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Towards an improved first principle based transport model

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In order to gain reliable predictions on turbulent fluxes in tokamak plasmas, physically comprehensive transport models have to be improved. Unfortunately nonlinear gyrokinetic simulations are still too costly in terms of computing time; on the other hand, the quasi-linear approximation can retain the relevant physics for fairly reproducing both experimental results [1] and nonlinear gyrokinetic simulations [2]. This work aims at improving the recently developed quasi-linear model QuaLiKiz [3], based on a fast linear gyrokinetic code. Three main issues are presented: i) test the validity of the quasi-linear approach using the Eulerian δf code GYRO [4] for coupled ITG-TEM turbulence and the semi-Lagrangian full-f code GYSELA [5] for ITG only, ii) optimize the QuaLiKiz assumptions on the saturated electric potential by comparison with turbulence measurements on Tore Supra and nonlinear simulations, iii) successful comparison of both energy and particle diffusivities predicted by GYRO and QuaLiKiz for several tokamak relevant conditions.

1. Validating the fundamentals of quasi-linear approach

The quasi-linear predictions of turbulent fluxes have an intrinsic dependence on the choices adopted for the structure of the saturated turbulent electric field, which is not self-consistently solved in the quasi-linear approximation. Hence, the validation of the quasi-linear approach has to be done apart from any hypothesis on the saturation spectrum. Therefore we study the radial **E**x**B** turbulent flux from the k mode $\Gamma_k = \left\langle \delta n_k \delta v^*_{ExB,k} \right\rangle \cong \left\langle i k_\theta c / B \delta n_k \delta \phi^*_k \right\rangle$ (example of particle flux, brackets stand for a statistical average). The flux is proportional to the sinus of the cross-phase $\Delta\Phi_k$ between the fluctuating electric potential and the transported quantity (density or energy fields). Firstly, local (with no radial profiles variations) electrostatic gyrokinetic simulations of coupled ITG-TEM turbulence have been performed with the Eulerian δf code GYRO; the probability density function (PDF) of these cross-phases from each k-mode has been calculated for the nonlinear saturation phase and compared to the linear cross-phases from a GYRO simulation of the linear most unstable mode. Fig. 1a shows a very good agreement between the nonlinear and the linear cross-phases in the plane $\theta=0$, where the interchange instability is supposed to be dominant. In the case of pure ITG turbulence, i.e. with adiabatic electrons, the nonlinear de-phasing between δp_i and $\delta v_{\mathbf{ExB}}$ has been directly studied through global nonlinear full-f gyrokinetic simulations with GYSELA, and compared to the δp_i-$\delta\phi$ de-phasing from local δf GYRO simulations (Fig. 1b). The two codes predict coherent total ion heat fluxes; nevertheless, phase shifts more peaked towards low k_θ scales are obtained by the global GYSELA simulations in the plane $\theta=0$ with respect to the local ones by GYRO.

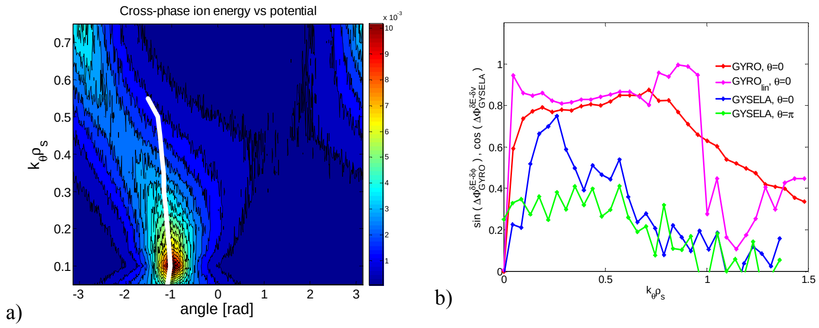

Fig 1a: Local GYRO simulation (kinetic electrons) with $R/L_{Ti}=R/L_{Te}=9.0$, $R/L_n = 3.0$, $R/a = 3.0$, $r/a=0.5$, $q=2.0$, $s=1.0$, $\rho^*=1/400$ (GA-std case); PDF of the nonlinear $\Delta\Phi_k$, white line is the linear $\Delta\Phi_k$.
Fig 1b: Local GYRO versus global GYSELA simulation of pure ITG turbulence: $\sin(\langle\Delta\Phi(\delta p_k\text{-}\delta\phi_k)\rangle)$ for GYRO and $\cos(\langle\Delta\Phi(\delta p_k\text{-}\delta v_k)\rangle)$ for GYSELA are shown.

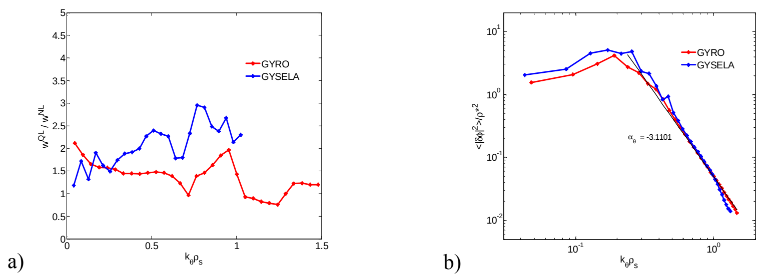

Fig 2a: Local GYRO and global GYSELA simulations (adiabatic electrons) with $R/L_{Ti}=8.28$, $R/a=2.78$, $r/a=0.4$, $q=1.23$, $s=0.6$, $\rho^*=1/256$. The ratios of the quasi-linear and nonlinear transport weights versus $k_\theta\rho_s$ are shown.
Fig 2b: $\langle|\delta\phi_{k\theta}|^2\rangle$ saturation spectra from local GYRO and global GYSELA simulations.

The following transport weight has been moreover defined, $w_k^{QL,NL} = \left\{ \langle \Gamma_k(r,\theta)\rangle, \langle Q_k(r,\theta)\rangle / \left\langle |\delta\phi_k(r,\theta)|^2 \right\rangle \right\}_t$ (Γ_k and Q_k are respectively the particle and energy fluxes, while brackets stand for a flux-surface and radial average), such that this quantity can be calculated in the full nonlinear as well in the linear regimes. The ratio between the linear and the nonlinear transport weights has been studied by mean of local δf (with GYRO) and global full-f (with GYSELA) gyrokinetic simulations. Fig. 2 refers to pure ITG turbulence, where scales up to $k_\theta\rho_s=1.48$ have been resolved (results corresponding to $k_\theta\rho_s>1.0$ are omitted for GYSELA since a simplified gyro-averaging operator is applied on these ranges). Both the local and the global simulations agree in recognizing a systematic over-prediction of the linear transport with respect to the nonlinear regime. The most relevant evidence is that these linear/nonlinear ratios stay reasonably constant when changing the plasma parameters and over the k_θ-spectrum, especially at low k_θ scales, where the driven transport is maximum. A remarkable agreement is observed between the local GYRO and the global GYSELA $<|\delta\phi_{k\theta}|^2>$ saturated spectra, exhibiting a power law shape clearly peaking at low $k_\theta\rho_s\approx0.2$. Consequently, the following relation for the quasi-linear expectations on all the turbulent fluxes can then be applied $\Gamma^{QL}, Q^{QL} = C_0 \sum_{k,i} w^{QL}_{k,i} \left\langle |\delta\phi_k|^2 \right\rangle^{NL}$ (the index i eventually stands for the i-th linear unstable mode): the saturated $|\delta\phi_k|^2$ spectrum is externally imposed from the nonlinear saturated regime and $C_0\approx1/1.55$ is the only arbitrary constant needed to properly renormalize the quasi-linear over-prediction to the nonlinear fluxes. Results from Figs. 1, 2 provide then a very relevant justification of the quasi-linear approach, if suitable hypotheses on the saturated $\delta\phi$ spectrum are assumed.

2. k_θ-spectra from experimental measurements and nonlinear simulations

The quasi-linear gyrokinetic transport model QuaLiKiz has been recently improved against linear GYRO simulations of the most unstable mode. Peculiar focus has been devoted to the hypotheses adopted in the model on the saturated $|\delta\phi_{k\theta}|^2$ spectrum. A power law of the type $(k_\theta\rho_s)^{-\alpha}$ is generally able to fit very well both the potential and the density fluctuations $|\delta n_{k\theta}|^2$ spectrum obtained by nonlinear GYRO simulations for $k_\theta>k_{\theta,nl\text{-}max}$. A slope $3<\alpha<3.5$ has been typically observed, reproducing reasonably well the laser scattering turbulence measurements in the medium k_θ range observed on Tore Supra plasmas [6] (Fig. 3). On the other hand, the transition towards $\alpha\approx6$ seen by the measurements at high k_θ scales has not been reproduced by GYRO nor GYSELA simulations within the explored k_θ ranges (up to $k_\theta\rho_s\approx2$): this issue should be deepened in further studies.

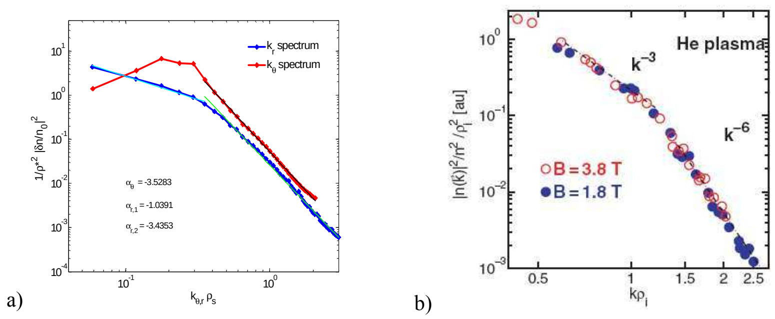

Fig 3a: Local GYRO simulation (with kinetic electrons and collisions) of a Tore Supra discharge. Density fluctuations spectra in both k_θ and k_r are represented.
Fig 3b: Experimental k_θ density fluctuations spectra on typical Tore Supra discharges from Ref. [6].

In QuaLiKiz, we have consequently assumed a power law $S_k=(k_\theta\rho_s)^{-3}$ spectrum symmetric around a $k_{ql\text{-}max}$; $k_{ql\text{-}max}$ is chosen in order to maximize the mixing length factor $\gamma_k / \left\langle k_\perp^2 \right\rangle$ on the most unstable mode, where $\left\langle k_\perp^2 \right\rangle = k_\theta^2\left(1+s^2\left\langle \theta^2 \right\rangle\right)$ [2, 3]. All the unstable modes i are accounted in the model, and each of them is retained with a different weight factor $S_k \max_k\left(\gamma_{k,i} / \left\langle k_\perp^2 \right\rangle_i\right)$.

3. QuaLiKiz versus GYRO and application to experimental discharges

QuaLiKiz expectations have been compared against a large number of nonlinear GYRO simulations with kinetic electrons, and only one renormalisation factor C_0 (as defined in section 1) for both particle and energy fluxes has been used in order to get the best fit to the nonlinear fluxes. Fig. 4a shows an example of the ion/electron energy and particle turbulent diffusivities: the scan of the plasma thermal gradients reveals that the quasi-linear approach respects the nonlinear ratios between the different transport channels.

a) b)

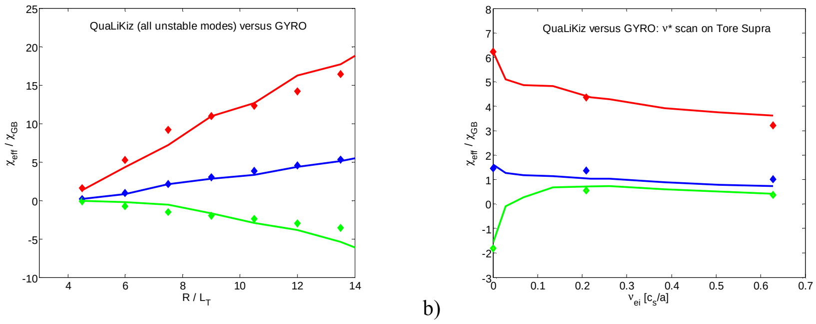

Fig 4a: Ion energy (red), electron energy (blue) and particle (green) effective diffusivities from GYRO (points) and QuaLiKiz (lines) for a wide scan of plasma thermal gradients (GA-std case)
Fig 4b: Ion energy (red), electron energy (blue) and particle (green) effective diffusivities from GYRO (points) and QuaLiKiz (lines) for a collisionality scan on Tore Supra plasmas

A second example is a direct application to an experimental collisionality (ν*) scan realised on Tore Supra plasmas [7]. The ν* scaling of transport is particularly challenging for quasi-linear models [8]. Indeed, the nonlinear collisional damping of the zonal flows dynamics could enhance turbulence and hence transport, while linearly the opposite effect (transport decrease) is expected, driven by the collisional quenching of TEM. The latter effect is dominant in the range of the experimental parameters here studied, as shown by the decrease of transport with increasing collisionality. Fig. 4b demonstrates that, for realistic values of ν_{ei}, QuaLiKiz is able to well reproduce the nonlinear diffusivities predicted by comprehensive GYRO simulations (performed with pitch-angle scattering operators on both electrons and ions). Hence the zonal flows dynamics driven by ν* variations plays a subdominant role, whereas the coupled dynamics between ion and electron non-adiabatic responses is crucial for both GYRO and QuaLiKiz, in order to account for the TEM quenching.

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