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Abstract

The Numerical Tokamak Project undertook a code comparison using a set of TFTR tokamak parameters. Local radial annulus codes of both gyrokinetic and gyrofluid types were compared for both slab and toroidal case limits assuming ion temperature gradient mode turbulence in a pure plasma with adiabatic electrons. The heat diffusivities were found to be in good internal agreement within ±50% of the group average over five codes.

In March 1994, the Numerical Tokamak Project (NTP) completed a code comparison using a set of standard case parameters from TFTR suggested by G. Hammett and M. Zarnstorff (PPPL). In 1992-93 many groups participating in the NTP were doing electrostatic ion temperature gradient mode turbulence simulations with adiabatic electrons and pure ion plasmas. While this does not encompass many aspects of turbulence in tokamaks, it is believed to be a good initial paradigm with easily standardized physics. This made the problem well suited to a code comparison.

The compared codes are of three types: gyro-landau fluid (GLF) presented by Beer, Dorland, and Waltz; gyrokinetic particle (GKP) presented by Byers, Dimits, Sydora, and Santoro; and gyrokinetic fluid (GKF) presented by Wong. The details for most of these codes may be found in the references below. Two types of simulations were compared: "slab" and "toroidal", the former with curvature and ∇B drifts and the magnetic mirroring force excluded. These particular codes also have the important common feature that they are all local homogeneous turbulence models and represent the turbulence in a narrow radial annulus with cyclic boundary conditions: eddies leaving one side cyclically enter the other. This is believed at present to be a reasonable first approximation if the eddies and radial correlation lengths are small compared to the radial width of the box and the temperature gradient lengths. As long as the simulations are insensitive to the numerical grid density, the transport must then scale to the gyro-Bohm unit $c_s\rho_s^2/L_T$ where $c_s = (T/m_i)^{1/2}$ is the sound speed and $\rho_s = c_s/\Omega$ is the ion gyroradius ($T_e=T_i$) with the ion cyclotron frequency $\Omega= eB/m_ic$ and L_T the temperature gradient length. Furthermore, the cross-field wavelengths scale to ρ_s, and the growth rates and frequencies scale to c_s/L_T. Thus we have a convenient system of units. This annulus approach has the added virtue that it is easy to hold the temperature gradients fixed and avoid any quasilinear relaxation of the gradients driving the turbulence. These are all features which allow easy standardization of the problem. We expect that future work with global codes, which allow turbulent energy to leave local annuli and the eddy sizes to be influenced by variation in the plasma conditions across the radius, will be required to determine the scaling with ρ_s/L_T. All the codes presented here are believed to have gyro-Bohm scaling.

The inclusion of "radial" modes was found to be an important physics consideration required to get meaningful comparison. These modes have toroidal mode number n=0 (and m=0, ±1). In a slab model the "radial" modes correspond to those modes with $k_z=k_y=0$ and $k_x\neq0$. They correspond to nonlinearly driven $\mathbf{E}\times\mathbf{B}$ rotational shears that have an important stabilizing effect on the turbulence. (They also provide local steepening and flattening of the driving temperature gradient.). The physics of these modes appears to be crucial and the adiabatic electron assumption must be carefully specified by $\tilde{n}/n_0=(e/T_e)(\phi-\langle\phi\rangle)$ where $\langle\phi\rangle$ is a field-line-averaged potential. All the simulations presented made these common assumptions.

The parameters of the code comparison are from a deuterium TFTR L-mode (Shot No. 41309) [S.D. Scott, et al, Phys. Fluids B **2**, 1300 (1990)] at mid radius $r/a=0.576$. The relevant parameters for the simulations are $\eta_i=L_n/L_T=4$, $T_i/T_e=1$, $q=2.4$, $\hat{s}=(d \ln q \ / \ d \ln r)= 1.5$, $R/L_T=10$. For the slab simulations, only the combination $L_T/L_S=0.0625$ where $L_S=Rq/\hat{s}$ enters. Other parameters of interest are $\rho_s/L_T=0.0056$, $R/a=2.8$, $a=0.92$m, $B=3.8$T, $n=3.3\times10^{19}$ m^{-3}, $Z_{eff}=2.2$. A TFTR supershot (Shot No. 44669) has previously been the focus of detailed analysis [W. Horton, D. Lindberg, et al., Phys. Fluids B **4**, 953 (1992)].

The experimental effective heat diffusivity was $2.2\ c_s\rho_s^2/L_T$. Again we caution that the codes are considering the idealized case of a $\beta=0$ pure ion plasma with adiabatic electrons. Impurity gradient effects are known to have important stabilizing effects, and trapped electrons are known to have important destabilizing effects under these particular plasma conditions. Thus, any close proximity to this value of heat diffusivity from the codes may be fortuitous.

The slab simulations are presented in Table 1 and the toroidal simulations in Table 2. Figures 1 and 2 present the corresponding results for the heat diffusivity in graphical form. In the slab case, the diffusivity is within ±50% of the average (0.0275) (excluding Byers' result) and in the toroidal case also within ±50% of the average (0.817). Considering the deviations from different mesh sizes, the fluctuations in the time histories, the statistical noise in the GKP simulations, and the fact that scaling is of more interest than exact magnitude, *we regard this as good agreement !* Note that the toroidal results are consistently 20-30 fold larger than slab results because of the important curvature and ∇B destabilization. The toroidal results are comparable to experimental diffusion levels as we would hope.

Slab case comparisons among codes at PPPL are discussed in detail in Parker et. al. [Phys. Plasmas **1**, 1461 (1994)]. Discussing the toroidal case in somewhat more detail here, the growth rates of the fastest mode are within ±30% of the average (0.0375). The result from an accurate gyrokinetic stability code GKS [M. Kotschenreuther, Bull. Am. Soc **37**, 1432 (1991)] is 0.0336. The deviation in the diffusivity does not necessarily follow the deviation in the growth rate. In some cases one model is known to be better than another. For example, Beer used a 6-moment GLF model which gives excellent agreement with the GKS code, whereas Waltz used a simple 4-moment model which is known to give lower growth rates. There is also some dependence of the results on spatial resolution characteristics: for example, Waltz obtained 28% higher diffusion with a 3× more dense wavenumber mesh. Differences in diffusion, however, were not always accounted for by mesh, model, or technique. For example, Beer and Waltz made a separate comparison with an identical 4-moment GLF model with the same spectral resolution, obtaining exactly the same linear spectrum (with 1% differences in growth rates), but Beer's result was about 30% systematically *lower* than Waltz's result for the diffusivity.

For completeness, Table 3 contains some of the computational details on grid sizes, particle numbers, timings, etc. All cases were run on the C-90 at NERSC. Several of the codes have been run on the CM-200 and CM-5 at the Advanced Computing Laboratory at Los Alamos National Laboratory. In the process of doing the code comparisons, it was discovered that using the same spatial filtering algorithm was important in bringing the results into closer quantitative agreement. The code comparison activity was also instructive in determining convergence characteristics with respect to mesh resolution and particle statistics. One should note that in Table 3 the GLF simulations of Beer and Waltz use a significantly smaller number of modes than do the GKP simulations of Parker and Dimits. This apparent difference is deceptive, however. The GKP simulation model uses a spatial grid on which charge densities are obtained by interpolation from the particle positions and from which forces are interpolated back to the particle positions to accelerate the particles, while the GLF model uses a spectral model. Because of the grid, short wavelength modes in the GKP model are distorted. The grid-induced distortion scales as $(k\Delta x/2)^2$, and roughly half of the Fourier modes in each spatial dimension are significantly distorted. The use of spatial filtering also limits the amount of the wavelength spectrum that is undistorted. Thus, the number of weakly distorted mode pairs in Table 3 for the GKP simulation models is less than 1/4 of the number of pairs given there; and the spatial resolutions of the GKP and GLF simulations are comparable.

Acknowledgment

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Table 1. Slab Simulations

Research Group	Dorland	Waltz	Byers	Sydora	Santoro	Parker
code type	GLF	GLF	GKP	GKP	GKP	GKP
$\chi L_T/(c_s \rho_s^2)$ average	0.033	0.040	0.11	0.015 ±0.005	0.02	0.03
$\chi L_T/(c_s \rho_s^2)$ 1st time peak	0.044	0.02-0.08	0.11	0.03-0.05	–	–
$(e\phi/T) L_T/\rho_s$ rms	0.25	0.55	1.4-0.3	0.18	0.01	0.25
$k_\theta \rho_s$ spec. peak	0.3	0.5	0.25	0.4	0.2	–
$\gamma L_T/c_s$ fastest mode	0.015	0.012	0.011	0.02	0.015	0.019
$\omega L_T/c_s$ fastest mode	-0.042	-0.048	-0.052	-0.05	-0.051	-0.05
$k_\theta \rho_s$ fastest mode	0.5	0.5	0.5	0.5	0.5	0.5
$(\Delta x/\rho_s)_{rms}$ fastest mode	1.25	0.93	1.5-2	2	2	–
η_{i_crit}	–	2.5	1.6	2.1	1.5	–

Table 2. Toroidal Simulations

Research Group	Beer	Waltz	Parker	Wong	Dimits
code type	GLF	GLF	GKP	GKF	GKP
$\chi\, L_T/(c_s \rho_s^2)$ average	1.2	0.553	0.73	1.0	0.6
$\chi\, L_T/(c_s \rho_s^2)$ 1st time peak	_	0.27-1.0	_	_	0.6
$(e\phi/T)\, L_T/\rho_s$ rms_flux avg	2.5	1.8	4		2.2
$k_\theta \rho_s$ spec. peak	0.15	0.2	0.1	_	0.1
Flow asymmetry out : in	_	10 : 1	_	_	_
Turbulence out : in	2 : 1	3 : 2	_	_	_
$\gamma\, L_T/c_s$ fastest mode	0.035	0.023	0.047	0.04	.045
$\omega\, L_T/c_s$ fastest mode	-0.16	-0.136	-0.18	-0.15	-.085- -.13
$k_\theta \rho_s$ fastest mode	0.45	0.4	0.49	0.45	0.37-0.49
η_{i_crit}	2.7	2.9	_	_	<2.5

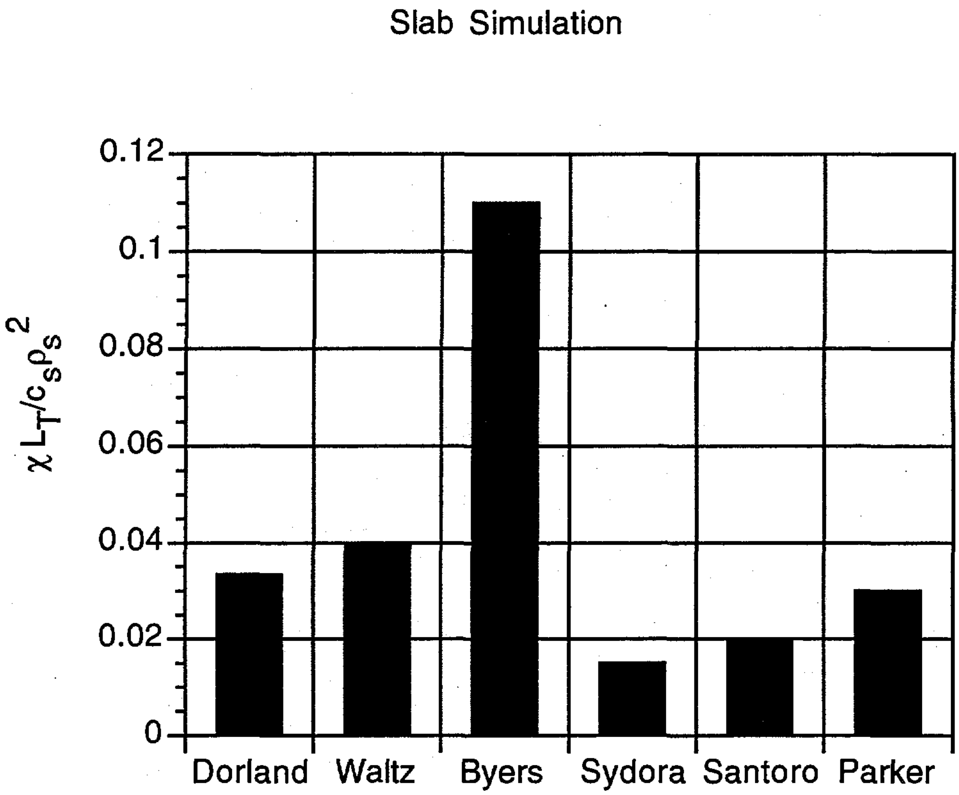

Figure 1. Slab simulations. Excluding Byers all results with ±50% of group average value 0.0275.

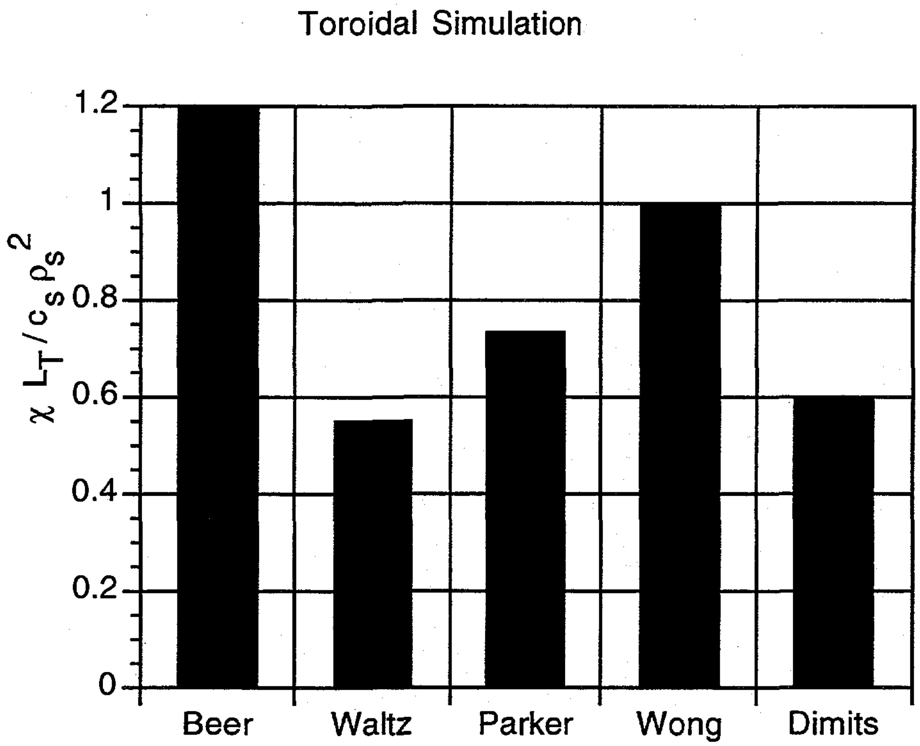

Figure 2. Toroidal Simulation. All within ±50% of group average value 0.817.

Table 3. Computational Parameters

Research Group	Beer	Waltz	Parker	Wong	Dimits
time step×c_s/L_T nonlinear phase	0.04	0.18	0.1	0.064	0.2
number of steps	16000	15000	2000	_	4000
CPU/step (sec)	2	1	4.2 (1 proc.)	_	6-12 (1 proc.)
total CPU (hrs)	12	4	2.8 (1 proc.)	_	7
wall clock turn around	3-4 4cpu	6 1.5cpu	0.2 (14 cpu)	_	0.4 -0.8 (12 cpu)
code size (MW)	27	40	20		54-107
radial grid= j	96	64	64	_	64-128
no. (m.n) or (ky,kz) pairs=k	1318	850	4096	_	2000-8000
no. particles=p	0	0	0.5M	_	2M-4M
size and time= j × k+p	j × k	j × k	j × k +p	_	j × k +p
$k_\theta\rho_s$_max	0.951	1.0	_	_	3
$k_\theta\rho_s$_min	0.063	0.1	_	_	0.125

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