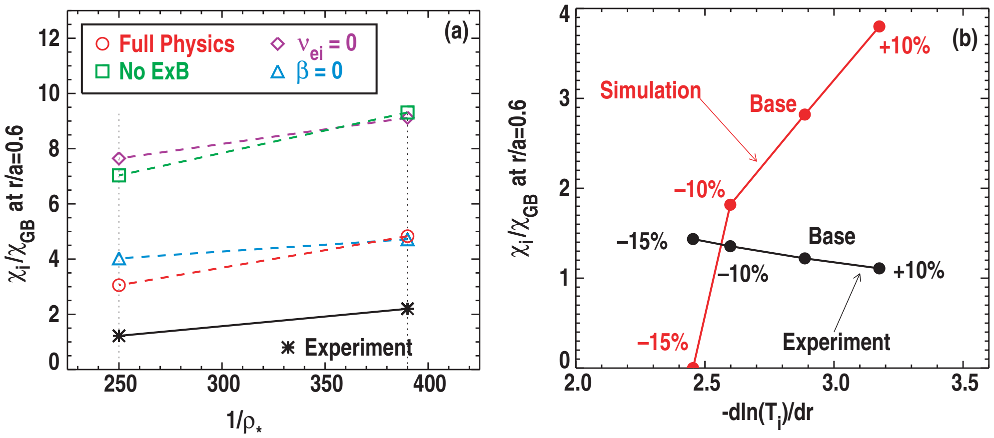

Fig. 1. Simulated and experimental ion energy diffusivities from DIIID L-mode ($\rho_* = 0.0025$ and 0.004) pairs near r/a = 0.6 in (a) and the effect or small changes in the base experimental ion gradients for $\rho_* = 0.004$ in (b).

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diffusivities normed to gyroBohm ($\chi_{GB} = [c_s / a]\rho_s^2$) are 1.6x smaller for the 1.6x larger ρ_* discharge. As indicated in Fig. 1(a), when the equilibrium E×B shear, or finite beta, or electron-ion collisions are removed (each increasing the linear growths compared to the mode velocity shear rates [4]), the ratio in normed diffusivities is closer to unity (gyroBohm). This strongly suggests that the onset of Bohm scaling at large ρ_* observed in experiments can only be understood with physically comprehensive simulations using actual profiles. For example H-modes which typically have larger ρ_*'s than L-modes, yet typically have gyroBohm scaling. Figure 1(b) shows that even core L-mode plasmas are close to a critical ion temperature gradient. A small 10% reduction in the ion temperature gradient brings both the ion and electron energy flows (not shown) into agreement with experiment and a 15% reduction eliminates turbulent transport. Corresponding figures for the electron channel are entirely similar [5] (even though the electron-ion collisional exchange is actually too large to accurately separate the channels). Such reductions are well within experimental uncertainty.

Since IAEA 2002 FEC, GYRO has switched to an implicit-explicit time integrator which is more efficient and stable for large-radial-box simulations. Only the fast parallel motion of the electrons needs be implicit. This now allows simulations with physical ion-electron mass ratios. Fully kinetic impurity dynamics, ion-ion collisions, and a neoclassical driving term have been added. The latter allow simulation of neoclassical flows embedded in turbulence. We plan to determine whether neoclassical and turbulent flows are simply additive as usually assumed. Plasma and impurity flow studies demonstrate thermal pinches and diffusion-velocity pinch impurity flow mechanisms allowing null flows at finite density gradients. Feedback algorithms for tuning temperature and density profiles to match experimentally observed power and particle flows have been developed. This feedback tuning is particularly important for simulating gyroBohm DIII-D H-mode discharges which are very close to the critical ITG gradient, and for staying close to the null plasma flow point typical of large tokamak cores. Contrary to previous work, global GYRO studies of plasmas with a q-minimum (s=0) point show that non-resonant eigenmodes fill the "singular surface gap" and give rise to smoothly increasing transport across s=0 [6]. Thus internal transport barriers can form without s=0 points (e.g. with E×B shear quenching turbulence). GYRO in flux-tube mode has been used to compile a transport database of parameter scans to serve as bench points for theory-based gyrofluid transport code models. Global GYRO has been used to evaluate electromagnetic turbulent dynamos in the neoclassical current-voltage relation [7]. These dynamos appear to drive only a small net current, but GYRO does predict large (and presumably observable) quasi-equilibrium corrugations of the toroidal current density (and temperature gradients) on the scale of a few ion gyroradii. These corrugations are localized to low-order rational surfaces.

Small ρ_* nearly full radius simulations of gyroBohm-scaled ITER cores will be about 10x more computationally expensive than DIII-D simulations but otherwise straightforward. A more formidable challenge is simulation of the steep gradient and high-shear edge pedestal regions with large fluctuations (comparable to background) for which the standard small ρ_* gyrokinetic ordering (neglecting parallel and field solve nonlinearities, non-eikonal cross field derivatives, etc.) breaks down. Our first approach will be to quantify the neglected terms.

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