33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, O-3.001 (2006)

Global Nonlinear Gyrokinetic Simulations of ETG turbulence using particles

A. Bottino[1], A.G. Peeters[1], R. Hatzky[2], T.M. Tran[3],
P. Angelino[3], S. Jolliet[1], E. Poli[1], O. Sauter[3] and L. Villard[3]
[1] *Max Planck Institut für Plasmaphysik, IPP-EURATOM Association, Garching, Germany*
[2] *Computer Center of the IPP and Max-Planck-Gesellschaft, Garching, Germany*
[3] *Centre de Recherches en Physique des Plasmas, EPFL, Lausanne, Switzerland*

Electron temperature gradient (ETG) driven turbulence may be responsible for the high level of residual electron transport observed in many tokamak internal transport barrier experiments. However, ETG turbulence can be experimentally relevant only if nonlinear saturation mechanisms lead to transport level higher than quasi-linear mixing length estimates. Quantitative ETG transport predictions made with nonlinear flux-tube simulations [1] indicate large level of radial heat transport ($\chi_e \simeq 13\chi_{gB}$). Such a high transport has been attributed to the presence of radially elongated turbulence structures (streamers) and to the consequent $E \times B$ convection. However, recent global particle-in-cell (PIC) simulations [2] yielded a much lower level of anomalous transport as compared to local flux tube Eulerian codes [1]. Radially elongated streamers which scale with the device size have been identified but their impact on the radial transport was found to be small. Two possible explanations have been proposed to justify this discrepancy: a new nonlinear saturation mechanism associated with toroidal mode coupling [2] and the influence of the non-physical statistical noise due to the particle discretisation [3]. The latter paper shows that in PIC simulations a large level of noise can reduce the ETG turbulence induced transport and can determine the saturation level of the instability. In this paper we use the global electrostatic collisionless gyrokinetic δf PIC code ORB5 to address the following issues:

- Level of radial transport and ρ_e^* scaling in global, large ρ_e^* simulations of ETG turbulence.
- Influence of the statistical noise on ETG driven transport.
- Scaling and saturation of the streamers with the machine size (ρ_e^*) and physical parameters.
- Investigation of the nonlinear toroidal mode coupling saturation mechanisms.

The code ORB5 solves the gyrokinetic equations of Hahm, using particles and the Poisson equation using finite elements on a fixed grid. In ETG ORB5 simulations ions are assumed to be adiabatic. Equilibrium n and T_e profiles self-consistently evolve in time. The code ORB5 uses several techniques of statistical noise reduction including optimised particle loading and Fourier filtering. Basic physical conservation properties (energy and particle number) can be used as indicators of the quality of the numerical simulations. Figure 2 (a) shows the temperature gradient evolution (R/L_T) for a $\rho_e^* = 1/450$ circular plasma. The value of R/L_T decreases in time in the region of maximum gradient and increases radially toward plasma edge and centre (radial spreading). In all the simulations presented in this paper, safety factor, density profile and aspect ratio have the nominal CYCLONE base case values, while $R/L_T(r/a = 0.5) = 8$. Time is measured in $[a/v_{Te}]$ units and the radial variable is $s \equiv \sqrt{\Psi_{\text{pol}}}$; 512 millions of numerical particles have been used for the $\rho_e^* = 1/450$ full torus simulation. In all the simulations the formation of radially elongated streamers is observed (Fig. 1 (a)). The radial length of the streamers does not converge in time and covers the entire radial region where drive is present, i.e. $R/L_T > R/L_{T,\text{crit}}$ (red vertical lines in Figs. 1 (a) and 2 (a)). Therefore, the radial extent of the streamers depends on the choice of the initial temperature gradient profile. The average value of R/L_T and of the diffusion coefficient χ/χ_{gB} (radial average over $0.52 < s < 0.62$) is plotted in Fig. 1 (b). During the overshoot the temperature gradient strongly relaxes and falls below the nominal value of the CYCLONE base case $R/L_T = 6.9$. For $t > 80$, R/L_T slowly decays from $R/L_T \simeq 6.5$ ($\chi/\chi_{gB} \simeq 17$) to $R/L_T \simeq 5.8$ ($\chi/\chi_{gB} \simeq 8.5$). Extrapolation for $R/L_T \simeq 6.9$, considering only the slow decay phase, $t > 100$, gives $\chi/(v_{Te}\rho_{Te}^2/L_T) \simeq [10:15]$ (Fig. 1 (c)) in agreement with flux-tube simulations. The time evolution of the poloidal wave number spectrum (Fig. 2 (b)) is consistent with the PIC simulations of Ref. [2]. The nonlinear downshift shifts the most unstable modes from $0.2 < k_\theta \rho_{Te} < 0.4$ during the linear phase to $0.1 < k_\theta \rho_{Te} < 0.3$ at the end of the simulation. Simulations presented in Fig. 3 (c) show that in the range $160 < \rho_e^{*-1} < 450$ the scaling of the transport is not gyro-Bohm. Note that in Ref. [2], where a gyro-Bohm scaling of ETG transport was identified, smaller values of ρ_e^* ($500 < \rho_e^{*-1} < 2000$) have been used.

In PIC codes the numerical particles (tracers) are projected on a fixed grid in order to provide the source term for the Poisson equation. The “statistical noise” is related to the error introduced when the moment of the distribution function is computed using a finite number of tracers in

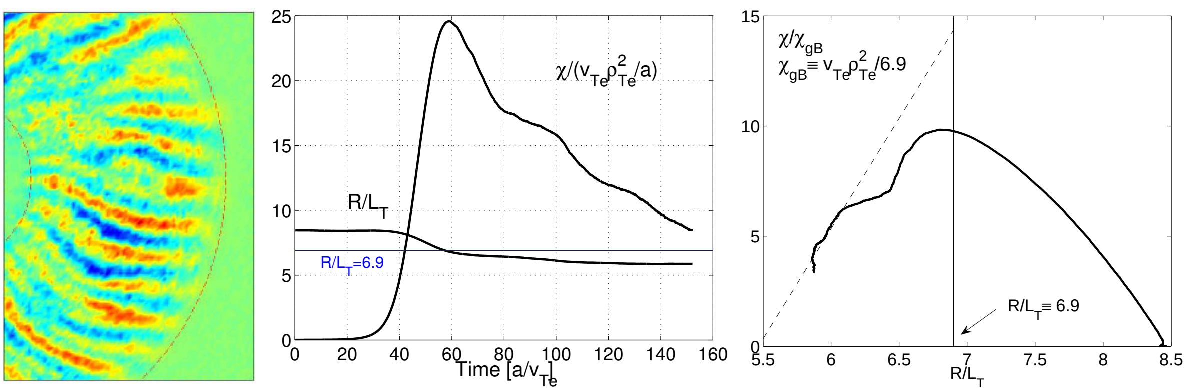

Figure 1: (a): electrostatic potential at $t = 140$ $[a/v_{Te}]$, $\rho_e^* = 1/450$. (b): time evolution of radial averaged R/L_T and χ/χ_{gB}. (c): χ/χ_{gB} (in $L_T = 6.9$ units) versus R/L_T; dashed line, linear fit for $t > 100$.

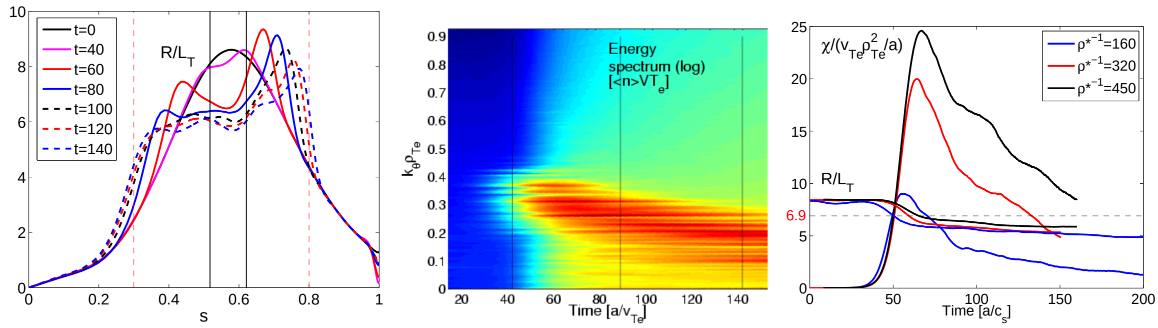

Figure 2: (a): Evolution of the electron temperature gradient in time, $\rho_e^* = 1/450$. (b): $E \times B$ energy spectrum in poloidal wave number. (c): ρ_e^* scaling: time evolution of radial averaged R/L_T and χ/χ_{gB}, $\rho_e^* = 1/450$.

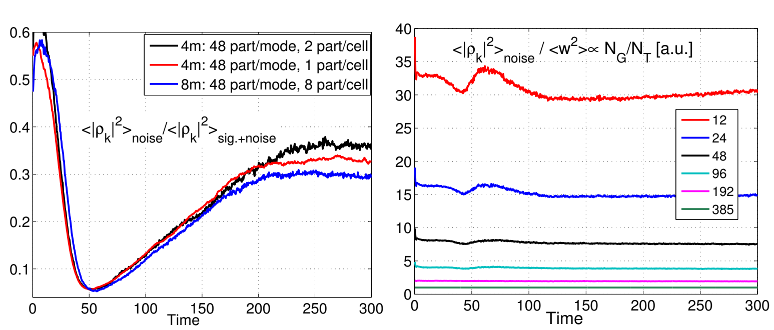

Figure 3: $\rho_e^* = 1/80$ (a): Noise to signal ratio for different simulation with same number of tracers per mode. (b): scaling of the noise in N_g/N_T. (c): level of noise as a function of the projection algorithm.

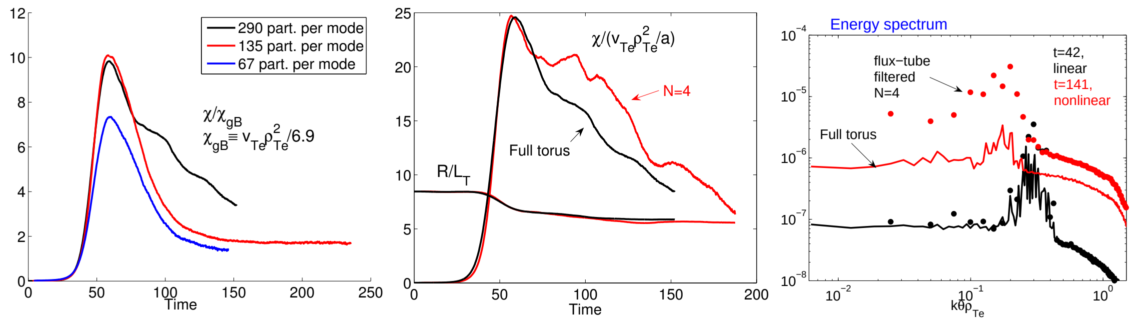

Figure 4: (a): time evolution of χ/χ_{gB} and R/L_T for different N_T/N_G, $\rho_e^* = 1/450$. (b): $k_\theta \rho_e^*$ spectrum for full torus and N=4 flux-tube filtered simulations. (c): time evolution of χ/χ_{gB} and R/L_T $(N = 4)$.

phase-space [4]. The Monte Carlo theory allows for estimating the contribution of the noise to the charge density ρ:

$$\rho^2_{\text{noise}} \simeq \frac{N_G}{N_T}\langle w^2\rangle G \ ; \qquad \langle w^2\rangle \equiv \frac{1}{N_T}\sum_{i=1}^{N_T} w_i^2 \tag{1}$$

where N_T is the number of tracers and N_G is the number of modes kept in the simulation. The function G accounts for additional filtering coming through finite Larmor radius effects and the grid projection algorithm. In ORB5 the charge is projected on the fixed grid by means of cubic B-splines. Equation (1) indicates that the statistical noise can be reduced either by increasing the number of tracers ($\sqrt{N_T}$ convergence) or by reducing the number of Fourier modes kept in the simulations (Fourier filtering of non-resonant modes). In addition to this, an important role is played by the control of the evolution of the variance of the distribution of the weights $\sigma \propto \langle w_i^2 \rangle$ (optimised loading). A new diagnostic has been implemented in the code which allows for a direct measure of the ρ_{noise} based on the average amplitude $|\rho_k|^2$ of the non-resonant (filtered) modes. Figure 3 (b) shows the scaling of the statistical noise as a function of the number of particles per mode, N_T/N_G. The scaling is in excellent agreement with the estimate of Equation (1). Moreover, the scaling of the noise with the number of particles shows that the important parameter in PIC simulations is indeed the number of particle per Fourier mode and not the number of particles per grid cell (Fig. 3 (a)). The importance of the choice of the projection algorithm is illustrated in Fig. 3 (c). Results not included in this paper show that linear B-spline simulations require in average four times more particle to recover the same level of noise as compared to cubic B-spline simulations.

The statistical noise reduces the level of transport driven by ETG turbulence, as illustrated in Fig. 4 (a). In addition to the reduction of linear drive proposed in Ref. [3], statistical noise can create spurious zonal flows. The ρ_e^* values used in this work are too large to verify the existence of the toroidal mode coupling saturation mechanism. However, flux-tube filtered simulations ($n = 0, \pm N, \pm 2N, \ldots$) keeping fixed N_G/N_T do not show significant differences in the downshift of the $k_\theta \rho_{Te}$ spectrum (Fig. 4 (c)). However, the level of transport is slightly higher as compared to full torus simulations as it is illustrated in Fig. 4 (b) for a $N = 4$ flux-tube filtered simulation.

In summary, global PIC simulations of freely decaying ETG turbulence ($\rho_e^* = 1/450$) show level of transport comparable with flux tube simulations when the statistical noise is sufficiently low. In global PIC simulations statistical noise reduces ETG driven transport and the level of noise scales with the number of particles per mode but the scaling coefficient strongly depends on the algorithms used in each code. Radially elongated streamers scale with machine size and cover the whole extend of the drive domain. Flux-tube filtered simulations present a similar spectrum (nonlinear downshift), but (slightly) higher level of transport, as compared to full torus simulations.

Acknowledgment: Simulations were performed on the IBM pSeries Supercomputer "Regatta" of the MPG-IPP Rechenzentrum, Garching, and on the cluster PLEIADES2 of the EPFL, Lausanne.

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