Gyrokinetic modelling of stationary electron and impurity profiles in tokamaks

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Introduction

- Particle transport due to Ion Temperature Gradient/Trapped Electron (ITG/TE) mode turbulence is investigated using the gyrokinetic code **GENE**.[1] Both quasilinear (QL) treatment and nonlinear (NL) simulations are performed for typical tokamak parameters. The results are compared to a computationally efficient fluid model.[2]
- A **selfconsistent** treatment is used, where the stationary local profiles are calculated corresponding to zero particle flux simultaneously for electrons and trace impurities. The scaling of the stationary profiles with **magnetic shear, safety factor, electron-to-ion temperature ratio, collisionality, toroidal sheared rotation, triangularity**, and **elongation** is investigated.
- The electron density gradient can significantly affect the stationary impurity profile scaling.[3] Thus, a selfconsistent treatment is important for parameters for which the stationary background density profile is sensitive.

Particle transport

- The local particle transport for species j can be formally divided into its diagonal and off-diagonal parts,

$$\frac{R\Gamma_j}{n_j} = D_j \frac{R}{L_{n_j}} + D_{T_j}\frac{R}{L_{T_j}} + RV_{p,j}, \quad (1)$$

  where the D_{T_j}-term is the thermopinch and $V_{p,j}$ includes contributions from curvature and parallel compression.

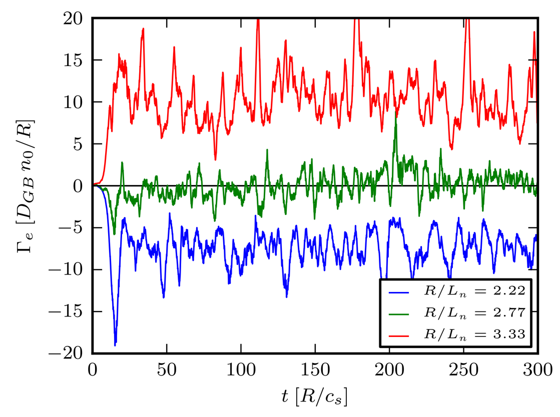


Figure 1: Electron particle flux at three density gradients

- Solving equation (1) for zero particle flux, with $V_j = D_{T_j} 1/L_{T_j} + V_{p,j}$ yields

$$PF_j \equiv \left.\frac{R}{L_{n_j}}\right|_{\Gamma=0} = -\frac{RV_j}{D_j}, \quad (2)$$

  the steady state gradient of zero particle flux for species j. It quantifies the balance between diffusion and advection, and gives a measure of how "peaked" the local density profile is at steady state, the peaking factor.

Simulation details

- NL GENE simulations were performed, PF_e was calculated first by finding the gradient of zero particle flux.
  - ▷ The results were compared to QL GENE and a fluid model.
- Impurities were included as trace species, they do not affect the turbulent dynamics:
  - ▷ PF_e was used as input while finding PF_Z.
  - ▷ Γ_Z scales linearly with the impurity gradients, the peaking factor and its contribution from thermopinch can be found.
- Parameter scans were done around those of Cyclone Base Case (Table 1).[4]

r/R	0.18
$\hat{s}$	0.796
q_0	1.4
$R/L_{n_{i,e}}$	2.22
$R/L_{T_{i,e}}$	6.96
T_i/T_e	1.0
$T_e[\mathrm{keV}]$	2.85
$n_e[10^{19}\mathrm{m}^{-3}]$	3.51
$B_0[\mathrm{T}]$	3.1
$R[\mathrm{m}]$	1.65
$\beta[\%]$	0
$\nu_{ei}[c_s/R]$	0.05

Table 1: CBC parameters

Scaling with temperature gradient

- When scanning over R/L_{T_i} (Figure 2):
  - ▷ $R/L_{T_i} < 4.5$, TE dominated, increasing peaking factor, low ion heat transport.
  - ▷ $R/L_{T_i} > 4.5$, ITG dominated, slowly decreasing peaking factor,[5] stiff increase in ion heat transport.
  - ▷ The addition of 3% Beryllium lowers the stiffness of the ion heat transport.
- Reduced models sensitive to choice of wavenumber.
- Zero particle flux is the result of a balance of outward and inward transport at different wavenumbers (Figure 3).
  - ▷ This represents a challenge for reduced models.

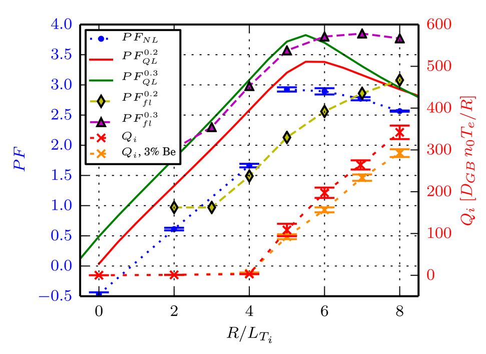


Figure 2: Scaling of PF_e and ion heat flux with R/L_{T_i}

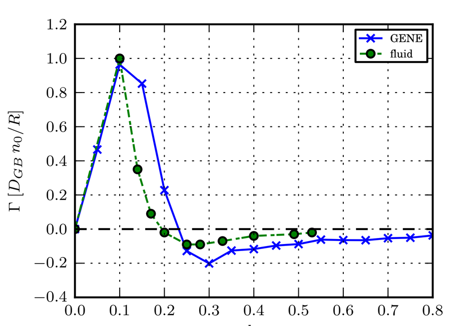
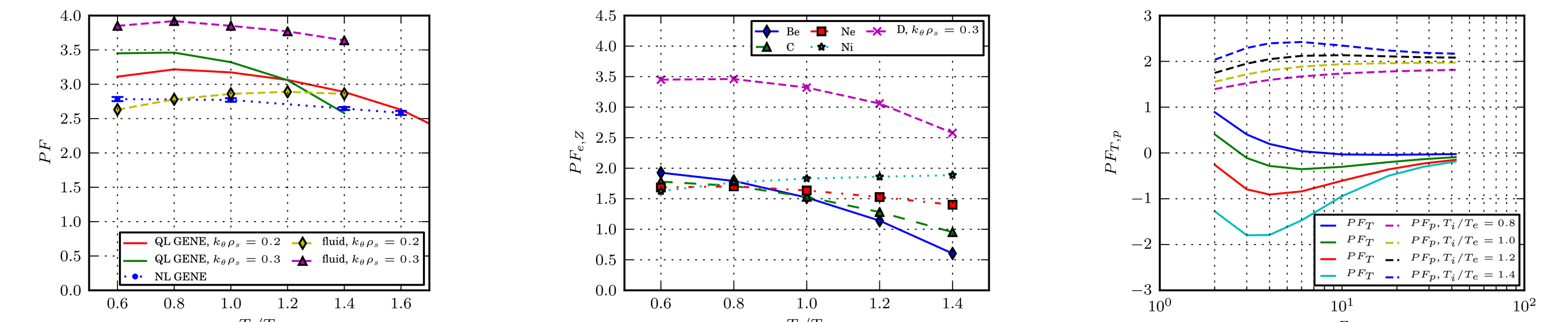


Figure 3: Normalized poloidal wavenumber spectrum at zero particle flux

Scaling with temperature ratio

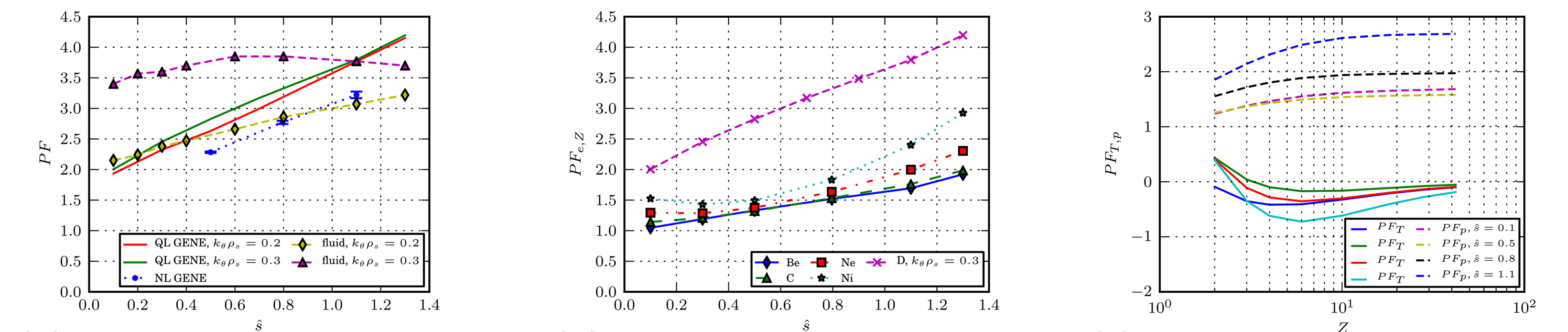


(a) NL, QL and fluid scalings of PF_e (b) Simultaneous QL scalings of PF_e and PF_Z (c) Contribution to PF_Z from thermopinch and pure convection

Figure 4: Scalings of background electron peaking and impurity peaking with T_i/T_e.

- Electron peaking reduced with increasing ion-electron temperature ratio.
- Same dependence on low-Z impurities while high-Z more flat.
  - ▷ Due to higher relative contribution of outward thermopinch for low-Z impurities $\sim 1/Z$.

Scaling with magnetic shear

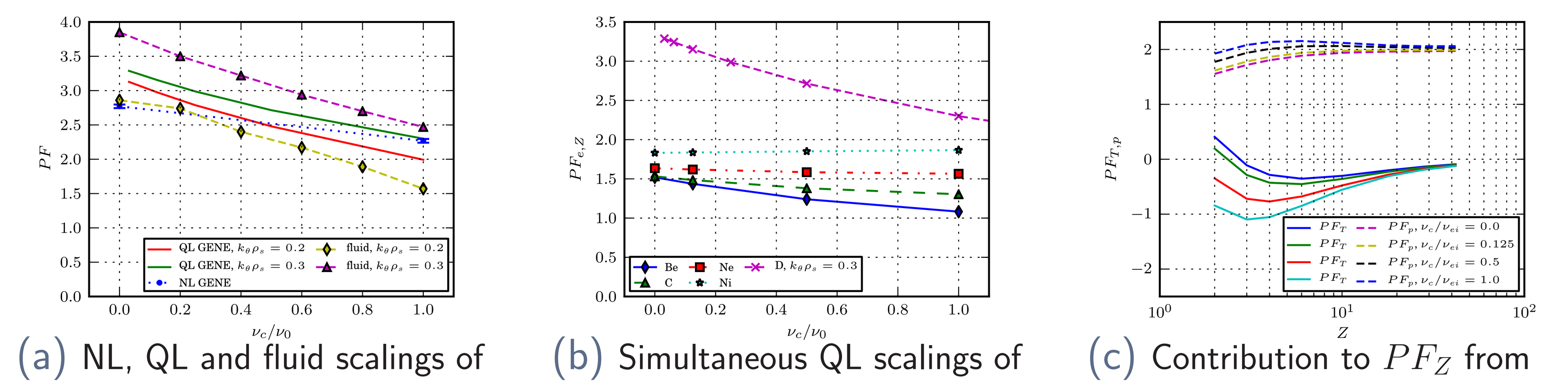


(a) NL, QL and fluid scalings of PF_e (b) Simultaneous QL scalings of PF_e and PF_Z (c) Contribution to PF_Z from thermopinch and pure convection

Figure 5: Scalings of background electron peaking and impurity peaking with $\hat{s}$.

- Electron peaking show strong nearly linear dependence of magnetic shear.
  - ▷ Due to stronger inward convective pinch as a result of the shear dependence on curvature pinch.
- PF_Z follows same trend, high-Z impurities more strongly affected.

Scaling with collisionality



(a) NL, QL and fluid scalings of PF_e (b) Simultaneous QL scalings of PF_e and PF_Z (c) Contribution to PF_Z from thermopinch and pure convection

Figure 6: Scalings of background electron peaking and impurity peaking with ν_{ei}.

- Higher collisionality reduces the peaking factors for both the background[6] and the impurities, but the effect on high-Z impurities is small.
  - ▷ Reduction in peaking factor due to larger contribution from outward thermopinch due to change in real frequency, $PF_{T,Z} \sim -\omega_r \frac{T_Z}{T_e Z} + \frac{7}{4}\left(\frac{T_Z}{T_e Z}\right)^2$.

Conclusions

- Reasonable qualitative agreement between NL, QL gyrokinetic, and fluid PF_e. Reduced models sensitive to choice of wavenumber.
- PF_e sensitive in scans over temperature ratio, magnetic shear, collisionality, and elongation, weak sensitivity for safety factor, sheared toroidal rotation, and triangularity.
- Selfconsistent treatment often results in similar trends for PF_e and PF_Z.
  - ▷ Parameter regions with simultaneously high PF_e and low PF_Z are rare.
- Low ν_{ei} favourable, allows for high PF_e with little effect on high-Z impurities.

Acknowledgements and references

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