Fluid and gyrokinetic modelling of particle transport in plasmas with hollow density profiles

D. Tegnered, M. Oberparleiter, H. Nordman, P. Strand

Department of Earth and Space Sciences, Chalmers University of Technology

CHALMERS UNIVERSITY OF TECHNOLOGY

Introduction

- Characteristics of particle transport in regions of hollow density profiles is an important issue for fusion plasmas.
  - Reactor grade plasmas will likely be fuelled by pellet injection that will transiently perturb the density and temperature profiles, making the density profile hollow.
  - Similar effect on the density profile may occur in connection with the L-mode to H-mode transition[1].
- A positive density gradient could stabilize the turbulence or change the relation between convective and diffusive fluxes, thereby reducing the turbulent transport of particles towards the center, making the pellet fuelling scheme inefficient[2,3].
- Here, the particle transport driven by ITG/TE mode turbulence in regions of hollow density profiles is studied by fluid as well as gyrokinetic simulations.
  - For the gyrokinetic simulations the GENE[4] code is used.
  - For the fluid simulations, an extended version of the Weiland transport model[5], Extended Drift Wave Model (EDWM)[6] is used.

Simulation details

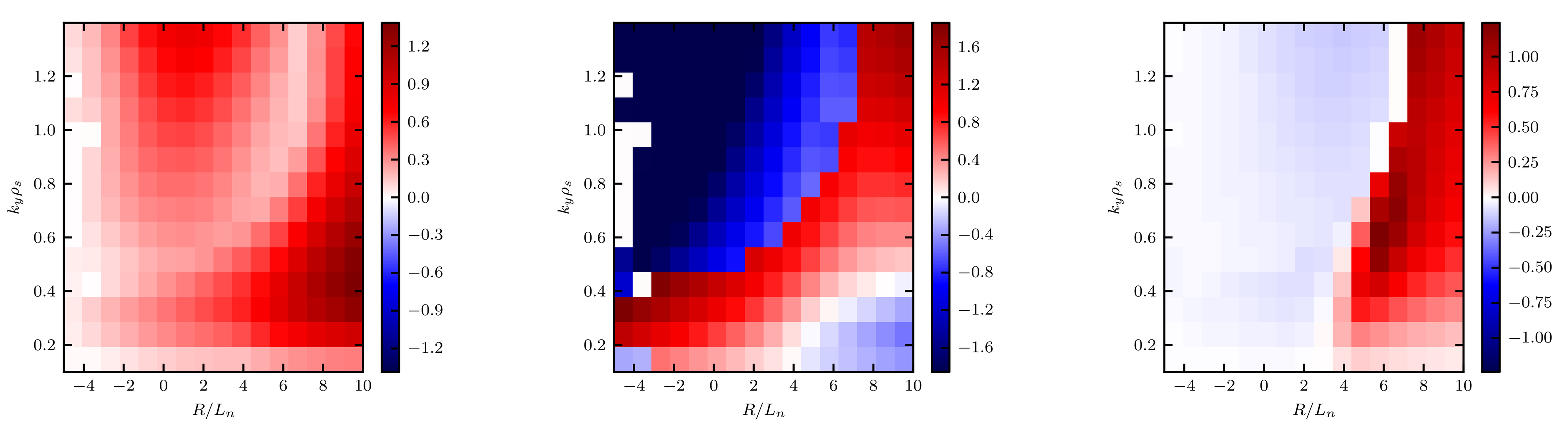
- Both linear and nonlinear simulations of ITG/TE mode turbulence performed using the gyrokinetic δf code GENE in a flux tube domain.
  - The base cases are without finite β effects and collisions, but scans has been performed in both. Fast particles and rotation are not included.

Parameter	Value
Collisions	No (unless noted)
β	No (unless noted)
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: Typical CBC parameters

  - For nonlinear GENE simulations, a simulation domain in the perpendicular plane of $[L_x, L_y] = [126, 126]$ is used, with a resolution of $[n_x, n_y] = [96, 48]$. In the parallel direction 32 grid points are used, and in the parallel velocity direction 64 grid points, and 16 magnetic moments. The simulations are typically run to $t = 300R/c_s$.
- EDWM incorporates an arbitrary number of ion species in a multi-fluid description, and an extended wavelength spectrum. Here, a single wavelength is used with $k_y\rho_s = 0.2$ or $k_y\rho_s = 0.3$.
- Parameter scans were done around those of Cyclone Base Case[7] (Table 1).
  - In the linear analysis, three main cases are studied, the original CBC with $R/L_{T_e} = R/L_{T_i} = 6.96$ which is mixed ITG/TE, an ITG case with $R/L_{T_i} = 6.96$ and $R/L_{T_e} = 0$ and a TE case with $R/L_{T_i} = 0$ and $R/L_{T_e} = 6.96$.

R/L_n and $k_y\rho_s$ scaling, $R/L_{T_e} = R/L_{T_i} = 6.96$ case

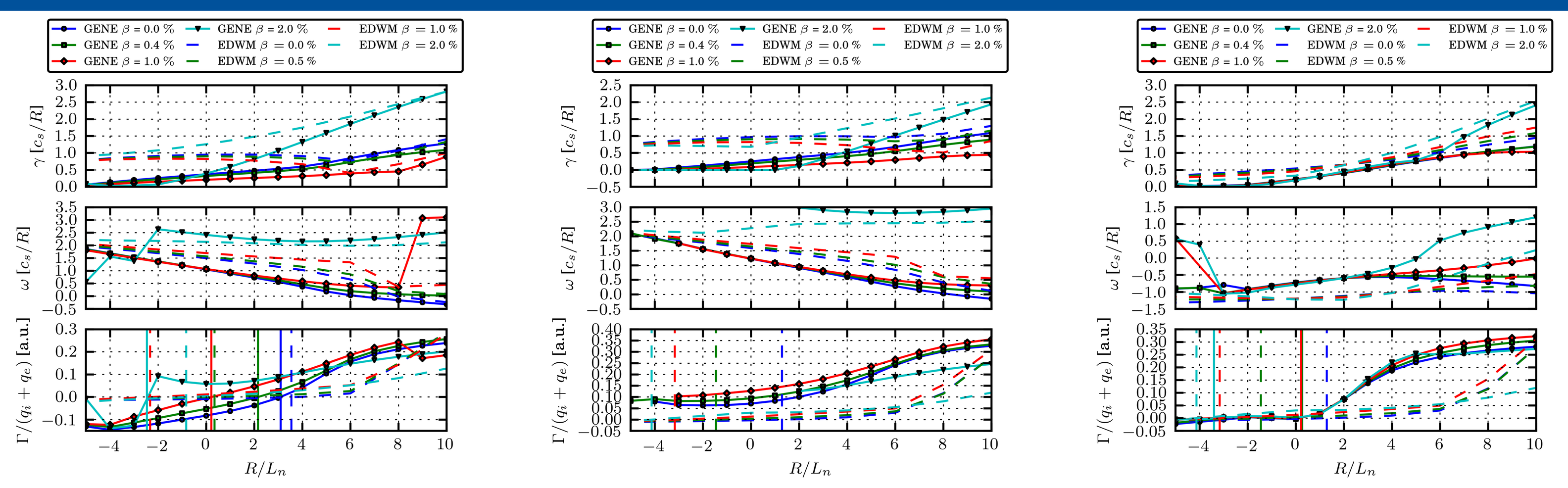


(a) Linear growth rate, γ (b) Linear real frequency, ω_r (c) Normalized flux, $\Gamma/\delta n^2$

Figure 1: GENE eigenvalues as a function of $k_y\rho_s$ and R/L_n for the mixed case where $R/L_{T_e} = R/L_{T_i} = 6.96$.

- ITG is dominating roughly in the area $k_y\rho_s < 0.5$ and $R/L_n < 4$ and the area $k_y\rho_s > 0.5$ and $R/L_n > 6$ as indicated by the positive ω_r.
- The TE-mode is dominant elsewhere, as indicated by the negative ω_r.
- The gradient of zero particle flux, indicating the background peaking factor, increases with wave number from $PF \approx 3$ at $k_y\rho_s = 0.2$ to 6 at $k_y\rho_s = 1.2$.

Fluid and gyrokinetic β and R/L_n scaling

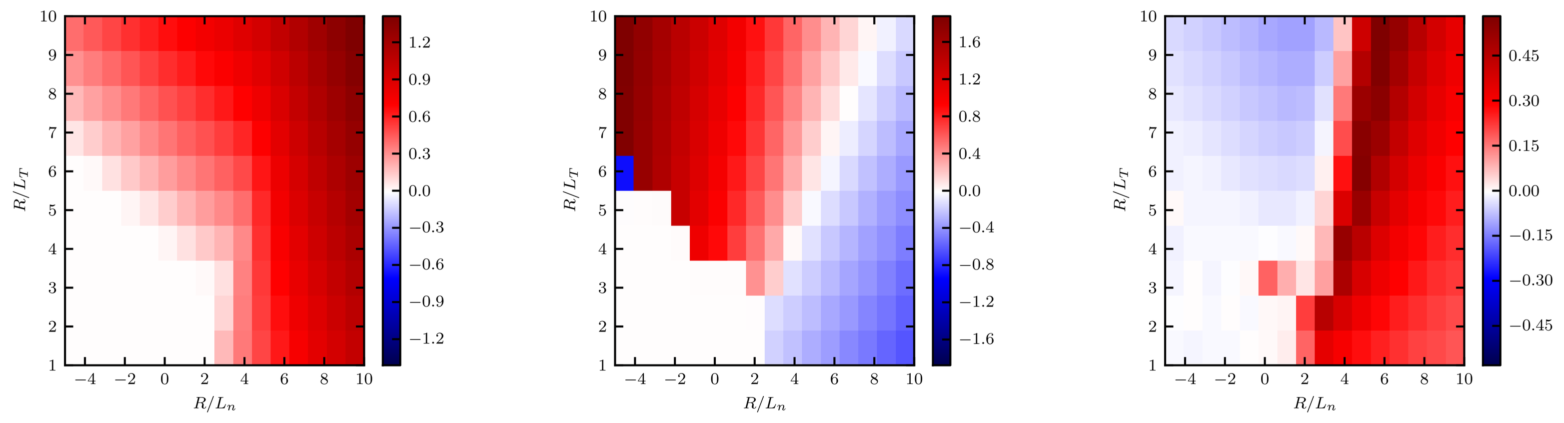


(a) The mixed ITG/TE case ($R/L_{T_e} = R/L_{T_i} = 6.96$) (b) The pure ITG case ($R/L_{T_e} = 0$, $R/L_{T_i} = 6.96$) (c) The pure TE case ($R/L_{T_e} = 6.96$, $R/L_{T_i} = 0$)

Figure 2: Linear gyrokinetic and fluid eigenvalues at $k_y\rho_s = 0.3$ in scan over R/L_n and β.

- β effects included as as magnetic field fluctuations parallel and perpendicular to the background field.
- Stabilizing effect in negative R/L_n region for ITG dominated cases.
- MHD ballooning limit higher in negative R/L_n region[8], ITG mode will stay dominant at higher β.
- Reduced background peaking factors with higher β in mixed ITG/TE case.

Scaling in R/L_n and $R/L_{T_i} = R/L_{T_e}$



(a) Linear growth rate, γ (b) Linear real frequency, ω_r (c) Normalized flux, $\Gamma/\delta n^2$

Figure 3: GENE eigenvalues as a function of R/L_n and $R/L_{T_i} = R/L_{T_e}$ at $k_y\rho_s = 0.3$.

- Pellet fuelling often leads to changes in R/L_T as well as R/L_n.
- In the negative R/L_n region the ITG-mode turbulence will eventually be stabilized with decreasing R/L_T while for higher R/L_n the TE-mode turbulence will instead be excited.
- This leads to a lower background peaking factor with the decrease in R/L_T.

Nonlinear results, $R/L_{T_e} = R/L_{T_i} = 6.96$ case

- The fluid and gyrokinetic particle fluxes agree reasonable well at $\beta = 0\%$ and $\beta = 0.5\%$.
- For $\beta = 0\%$ the particle flux is negative around $R/L_n = 0$, so particles in a pellet ablation peak would travel inwards.
- At higher β the inward flux decreases in the negative R/L_n region while it changes sign to outward in the positive region.
  - In this parameter regime, the pellet fuelling scheme would be less efficient.

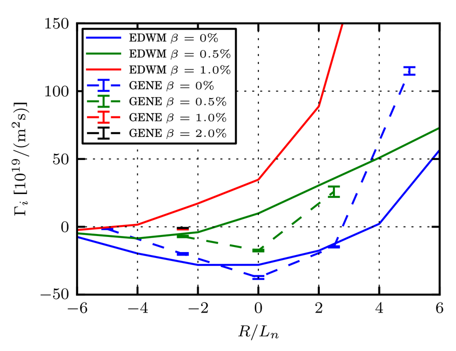


Figure 4: Nonlinear GENE and EDWM ($k_y\rho_s = 0.2$) scan in R/L_n and plasma β.

Conclusions

- In the linear gyrokinetic analysis it was found that the ITG mode is dominant in the negative R/L_n region for $k_y\rho_s < 0.5$ and that the TE mode was dominant otherwise in the $R/L_{T_e} = R/L_{T_i} = 6.96$ case.
- β was found to have a stabilizing effect in the ITG dominated cases in the negative R/L_n region in both GENE and EDWM. Increasing magnetic shear also had a stabilizing effect while adding collisions had a negligible effect.
- For the particle fluxes, a qualitative agreement between NL GENE simulations and EDWM was found, inwards around $R/L_n = 0.0$.
- Adding β effects, the inward particle flux in the negative R/L_n region decreases in both models while it changes sign to outwards in the positive gradient region. This may have serious consequences for the efficiency of the pellet fuelling scheme in high β plasmas.

Acknowledgements and references

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tegnered@chalmers.se