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Gyrokinetic simulations of microturbulence in tokamak plasmas presenting an electron internal transport barrier, and development of a global version of the GENE code

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Introduction

Using an interface with an MHD equilibrium code [1], linear and nonlinear gyrokinetic simulations are carried out with the flux tube version of the GENE code [2, 3] with the aim of analyzing a TCV shot for which an electron internal transport barrier (eITB) was obtained. Starting from experimentally relevant parameters, scans in the density and ion temperature gradient are carried out in order to investigate their influence on particle transport. In particular one is interested in finding gradient values for which the particle flux cancels out. In order to address the issue of non-local effects in turbulent transport, some of the standard flux tube assumptions have been released in the GENE code, which is thus extended to allow for radial variations of the equilibrium quantities. Comparisons with other global codes are presented.

Gyrokinetic equation

One shall present here the equations implemented in the global version of the GENE code, more details can be found in [4]. The corresponding local equations are obtained by neglecting radial variations of equilibrium profiles. The field aligned coordinate system $\vec{X} = (x,y,z)$ is considered, with x a radial like coordinate, y the binormal coordinate labeling the magnetic lines on a given magnetic surface and z a parallel coordinate. The directions $\vec{\nabla}x$ and $\vec{\nabla}y$ are perpendicular to the magnetic field $\vec{B}_0(x,z)$ with the relation $\vec{B}_0 = \mathscr{C}(x)\vec{\nabla}x \times \vec{\nabla}y$. The j^{th} particle distribution function $f_j(\vec{X}, v_\parallel, \mu)$, with $v_\parallel$ the velocity parallel to the magnetic field and $\mu = m_j v_\perp^2/(2B_0)$ the magnetic moment, is divided into an equilibrium and a perturbed part, $f_j = f_{0j} + f_{1j}$, with f_{0j} chosen as a time-independent local Maxwellian, and is assumed to be a stationary solution to the unperturbed gyrokinetic equation. Considering the assumption

$|k_\parallel| \ll |k_\perp|$ we obtain the following form of the gyrokinetic Vlasov equation :

$$\begin{aligned} -\partial_t g_{1j} &= \frac{1}{\mathscr{C}}\frac{B_0}{B_{0\parallel}^*}\left[\frac{1}{L_{nj}} + \left(\frac{m_j v_\parallel^2}{2T_{0j}} + \frac{\mu B_0}{T_{0j}} - \frac{3}{2}\right)\frac{1}{L_{Tj}}\right] f_{0j}\,\partial_y \bar{\chi}_1 \\ &+ \frac{1}{\mathscr{C}}\frac{B_0}{B_{0\parallel}^*}(\partial_x \bar{\chi}_1\,\Gamma_{y,j} - \partial_y \bar{\chi}_1\,\Gamma_{x,j}) + \frac{B_0}{B_{0\parallel}^*}\frac{\mu B_0 + m_j v_\parallel^2}{m_j \Omega_j}\left(\mathscr{K}_x \Gamma_{y,j} + \mathscr{K}_y \Gamma_{x,j}\right) \\ &- \frac{1}{\mathscr{C}}\frac{B_0}{B_{0\parallel}^*}\frac{\mu_0 v_\parallel^2}{\Omega_j B_0} p_0 \frac{1}{L_p}\Gamma_{y,j} + \frac{\mathscr{C} v_\parallel}{B_0 J}\Gamma_{z,j} - \frac{\mathscr{C}\mu}{m_j B_0 J}\partial_z B_0\,\partial_{v_\parallel} f_{1j}\,, \end{aligned} \quad (1)$$

where $g_{1j} = f_{1j} + q_j v_\parallel \bar{A}_{1\parallel} f_{0j}/T_{0j}$, $\bar{\chi}_1 = \bar{\Phi}_1 - v_\parallel \bar{A}_{1\parallel}$, $\Gamma_{\alpha,j} = \partial_\alpha f_{1j} + \partial_\alpha (q_j \bar{\Phi}_1) f_{0j}/T_{0j}$ for $\alpha = (x,y,z)$, and the overbar notation denotes gyroaveraged quantities. In addition one defines $n_{0j}(x)$, $T_{0j}(x)$, $p_0(x)$ as respectively the density, temperature and pressure, and their logarithmic gradients $L_A(x) = -(d\ln A/dx)^{-1}$ for $A = [n_j, T_j, p]$. Finally $\mathscr{K}_x(x,z)$ and $\mathscr{K}_y(x,z)$ are related to curvature and magnetic field gradient, $\Omega_j(x,z) = q_j B_0/m_j$, $B_{0\parallel}^*(x,z,v_\parallel) = B_0 + |(m_j/q_j)v_\parallel(\vec{\nabla}\times\vec{b}_0)\cdot\vec{b}_0$, with $\vec{b}_0 = \vec{B}_0/B_0$ and $J(x,z)$ is the Jacobian of the (x,y,z) coordinates. The perturbed electrostatic potential Φ_1 and vector potential $A_{1\parallel}$ which appear in Eq. (1) are self-consistently obtained by solving the quasineutrality equation, and the parallel component of Ampère's law. In the global version of the code, radial derivatives are computed using finite differences, and Dirichlet boundary conditions are used. In the local version, however, the radial direction is treated in Fourier space with periodic boundary conditions.

Particle transport in an eITB discharge

A TCV discharge for which an electron internal transport barrier was obtained [5] is studied with the local version of the GENE code. The local parameters are considered in the inner part of the transport barrier ($r/a = 0.4$), i.e. at the position where the safety factor and shear are respectively $q = 3.2$ and $\hat{s} = -0.5$. The simulations are carried out with 3 species, H^+, C^{6+}, e^-, with densities such that $Z_{eff} = 3$, and assuming $T_e/T_i = 3$. The electron temperature normalized gradient is kept fixed at $R/L_{Te} = 15.1$ and one considers two different cases with density gradients $R/L_n = 2.5$ and $R/L_n = 5.1$ for which a scan in the ion temperature gradients R/L_{T_i} is performed. Note that in these simulations one assumes R/L_{Ti} for H^+ and C^+ to be equal and R/L_n to have the same value for all three species. For these parameters the nonlinear heat flux typically peaks around $k_y\rho_i = 0.3$, which motivates for a linear study at this value of $k_y\rho_i$, in view of identifying the underlying driving instabilities. Fig. 1.a shows the growth rates and real frequencies of the two most unstable modes at $k_y\rho_i = 0.3$ for several values of R/L_{Ti}. Considering first the case $R/L_n = 5.1$, the dominant mode is TEM like with a real

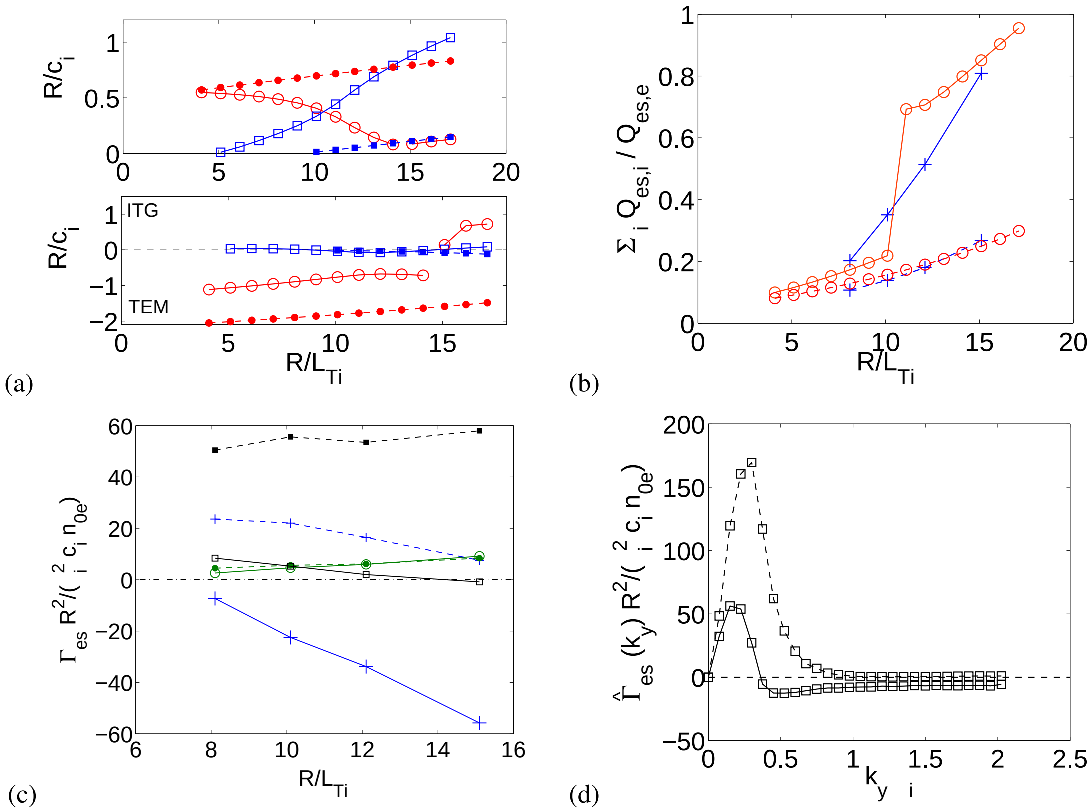

Figure 1: Results for case $R/L_n = 2.5$ (solid) and $R/L_n = 5.1$ (dashed) - (a) Linear growth rates and frequencies of the two most unstable modes - (b) Ratio $\sum_i Q_i/Q_e$ of ion and electron heat flux obtained linearly considering the most unstable mode (circle), and nonlinearly (cross) - (c) Nonlinear particle fluxes for H^+ (cross), C^{6+} (circle) and e^- (square) - (d) Electron particle flux spectra for $R/L_{Ti} = 15.1$

frequency in the electron diamagnetic direction (negative) for all considered values of R/L_{Ti}. On the contrary, for the case $R/L_n = 2.5$, a transition between ITG and TEM dominant mode is observed at $R/L_{Ti} \sim 11$. Such transition is further confirmed in Fig. 1.b, where the ratio $\sum_i Q_i/Q_e$ for the most unstable mode is shown. Nonlinear results presented in Fig. 1.c show that in the case $R/L_n = 2.5$ where an ITG-TEM transition is observed, it is possible to find a value of $R/L_{Ti} \sim 14$ such that the electron particle flux is zero, similar to results discussed in Refs [6, 7]. Such cancellation results from inward and outward flux contributions at different values of $k_y\rho_i$, as is clearly illustrated in Fig. 1.d. One finally notes that, for this particular value of R/L_{Ti}, the two ion species have non zero particle fluxes in opposite directions, with a total contribution ensuring ambipolarity.

Global results comparison

The global version of the GENE code is first compared with the linear PIC code GYGLES [8], for cyclone like parameters [9], i.e. considering only electrostatic fluctuations with adiabatic electrons. Both codes consider a circular concentric analytic model for the equilibrium with a

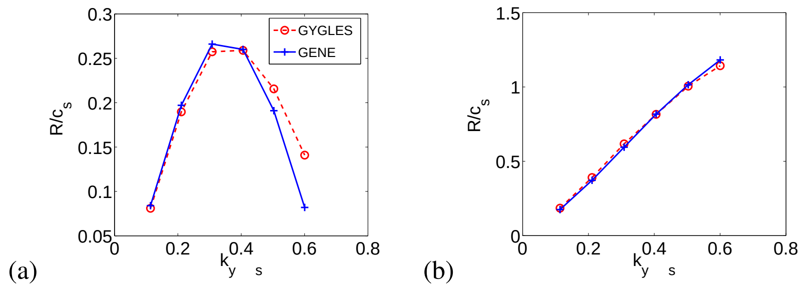

Figure 2: Comparison of linear growth rates (a) and real frequencies (b) as a function of $k_y \rho_s$ obtained with the global version of GENE and with GYGLES.

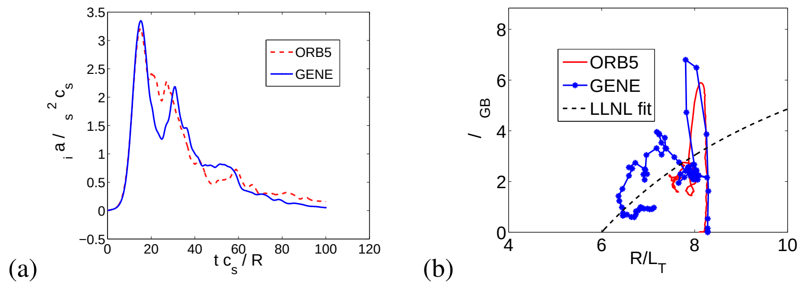

Figure 3: (a) Benchmark of the nonlinear ion heat diffusivity χ_i as a function of time for cyclone like parameters - (b) Nonlinear $(R/L_T, \chi_i)$ trace for parameters presented in Ref. [11].

safety factor profile $q(r) = 0.85 + 2.4(r/a)^2$. The temperature and density gradient profiles are peaked with maximum values $R/L_{Ti}(x_0) = 6.96$ and $R/L_n(x_0) = 2.2$. The resulting growth rates and real frequencies are plotted in Fig. 2 showing a very good agreement. Using similar parameters, nonlinear results are compared with the ORB5 code [10]. In Fig. 3.a time evolution of the heat diffusivity is shown for nonlinear relaxation simulations where the same initial conditions have been set in the two codes. The time traces of the first burst are essentially identical in both simulations, and remain very close till the end of the run at $tc_s/R = 100$. Finally, see Fig. 3.b, the global version of GENE recovers well nonlinear relaxation traces in the $(R/L_T, \chi_i)$ plane published in Ref. [11], where flat gradient profiles were used.

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