Simulating the effect of fine radial structures resulting from non-adiabatic passing electrons on turbulent transport in the ITG and TEM regimes

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Introduction: When studying turbulence driven by Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEMs) in magnetic fusion plasmas, it is often assumed that the response of the passing electrons is adiabatic. However near low order Mode Rational Surfaces (MRSs), where the safety factor equals $q_s = |m/n|$, the corresponding resonant Fourier modes (m,n) - (poloidal, toroidal) mode numbers - align with the magnetic field such that $k_\parallel \to 0$ and $|v_{\phi,\parallel}| = |\omega/k_\parallel(m,n)| \gg v_{th,e}$, with ω the real frequency of the mode, $k_\parallel$ the wave vector component parallel to the magnetic field, $v_{\phi,\parallel}$ the parallel phase velocity, and $v_{th,e}$ the electron thermal velocity. This break-down of the adiabatic assumption in the vicinity of MRSs is associated with the appearance of fine radial structures on the linear ITG/TEM eigenmode, both in global [1, 2] and local fluxtube simulations.

To our knowledge, besides first results in Ref. [4, 5], no systematic study of the non-adiabatic response of passing electrons near MRSs in the electrostatic non-linear, turbulent regime has yet been carried out. It is thus of interest to conduct such a dedicated study, first systematically characterising the effect of non-adiabatic electron response on the linear eigenmodes, then, in a second stage, identifying persisting structures and their effects on the fluxes in non-linear simulations. This study is conducted using the gyrokinetic code GENE [6] in its fluxtube version. As the flux-tube model accounts for the (linearized) radial variation of the safety factor q_s, as well as to correct boundary conditions in the parallel direction, it provides the simplest possible system for accurately studying the non-adiabatic electron dynamics near MRSs.

In GENE, one makes use of the following (x, y, z) coordinate system: radial coordinate x, binormal $y \sim q_s\chi - \varphi$, and "parallel" $z = \chi$, where χ is the straight field line poloidal angle, and φ the toroidal angle. To help identify the non-adiabatic response of passing electrons in fully kinetic simulations, results are compared to corresponding ones obtained with the so-called hybrid model, recently implemented in GENE [3], which accounts for the kinetic response of trapped electrons but enforces the passing electrons to respond adiabatically throughout the system. The so-called fully kinetic model represents all electrons kinetically.

In the following, we briefly introduce the GENE electron models, provide an illustration of how the fine structures resulting from non-adiabatic electron response near MRSs have been characterized, and finally present how these persisting structures affect the non-linear turbulent state, in particular the Zonal Flow (ZF) shearing rate profiles as well as the time-averaged density and temperatures profiles.

Electron models: GENE is an Eulerian based gyrokinetic code which solves for the evolution of the particle distribution f_j of each species $j =$ ions/electrons in an effectively 5-dimensional phase space $(x, y, z, v_\parallel, \mu)$, where $v_\parallel$ is the parallel velocity and μ the magnetic moment. In electrostatic simulations, the self-consistent fluctuating potential field ϕ_1 is provided by the quasi-neutrality equation:

$$
\begin{aligned}
0 = \quad & \frac{2\pi Ze}{m_i}\int dv_\parallel d\mu B^\star_{0,\parallel}\bar{f}_{1i} - \frac{Z^2e^2n_{0i}}{T_{0i}}\left[\phi_1 - \frac{B_0}{T_{0i}}\int d\mu\bar{\bar{\phi}}_1\exp(-\frac{\mu B_0}{T_{0i}})\right] \\
& -\frac{2\pi e}{m_e}\int_{\Delta V} dv_\parallel d\mu B^\star_{0\parallel}\bar{f}_{1e} - \frac{e^2n_{0e}}{T_{0e}}\left[\alpha\phi_1 - \frac{B_0}{T_{0e}}\int_{\Delta V} d\mu\bar{\bar{\phi}}_1\exp(-\frac{\mu B_0}{T_{0e}})\right] - (1-\alpha)\frac{n_{0e}e^2(\phi - \langle\phi\rangle)}{T_{0e}},
\end{aligned}
$$

where i/e stand for ions/electrons resp., Z for the ionization degree, $n_{0,j}$ and $T_{0,j}$ for background density/temperature, $f_{1,j} = f_j - f_{Mj}$ for the deviation of the distributions from a Maxwellian background f_{Mj}, overbars stand for gyro-averaging, $\langle\cdot\rangle$ for flux-surface averaging, and ΔV for velocity space (sub-)volume. Based on equation (1), the three electron models are defined as follows: the adiabatic model $(\Delta V = \emptyset, \alpha = 0)$, the kinetic $(\Delta V = \text{all}, \alpha = 1)$ and the hybrid $(\Delta V = \text{trapped } e^-, \alpha = \text{trapped fraction})$.

Fine structures in linear eigenmodes: As shown in Fig. 1, subtracting for a given $k_y \neq 0$ mode the linear eigenmode envelope $|\phi^{\text{hyb}}|$ obtained with a hybrid simulation from the corresponding one $|\phi^{\text{kin}}|$ obtained from a fully kinetic simulation enables to systematically identify a fine radial structure aligned with the MRS, located at $x = 0$, obviously the result from the non-adiabatic passing electron response. The Full Width at Half Maximum (FWHM) of $\langle\Delta|\phi|\rangle_z$, the z-average of $\Delta|\phi| = |\phi^{\text{kin}}| - |\phi^{\text{hyb}}|$, gives a numerical estimate Δx^{num} of the width. Results are plotted in Fig. 1, where the fine structure width is shown to be of the order of or less than an ion Larmor radius ρ_i.

Non-linear study of flux-surface-averaged profiles: In non-linear simulations with fully kinetic electrons, fine radial structures centered on low order MRSs survive, albeit somewhat broadened to the ones characterized in the linear runs, as can be appreciated in Fig. 3. The non-linear coupling of the $k_y \neq 0$ to the $k_y = 0$ modes leads to a modulation of the time-averaged ZF shearing rate and gradient profiles as illustrated in Fig. 4 and in agreement with [5]. The density profile appears flattened at lowest order MRSs, reflected by $(dn_1/dx)/(|dn_0/dx|)$ approaching $+1$, which coincides with a minimum of the ZF shearing rate. In turn, between MRSs, the

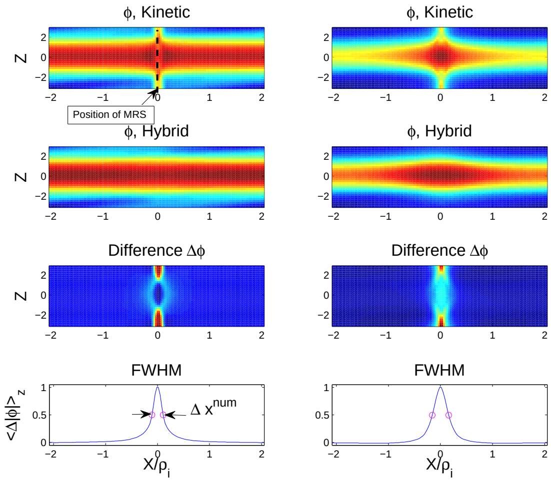

Figure 1: Electrostatic field ϕ_1 for $k_y\rho_i = 0.3$. Eigenmode envelopes for both ITG (left column) and TEM (right column) with kinetic electrons (first row) and hybrid electrons (second row).

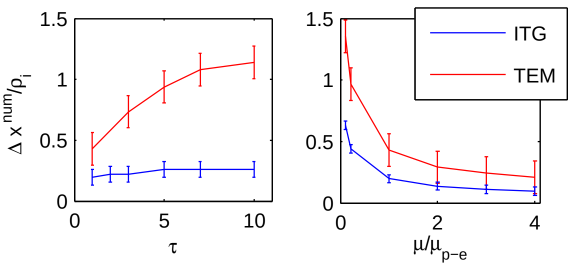

Figure 2: Numerical width Δx^{num} of the fine structures localised at MRSs of linear eigenmodes as a function of electron/ion temperature ratio $\tau = T_e/T_i$ (left) and ion/electron mass ratio $\mu = m_i/m_e$ (right) for ITG (blue) and TEM (red) cases. $\mu_{pe} = 1836$ = proton/electron mass ratio.

shearing rate becomes large, effectively shearing the turbulence and thus reducing the associated transport, reflected by $(dn_1/dx)/(|dn_0/dx|)$ taking on negative values. Similar modulation is also seen on the electron and ion temperature profiles (not shown). This self-organisation of the plasma near MRSs is only present in simulations with the fully kinetic electron model, while it is absent in simulations considering the hybrid model.

Conclusion: The non-adiabatic response of passing electrons leads to fine radial structures near MRSs of linear ITG/TEM modes with $k_y \neq 0$. These structures survive in turbulence simulations and modulate the ZF shearing rate and density/temperature profiles through non-linear coupling to $k_y = 0$ modes. It is thus of interest to pursue this study of the effect of non-adiabatic electron response near MRSs and quantify how heat and particle fluxes are affected.

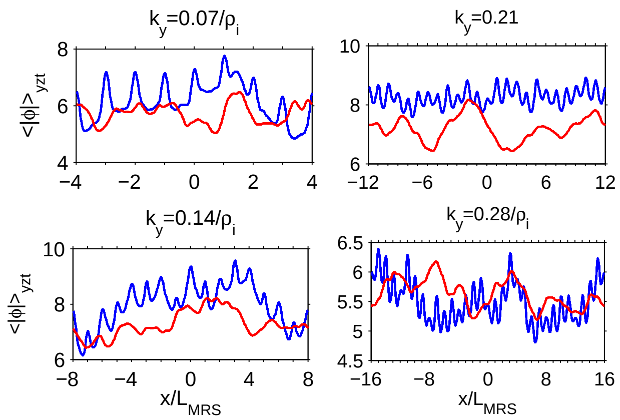

Figure 3: z- and time-averaged envelopes of different $k_y \neq 0$ modes in a non-linear ITG test case considering either fully kinetic (blue) or hybrid (red) electron models. For each k_y, $L_{\rm MRS}$ stands for the distance between corresponding MRSs.

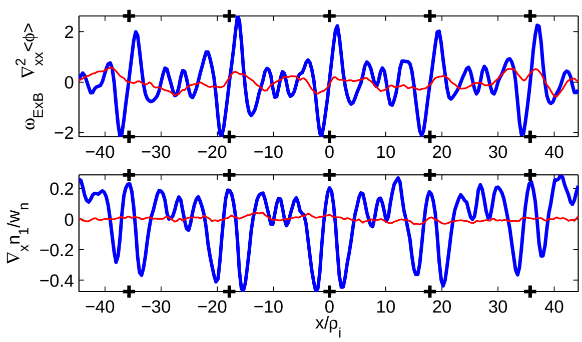

Figure 4: Time-averaged ZF shearing rate $\omega_{E\times B} = (d^2\langle\phi\rangle/dx^2)/B$ in units of $v_{th,i}/R$ and gradient profile $(dn_1/dx)/|dn_0/dx|$ for an ITG test case with kinetic electron model (blue) and hybrid electron model (red). MRSs related to $k_{y,\rm min}\rho_i = 0.07$ pointed out with black crosses.

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