Comprehensive Gyrokinetic Simulation of Tokamak Turbulence at Finite Relative Gyroradius*

R.E. Waltz , J. M. Candy, and M.N. Rosenbluth
General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA
email: waltz@fusion.gat.com

Over the course of the last three years, a nonlinear continuum gyrokinetic code GYRO [1] has been developed at General Atomics to comprehensively simulate turbulent transport in tokamaks and allow direct quantitative comparisons to the experimental transport flows using actual experimental profiles and parameters. To arrive at this goal, GYRO not only treats the now standard ion temperature gradient (ITG) mode turbulence, but also treats trapped and passing electrons with collisions and finite beta, and all in real tokamak geometry. Most importantly the code operates on a radial grid at finite relative gyroradius $\rho^* = \rho_s/a$ so as to treat the profile shear stabilization effects which break gyroBohm scaling: $\chi \propto \chi_{gB} = \chi_{Bohm} \cdot \rho^*$. ($\rho_s$ is the ion gyroradius and a is the outer minor radius.)

GYRO is designed specifically to treat the dependence of tokamak turbulent transport on ρ^* - a crucial parameter in scaling to reactors. While similar to the continuum gyrokinetic code GS2 [2], which effectively operates at vanishing ρ^* within a cyclic flux tube of infinitesimal small cross section and produces only gyroBohm scaled diffusion, GYRO can operate in a cyclic as well as radially noncyclic tube of finite size. The latter operation allows the addition of profile variation across a radial annulus and introduces a shearing in the mode phase velocities. It is now well established that shear in the equilibrium E×B velocities have a strong stabilizing effect on the plasma turbulence when the velocity shear rate is comparable to the maximum linear mode growth rate [3]. Shearing in the intrinsic mode phase velocities from variation in the plasma profiles (even without the E×B Doppler component) has a similar effect [3]. Apart from the E×B rotation driven by toroidal flows, the velocity shear rate from profile variation are proportional to ρ^* and the linear mode growth rates are independent of ρ^*. The competition between these rates results in the basic paradigm for broken gyroBohm scaling first explored by Garbet and Waltz [4]. The paradigm has a mixed power law scaling in ρ^*: $\chi \propto \chi_{gB}(1 - \rho^*/\rho^*_{crit})$. The ρ^*_{crit} for complete stabilization (as in an H–mode edge layer or internal transport barrier) is larger when far above threshold, where growth rates are larger. Thus Bohm scaling is apparent only when χ/χ_{gB} approximates a $1/\rho^*$ dependence over some limited range of ρ^*.

Figure 1 illustrates the paradigm with GYRO simulations [5]. Cases shown are for circular geometry ITG adiabatic electrons near threshold [$\eta_i = \hat{L}_n/\hat{L}_T = 1.3$ where $\hat{L}_T^{-1} = a(d\ln T/dr)$] with progressively larger profile shearing [S = 2, 4 and 6 e.g., with $[\hat{T}](r) = (1 - r^S)^\alpha/(1 - r_o^S)^\alpha$ where $\alpha = (1 - \hat{r}_o^S/S\hat{r}_o^{(S-1)})\hat{L}_T^{-1}(r_o)$]. Note that at low ρ^* the diffusivity will approach gyroBohm scaled $\chi \propto \chi_{gB}$ result obtained without profile variation. The noncyclic boundary condition on the radial annulus enforces zero value on the perturbations. We have verified that when profile variation is turned off (all r-dependent plasma parameters, including the logarithmic gradient lengths, fixed to their values at the reference point r/a = 0.5), simulations with the noncyclic boundary conditions recover the cyclic flux tube gyroBohm scaled diffusion. This insures that the radial slice noncylic boundary conditions are benign. When profile variations are present, an “adaptive source” is used to maintain the equilibrium profiles and prevent “false” Bohm scaling which can result because long scale

*Work supported by U.S. Department of Energy under Grant No. DE-FG03-95ER54309.

relaxation of the driving temperature gradients increase with ρ*. In these examples Bohm-scaling $\chi/\chi_{gB} \propto 1/\rho^*$ is obtained only near r/a ≤ 0.5 [see Fig 1(b)]. At outer radii (e.g. r/a = 0.65) gyroBohm scaling obtains because growth rates greatly exceed the shear rates there. In the Bohm (gyroBohm) regime we that find the radial correlation length scales as $a\rho^{*1/2}$ ($a\rho^*$). We have also shown that the diffusion at r/a=0.5 in the Bohm regime can be significantly influenced by changes in the driving temperature gradients at radial distances more than four (density) correlation lengths away. It is thought that this “action at a distance” results from the very long [O(a)] correlation lengths of the n=0 “zonal flow” perturbations. In other examples with less peaked density and less profile shearing, we find gyroBohm scaling over the whole radial annulus and we show that the local diffusion is independent of annular extent simulated.

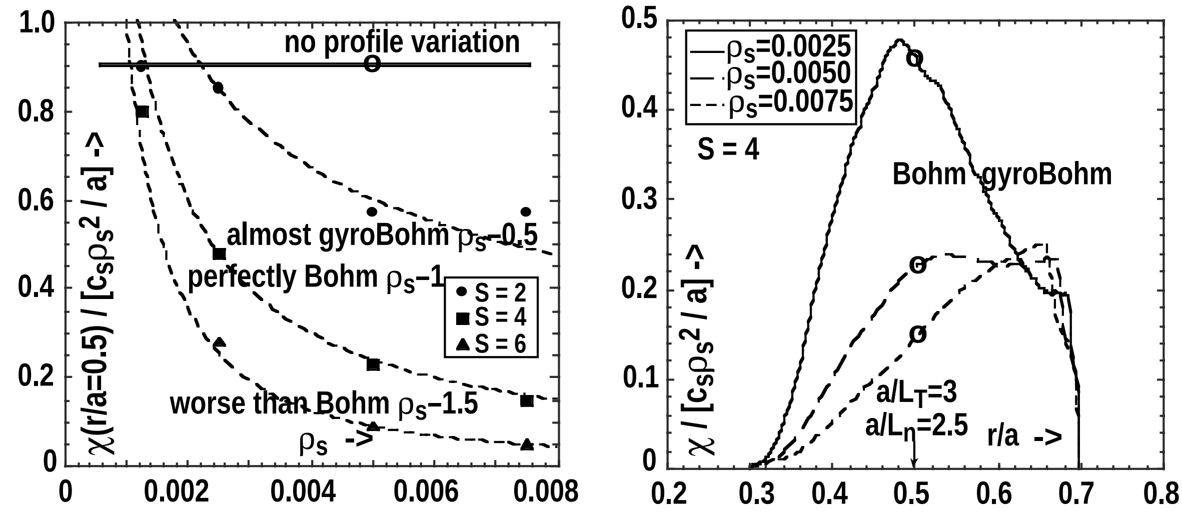

Fig. 1. Ion heat diffusivity normed to gyroBohm versus ρ* at the reference radius r/a = 0.5 in (a) and versus minor radius r/a in (b). R/a=3, q=2, s=1, a/L_T=3, a/L_n=2.5, and T_e/T_i=1, at r/a=0.5. For a=1 $\rho^* = \rho_s$. The E×B shear is derived from the density profile assuming no toroidal rotation.

A key focus of the work to be presented is direct quantitative comparison of comprehensive simulations to the DIII–D L–mode ρ* scaling experiments which had broken gyroBohm scaling and exceptionally well matched dimensionally similar discharge pairs [6]. This will serve not only as the ultimate test of gyrokinetic simulations but also the paradigm for broken gyroBohm scaling described above. Real geometry, trapped and passing electrons with finite beta and collisions, and actual E×B beam driven rotational profiles are used. The real geometry methods use the Miller local MHD equilibrium parameterization [7]. Simulation profiles of both ion and electron energy (and particle) diffusivites or the resultant power flows are directly matched with the experimental. We treat a core region (near r/a = 0.5) and an edge region (near r/a = 0.8) more accessible to some diagnostics. Crucial to the match are the stabilizing effects of profile variation and a careful treatment of experimental error bars on driving temperature gradients and E×B shear profiles.

[1] J.M. Candy and R.E. Waltz, “An Eulerian Gyrokinetic-Maxwell Solver” submitted to J. Comp. Phys.

[2] W. Dorland, B.N. Rogers, F. Jenko, et al., Proc. 18th IAEA Fusion Energy Conference, Paper TH2/5.

[3] R.E. Waltz et al Phys. Plasma **2**, 2408 (1995 also **5**, 1784 (1998).

[4] X. Garbet and R.E. Waltz, Phys. Plasma **3**, 1898 (1996).

[5] R.E. Waltz, J.M. Candy, and M.N. Rosenbluth, Phys Plasmas May 2002.

[6] G.R. McKee, C.C. Petty, R.E. Waltz et al., “Relating Nondimensional Scaling of Microturbulence to Global Confinementand Transport,” Proc. 18th IAEA Fusion Energy Conference, Paper EX6/5.

[7] R.L. Miller, M.S. Chu, J.M. Greene, Y.R. Lin-Liu, and R.E. Waltz, Phys. Plasma 5, 973 (1998); also R.E. Waltz and R.L. Miller, Phys. Plasma 6, 4265 (1999).