Impact of fast particles and nonlocal effects on turbulent transport in plasmas with hollow density profiles

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Introduction

While tokamak plasmas in their usual state have a peaked density profile, situations can occur where it becomes hollow. For example, the perturbations due to pellet fuelling[1] or L to H transitions can lead to regions with positive density gradients. Thus it is important to understand turbulent transport under these conditions. In Ref. [2], the particle and heat transport driven by Ion Temperature Gradient/Trapped Electron (ITG/TE) mode turbulence in those regions is studied by fluid as well as gyrokinetic simulations. This work extends the insights gained therein with extended studies of fast particle and nonlocal effects.

Simulation setup

The investigated system is a typical tokamak scenario based on Cyclone Base Case-like parameters[3] which are shown in Table 1.

Parameter	Value
q_0	1.4
$\hat{s}$	0.8
B_0	3.1 T
r/R	0.18
R	1.65 m
$T_e = T_i$	2.85 keV
$n_e = n_i$	$3.5 \times 10^{19}\,\mathrm{m}^{-3}$
$R/L_T = R/L_{T_i} = R/L_{T_e}$	6.96

Table 1: CBC-like parameters

Gyrokinetic simulations are performed with the Eulerian code GENE[4, 5] which supports an arbitrary number of gyrokinetic species, electromagnetic effects and collisions and can operate in both a flux-tube and a radially global domain.

The fluid model used is the extended version of the Weiland drift wave model EDWM[6] and allows to treat an arbitrary number of species in a multi-fluid description.

Fast particle effects

It has been shown that fast ions stabilise ITG turbulence through a number of effects: dilution of the main ions[7], Shafranov shift stabilisation[8] and electromagnetic stabilisation through the suprathermal pressure gradients[9].

The fast particle species is modelled with a Maxwellian background distribution in the gyrokinetic simulations. Since it is necessary to ensure quasineutrality, the density gradient of the electrons has to be modified when a fast particle species with a density gradient is added.

In Fig. 1 the stabilisation of ITG turbulence due to fast particles in EDWM simulations with $k_\perp \rho = 0.3$ is shown. For two different temperatures an increased fast particle fraction consistently leads to a decrease in the growth rate of the mode with positive real frequency. The strength of this effect is dependent on the temperature of the fast species.

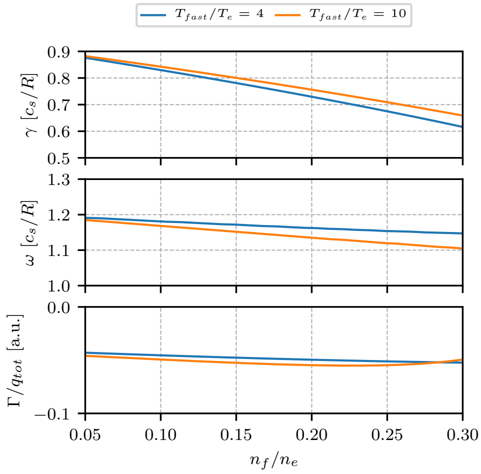
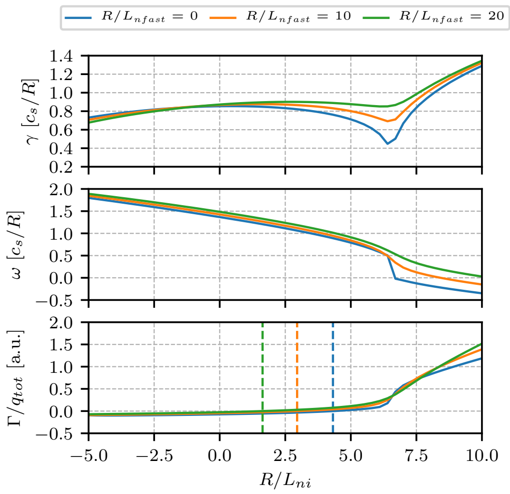


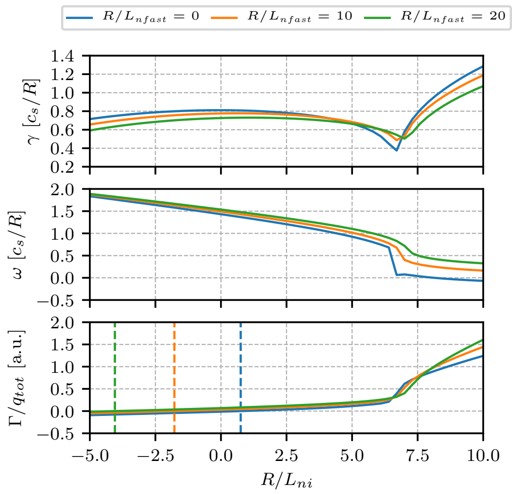
Figure 1: Dependency on the fast particle fraction in EDWM simulations with $k_\perp \rho = 0.3$

When the growth rate as a function of the main ion $R/L_{n,i}$ is compared for different $R/L_{n,fast}$ it appears that at $\beta_e = 0$ the fast ion density gradient destabilises both the ITG and the TE mode(Fig. 2a). At $\beta_e = 0.5\%$, however, this is reversed and the modes are stabilised by a larger $R/L_{n,fast}$(Fig. 2b). The main ion density gradients of zero flux are accordingly shifted to lower $R/L_{n,i}$. These results from the fluid model can also be qualitatively reproduced in linear GENE simulations.

Consequently, we find in nonlinear GENE and EDWM flux predictions that both β and fast particles decrease the usually desired inward particle flux in a hollow density profile region. The effect is, however, less pronounced in the gyrokinetic result whereas the fluid model even predicts an up-gradient flux.



(a) $\beta = 0$



(b) $\beta = 0.5\%$

Figure 2: Dependency on $R/L_{n,fast}$ in EDWM. Dashed lines: Gradient of zero flux

Nonlocal effects

As the region of negative R/L_n due to a pellet can be rather narrow, it is also relevant to investigate a system where nonlocal (finite ρ_*) effects can play a role. In the simulations presented here the strength of nonlocal effects is determined by both the normalized ion gyroradius $\rho_* = \rho_i/a$ and the "peakedness" of the gaussian shaped radial profiles of R/L_n and R/L_T.

Since global simulations are considerably more costly, the electrons are approximated as adiabatic. The physical parameters of the global GENE simulations are chosen so that at $x = 0.5a$ they correspond to the CBC parameters in Table 1. The safety factor profile $q(x)$ is a monotonically increasing polynomial. To gain a comparable measure with results from flux-tube (local) simulations the heat flux can be averaged over the region $x/a = 0.4 - 0.6$.

To understand the role of nonlocal effects we compare the time averaged radial heat flux Q_{turb} from nonlinear global ($\rho_* = 1/300$) simulations with local nonlinear simulations and EDWM results for different values of R/L_n ($R/L_n(x/a = 0.5)$ in the global case).

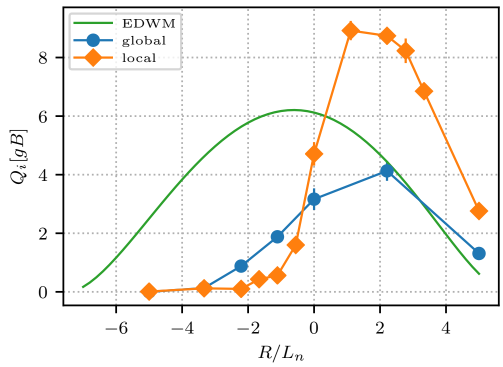
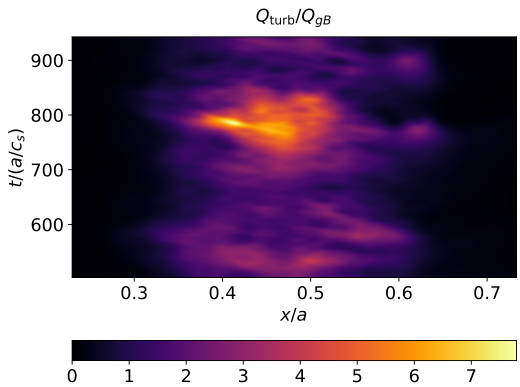


Figure 3: Time and radially ($x/a = 0.4 - 0.6$) averaged heat flux depending on the amplitude of R/L_n profile

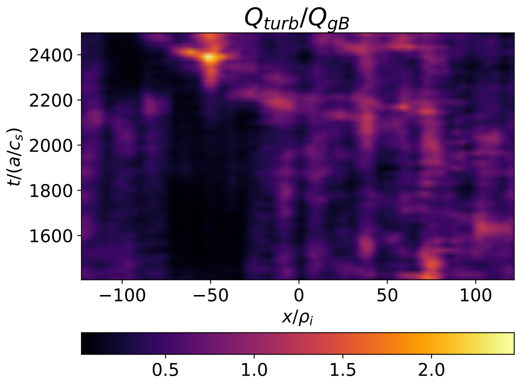
As Fig. 3 shows, EDWM only very qualitatively reproduces the dependency of Q on the density gradient found in GENE simulations. Since the fluid model is orders of magnitude cheaper to run and the current result only takes one mode ($k_\perp \rho = 0.2$) into consideration, we consider this a good base for further tests and refinements.

For positive R/L_n the GENE results reproduce the well-established observation that a system with finite ρ_* has lower turbulent heat flux then its local counterpart[5, 10]. When the density profile becomes hollow, however, the local system has a higher and sharper critical threshold value for R/L_n. Thus we observe finite heat flux in the global simulation while there is no more transport in the flux-tube limit.

A possible explanation for this can be found in the time and spatially resolved flux patterns which we show in Fig. 4 for $R/L_n = -1.1$. While the regions of stronger flux remain very localised in the local case (Fig. 4b), the global system exhibits radially extended avalanche events (Fig. 4a). This could indicate that the damping mechanisms are more affected by the profile shearing and turbulent spreading can occur.



(a) global, $\rho_* = 1/300$



(b) local

Figure 4: Temporal-radial behaviour for $R/L_n = -1.1$

Conclusion

In conclusion, we find that due to the behaviour of turbulence in a plasma region with hollow density profiles a high β and fast particles could pose problems for pellet fuelling. When nonlocal effects are important, a negative R/L_n can also have unusual consequences as they can lead to higher transport than in the flux-tube prediction.

Acknowledgements

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