How non-adiabatic passing electron dynamics and density of mode rational surfaces affect turbulent transport in magnetic fusion plasmas

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Gyrokinetic Simulation of Micro-turbulence

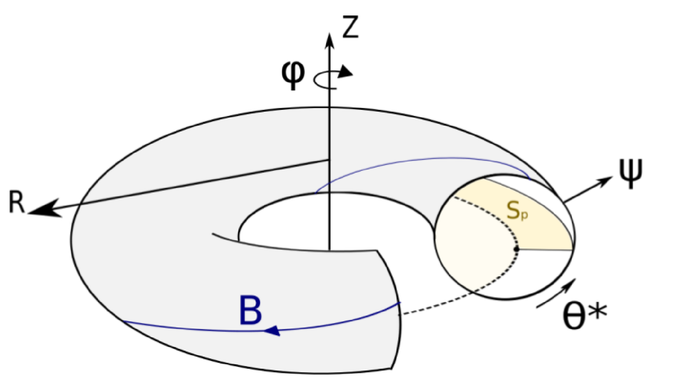
- Study of micro-turbulence and the instabilities driving them (**Ion Temperature Gradient [ITG]**, **Trapped Electron Mode [TEM]**, etc.) is essential to understand turbulent transport in the core of tokamaks.
- Kinetic simulations solving a reduced form of Vlasov + Maxwell's Equations in a tokamak geometry are useful for modelling and studying micro-turbulence.
- **Gyrokinetic model**: Since the gyro-frequencies of particles around the magnetic field lines are much higher than the time scales of most micro-instabilities of relevance, the gyro-motion can be averaged out, thereby reducing computation cost.

The GENE code [1]

- Eulerian gyrokinetic code, simulating micro-turbulence in magnetic confinement devices.
- Linear and non-linear simulations, multi-species kinetic dynamics, electrostatic and electromagnetic fluctuations, collisions, interface with MHD equilibrium.
- Uses a field-aligned coordinate system (x, y, z)

$\boldsymbol{x} = \mathrm{fct}(\psi)$: radial coordinate
$\boldsymbol{y} \sim \boldsymbol{q_s}(\psi)\theta^* - \varphi$: binormal coordinate
$\boldsymbol{z} = \theta^*$: parallel coordinate

$(\psi, \theta^*, \varphi)$: Straight field line magnetic coordinates



- Local (flux-tube) and global versions.

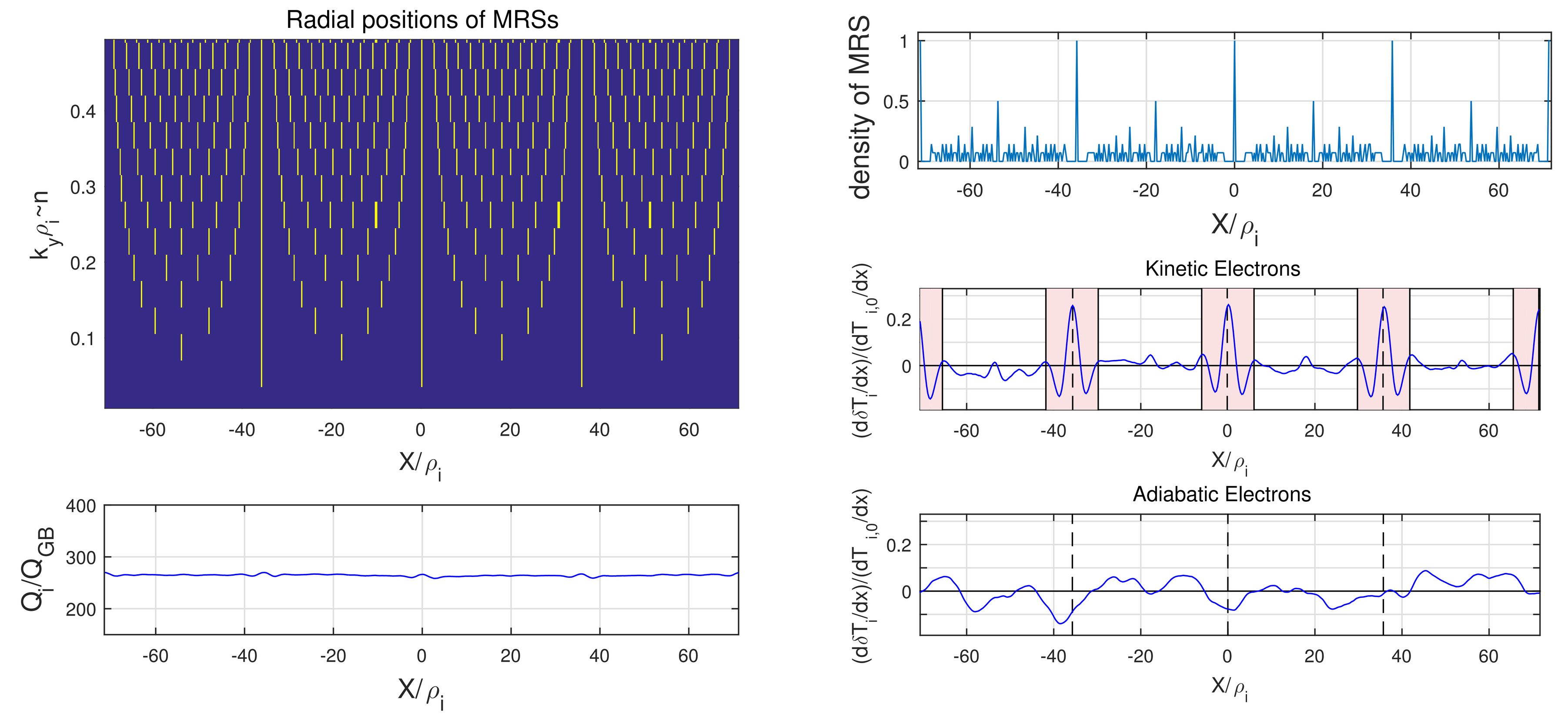
Global: Radial variation of profiles (density, temperature, geometrical coefficients), non-periodic radial boundaries, particle and heat sources/sinks.

Flux-tube: Limit $\rho^* = \rho_s/a \to 0$. Background magnetic equilibrium quantities and their gradients approximated as constants in the local limit.
Linear variation of safety profile: $\boldsymbol{q(r)} = \frac{d\phi}{d\chi} \sim \boldsymbol{q_0(r_0)} + \boldsymbol{r}\frac{dq}{dr}|_{r_0} = \boldsymbol{q_0}(\boldsymbol{1} + \hat{\boldsymbol{s}}\frac{r}{r_0})$

Introduction

- **Mode Rational Surface (MRS)**: For a given mode (m,n), $q(r_{m,n}) = m/n \Rightarrow k_\parallel \sim (nq - m)/Rq \to 0$ at associated MRSs.
- Adiabatic condition: $|\omega_r/k_\parallel| \ll v_{th,e}$ violated at MRSs.
- Physical and numerical reference parameters

Flux tube, ITG case	$k^*_{y,min}\rho_i = 0.035$	* Variable changes with simulation	
$N_x x N^*_y x N_z x N_{v_\parallel} x N_\mu x N_{sp}$	$= 512x128x16x64x9x2$	$L_x = 142.9\rho_i$	$L^*_y = 179.5\rho_i$
$R/L_N = 2.0$	$R/L_{T_e} = 2.0$	$R/L_{T_i} = 6.0$	$\beta = 0.001$
$q_o = 1.4$	$\hat{s} = 0.8$	$T_e/T_i = 1.0$	$m_i/m_e = 400$



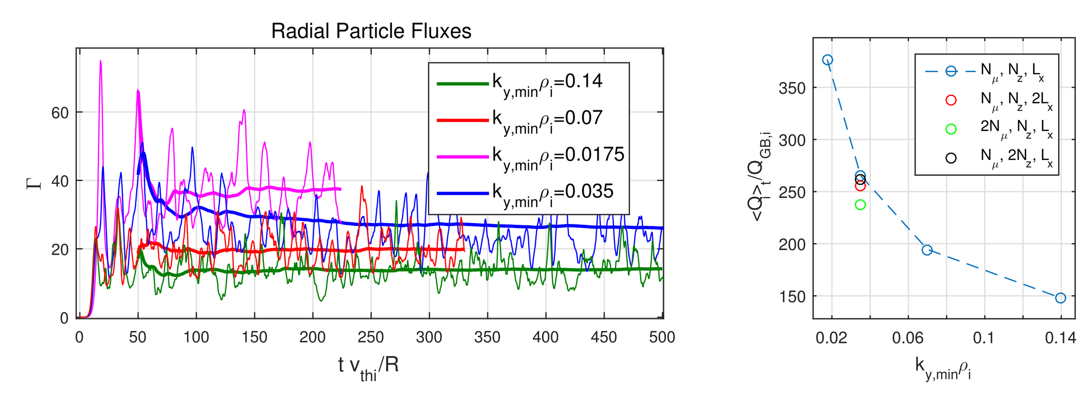
- **MRSs are channels for the particle and heat transport of non-adiabatic passing electrons** [2] $\Rightarrow$ Particle and heat diffusivities associated to passing electrons is largest at **Lowest order mode rational surfaces (LMRS)** $\Rightarrow$ Self-organization to maintain constant flux profile along the radial direction; Modulation of density and temperature gradients $\Rightarrow$ Flattening of the gradients at radial positions of LMRS and steepening in adjacent regions [3].
- Radial electric field E_x verifies ion force balance: $eE_x \sim \frac{\partial}{\partial x}\delta P_i = \frac{\partial}{\partial x}(n_0\delta T_i + \delta n_i T_{i,0})$ $\Rightarrow$ Intense $E \times B$ shearing at LMRS.
- Modulations on gradients and $E \times B$ shearing at LMRSs absent in simulations with adiabatic electrons.

Objective

- **Study the effect of density of LMRS and k_y resolution on flux-tube simulations.**
- $k_{y,min} = n_{min}q_0/r_0$, where n_{min} is the minimum toroidal mode number.
- Distance between LMRS, $\Delta x_{LMRS} = 1/(\hat{s}k_{y,min}) \to$ scan on $k_{y,min}$ with fixed L_x.

Results

- **Turbulent fluxes increase with decreasing $k_{y,min}$.**



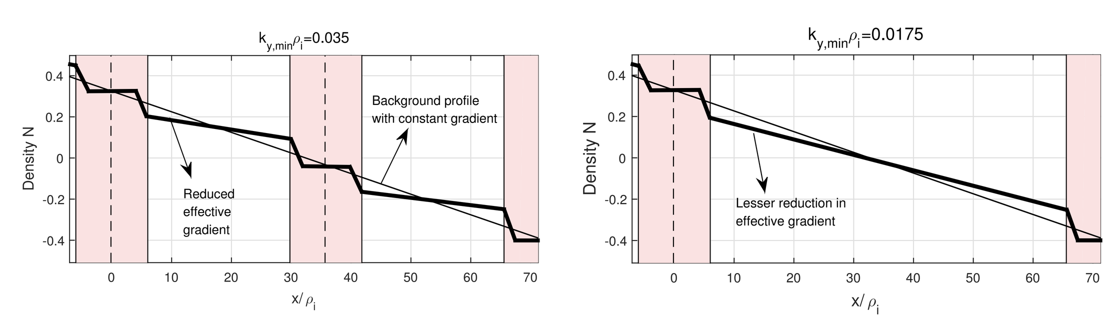
- **Possible numerical causes:**

N1 Insufficient phase space grid resolutions or radial box size?
- Doubled N_z, N_μ and L_x. Original resolutions and radial box size found to be sufficient.

N2 Simulation time insufficient for relaxation of individual modes?
- Verified that the longest wavelength zonal components have fully relaxed.

- **Possible physical causes:**

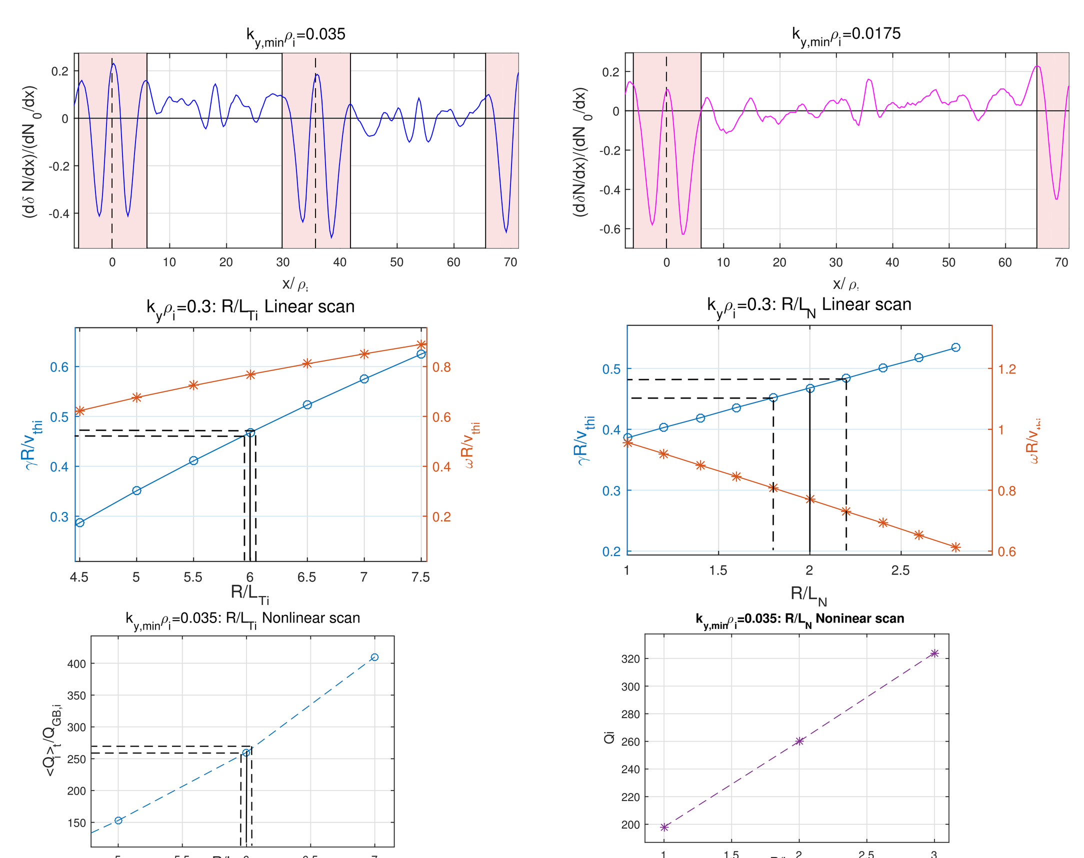
P1 Different effective gradients between LMRSs?
- Regions of intense shearing around LMRSs could act as local transport barriers $\to$ Sustain reduced effective gradients between LMRSs $\to$ Lesser effective flattening when LMRSs are farther apart $\to$ Reduced fluxes?
- Need to address profile stiffness.



P2 Change in $E \times B$ shearing rate and profiles?
- Smaller $k_{y,min} \to$ lesser density of LMRS $\to$ fewer positions of higher shearing and smaller effective shearing rate $\to$ less effective suppression of turbulent fluxes through the zonal flow quenching mecahnism $\to$ higher fluxes?

Investigation of Possible Cause P1

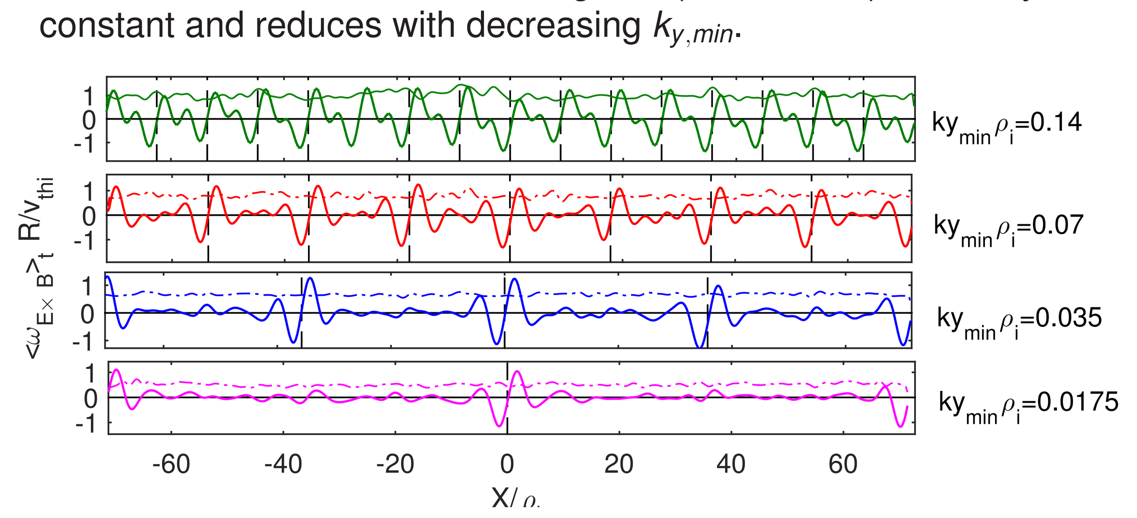
- One indeed observes higher average relaxation of density gradients between (white regions) local transport barriers centered at LMRSs (pink region) in higher $k_{y,min}$ than in lower $k_{y,min}$.
- However the change in the average gradients in the white region is found to be less than 10% and 1% of the background gradients for density and ion temperature respectively for all values of $k_{y,min}$. The maximum change in linear growth rates corresponding to these changes in gradients is only 5%.



- Change in flux levels in nonlinear simulations with altered gradients is also not sufficient to explain the observed difference in fluxes for different $k_{y,min}$s.

Investigation of Possible cause P2

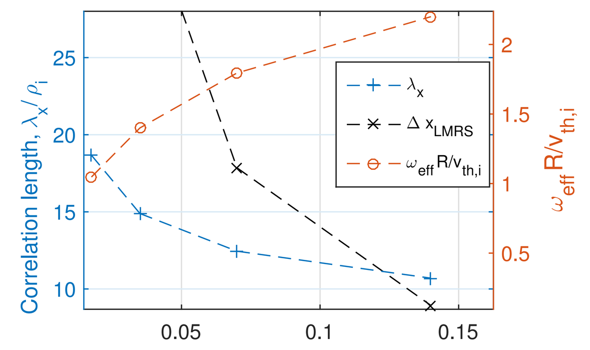
- LMRSs are regions of intense shearing. Amplitude and width of the time averaged shearing rate $\omega_{E\times B}$ (solid lines) remain invariant with $k_{y,min}$.
- The standard deviation of shearing rate (dotted lines) is radially constant and reduces with decreasing $k_{y,min}$.



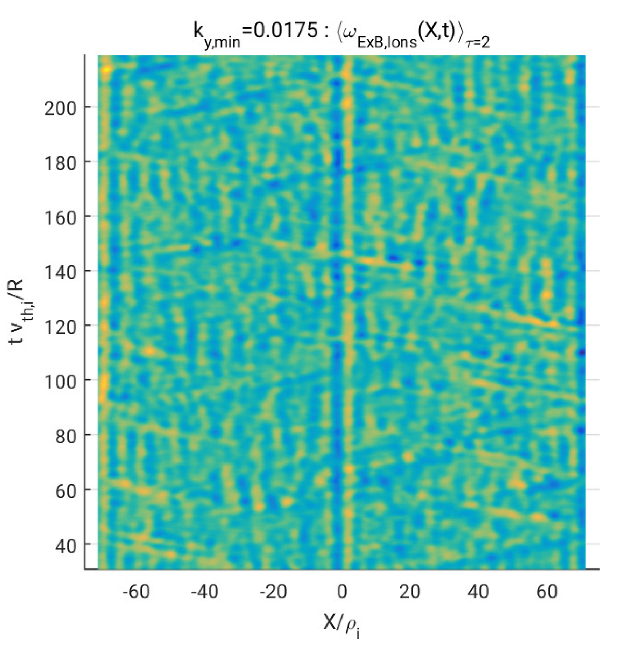
P2 [contd..]

- Effective shearing rate ω_{eff} decreases with decreasing $k_{y,min}$.
$\omega_{eff} = \sqrt{\langle|\langle\omega_{ExB}\rangle_\tau|^2\rangle_{x,t}}$, where $\tau = 1/\gamma_{max}$ and $\gamma_{max} = 0.5$ the growth rate of the most unstable mode.

- Radial correlation length λ_x increases with decreasing $k_{y,min}$. However it is not of the order of distance Δx_{LMRS} between LMRSs.



- The significant fluctuating components of the ω_{ExB} field probably also play an important role in regulating the size of turbulent eddies and the associated fluxes.
- It remains to be understood why these fluctuating components decrease with $k_{y,min}$.



- Since the zonal $E \times B$ flows are driven by Reynolds Stress, we plan to investigate its role in explaining the reduced effective shearing rate for lower $k_{y,min}$s. In particular, the statistical dependence of Reynolds stress on the number of contributing k_y modes will be analysed.

Conclusions

- Turbulent fluxes depend on $k_{y,min}$ ($\sim$ minimum toroidal mode number) *i.e.* the density of LMRS in flux-tube simulations.
- Difference in the effective gradient between LMRSs does not explain the difference in flux levels.
- Decrease in effective shearing rate with decreasing $k_{y,min}$ appears to explain the increase in fluxes. The shearing structures at and between LMRSs control the level of fluxes.
- Investigation into explaining the reason for decreased effective shearing rate with decreasing $k_{y,min}$ is ongoing.

References :

[1] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, Phys. Plasmas 7, 1904 (2000).
[2] J. Dominski, et al., Physics of Plamas 22, 062303 (2015).
[3] J. Dominski, et al., Physics of Plamas 24, 022308 (2017).

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