ITG & TEM Gyrofluid Model

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Introduction

Typical tokamak plasmas are low β and operate in the low collisionality limit. In this regime the toroidal ion temperature gradient driven instability or the trapped electron mode is the dominant instability. These instabilities explain turbulent transport in most of the device except near the edge.

Model

We combine the results of [Waltz *et al.*, 1984] and [Brizard, 1991] to obtain the four field $(P, v_\parallel, \phi, n_{te})$ model for ITG driven instability and TEM:

$$d_t P + (1+\eta_T)\kappa_n \partial_y \phi = -\gamma \nabla_\parallel v_\parallel \tag{1}$$

$$d_t v_\parallel = -\nabla_\parallel (P + \phi) \tag{2}$$

$$\begin{aligned} d_t\big((1-\sqrt{\epsilon})\tau\tilde{\phi} - \nabla_\perp^2 \phi\big) + \nabla_\perp \cdot \{\nabla_\perp \phi, p\} + (1-\sqrt{\epsilon})\kappa_n \partial_y \phi \\ +(1+\eta_T)\kappa_n \partial_y \nabla_\perp^2 \phi - 2\eta_B \kappa_n \partial_y (P + n_{te}/\tau) \\ = -\nu_{eff}(\sqrt{\epsilon}\tau\phi - n_{te}) - \nabla_\parallel v_\parallel \end{aligned} \tag{3}$$

$$d_t n_{te} + \sqrt{\epsilon}\kappa_n \partial_y \phi = \nu_{eff}(\sqrt{\epsilon}\tau\phi - n_{te}) \tag{4}$$

where $d_t = \partial_t + \boldsymbol{b} \times \nabla\phi$. $\kappa_n = \rho_i L_n^{-1}$, $\eta_T = L_T^{-1}/L_n^{-1}$ and $\eta_B = L_B^{-1}/L_n^{-1}$ characterize the equilibrium density gradient, equilibrium temperature gradient and the magnetic field gradient respectively. The model presented above makes the small η_B assumption which is physically reasonable considering a/R is small in tokamaks.

Linear Analysis

Linearising the model allows us to determine an optimal k_z that can be used for simulations and also understand the values of k_x and k_y that maximise γ. This allows use to have an idea about the size of the box required for the simulation.

Growth rate, γ

All equations are damped by $D\nabla_\perp^2 X_i + \nu \nabla_\parallel^2 X_i$ with $D = 5 \times 10^{-3}$, $\nu = 3 \times 10^{-2}$

- $\gamma(k_x, k_y)$ is symmetrical about k_x and peaks at around $k_y \approx 1$.
- There is a max value of k_z, depending on ν, up to which γ is positive. $k_z = 1$ is chosen later on for the simulation since it is small enough to not damp instabilities for most values of ν used.

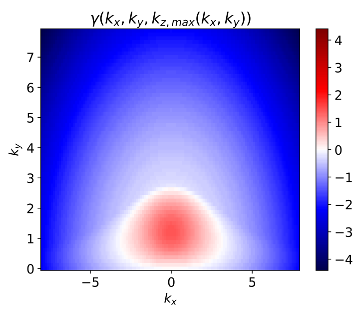


Figure 1: $\gamma(k_x, k_y)$

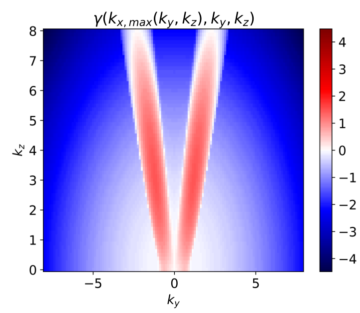


Figure 2: $\gamma(k_y, k_z)$

$\gamma(k_y)$ for different $\eta_T/\sqrt{\epsilon}$

- The k_y values that maximise γ are confined to < 3.8 (for η_T scan) and < 2.7 (for $\sqrt{\epsilon}$ scan). This gives us an idea of the minimum box size ($L_{min} = 2\pi/k_{max}$) to be used for non linear simulations of the system.
- γ_{max} decreases shortly but increases after a critical value in the case of η_T. The value of k_y that maximises γ steadily decreases except for the jump at the critical η_T.
- γ_{max} steadily increases for $\sqrt{\epsilon}$ with a steady decrease in the value of k_y that maximises γ.

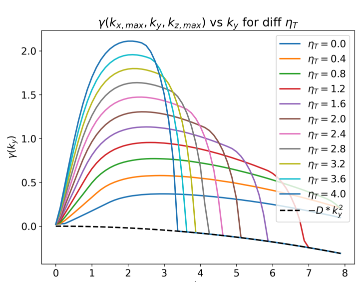
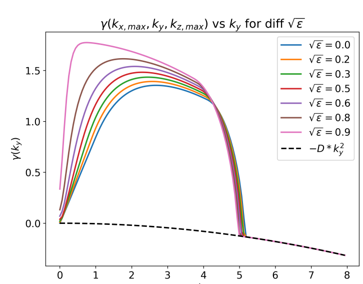


Figure 3: for differen



$\omega(k_{y,max})$ vs $\eta_T/\sqrt{\epsilon}$

- The phase velocity of propagation of convective instabilities is $\sim \omega_r/k_y$ which makes ω_r an interesting quantity to study.

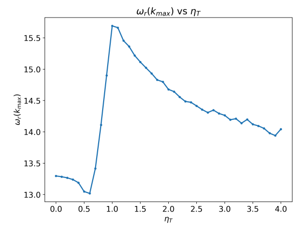


Figure 5: for different η_T

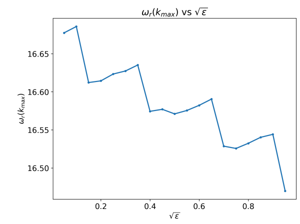


Figure 6: for different $\sqrt{\epsilon}$

2D ITG simulation

We ignore trapped electrons and set $\kappa_n = 0$ to obtain a model as in [Ivanov *et al.*, 2020; Ivanov *et al.*, 2022] and simulate the system using a pseudo-spectral code. We observe large scale ($k_y = 0$) structures (zonal flows) that irregularly oscillate along x. The four following plots are generated at the final time step.

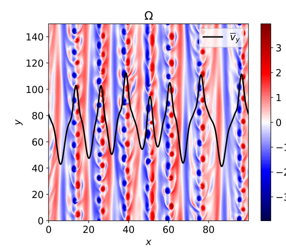


Figure 7: Vorticiy, $\Omega = \nabla_\perp^2 \phi$

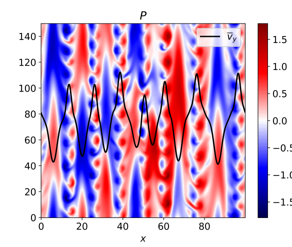


Figure 8: Pressure, P

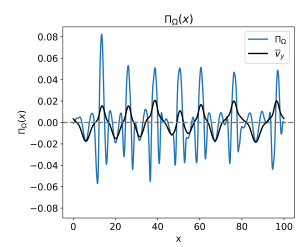


Figure 9: Vorticiy flux, $\Pi_\Omega = -\langle \partial_y \nabla_\perp^2 \phi \rangle$

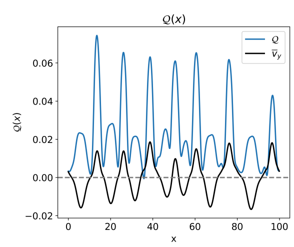


Figure 10: Heat Flux, $Q = -\langle \partial_y \phi T \rangle$

Flow Evolution

- Zonal flows merge early on and we also see that the extrema of zonal flows oscillate in time.
- Heat flux's time evolution, including the oscillations, resembles the evolution of the zonal flows.
- The heat flux is minimised in regions of high zonal shear.

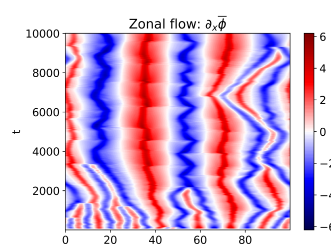


Figure 11: Zonal E $\times$ B velocity, $\partial_y \overline{\phi}$

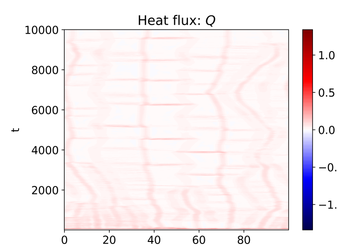


Figure 12: Heat Flux, $Q = -\langle \partial_y \phi T \rangle$

Conclusion and Perspectives

- Developed 4 field model and solver.
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- lominated state using 4 field model.