Turbulent impurity transport driven by temperature and density gradients

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Introduction

The modelling of a modern fusion device is very challenging both theoretically and numerically, much owing to turbulence driven by sharp gradients in density and temperature. However, understanding the resulting transport is crucial for the success of future fusion devices such as ITER.

In this work, the turbulent transport of trace impurities in a tokamak device has been studied through quasilinear (QL) and non-linear (NL) gyrokinetic simulations using the GENE code [1, 2]. The parameters are chosen for trapped electron (TE) mode turbulence, driven primarily by steep electron density gradients relevant to H-mode physics, but with a transition to temperature gradient driven turbulence as the density gradient flattens. [3] The results are quantitative assessments of the transport properties of several impurity species, and the dependence thereof on various plasma parameters.

Theoretical background

Impurity transport: The transport of a *trace impurities* is locally described by:

$$\Gamma_Z = -D_Z \nabla n_Z + n_Z V_Z \tag{1}$$

where Γ_Z is the flux, n_Z the density of the impurity and R the major radius of the tokamak [4]. For the domain studied ∇n_Z is constant:

$$-R\nabla n_Z / n_Z = R/L_{n_Z}, \tag{2}$$

leading to the linear impurity flux relation:

$$\frac{R\Gamma_Z}{n_Z} = D_Z \frac{R}{L_{n_Z}} + RV_Z. \tag{3}$$

Equations (1) and (3) highlights the two main contributions to impurity transport: [5]

- diffusive transport – diffusion coefficient: D_Z,
- convective transport – convective velocity ("pinch"): V_Z.

In the core region convection and diffusion balance to give zero flux. The *zero flux peaking factor* that quantifies this:

$$PF_Z = -\frac{RV_Z}{D_Z}\bigg|_{\Gamma_Z=0}. \tag{4}$$

Thus PF_Z is interpeted as the *gradient of zero flux*. This is illustrated in figure 1.

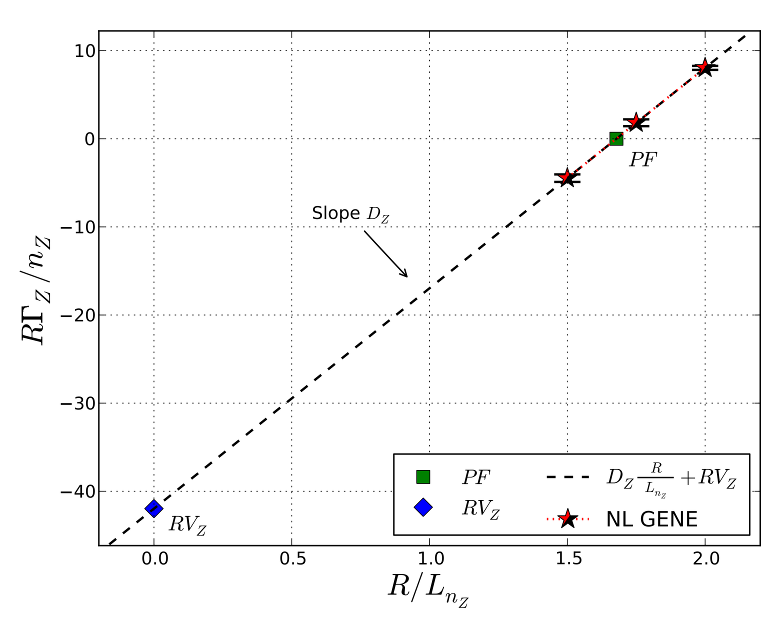

FIGURE 1: The **impurity flux dependence** on ∇n_Z, illustrating PF_Z and the validity of the linearity assumption (3) of **equation** (1) for $\Gamma_Z \sim 0$, and how the parameters of **equation** (3) are estimated. Data from NL GENE simulations.

The impurity transport equation (1) can be derived from

$$\Gamma_{nj} = \langle \delta n_j \boldsymbol{v}_{\boldsymbol{E}\times\boldsymbol{B}} \rangle, \tag{5}$$

where $\langle\cdot\rangle$ means a spatial averaging; see [4, 6] for details.

Gyrokinetic simulations: Non-linear models are neccessary to capture the full dynamics of the fusion plasma, including actual fluctuation levels. To this end, NL and QL simulations were performed with the GENE code [1, 2], a massively parallel gyrokinetic code.

Results

Main parameters: Parameters were chosen with [3] in mind, to be in the ∇n_e driven TEM regime. Unless otherwise noted, $R/L_{n_e} = R/L_{n_i} = 8.0$, and $R/LT_e = 5.0$ and $R/L_{T_i} = R/L_{T_Z} = 2.0$. QL simulations were performed with $k_\theta \rho_s = 0.2$.

Scaling of PF_Z with Z: NL and QL results for the ∇n_e driven TEM impurity pinch are similar to those for ∇T_e driven TE mode reported in [6]. Only a very weak scaling is observed, with PF falling toward saturation for higher Z.

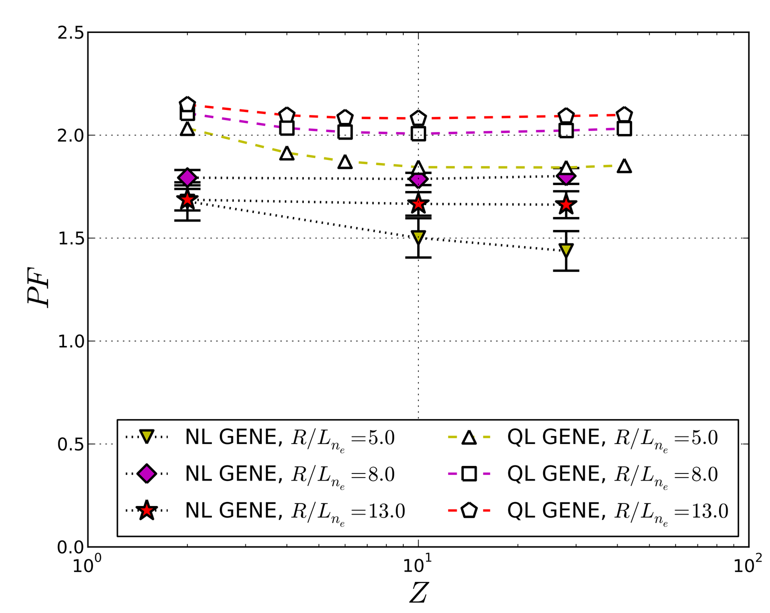

FIGURE 2: Scaling of PF with **impurity charge** (Z) shows saturation for heavt impurities.

Scaling of PF_Z with ∇n_e: As the density profile becomes more peaked, a corresponding increase in difusion is expected. Both NL and QL results indicate that this is balanced by the pinch for very steep gradients, leading to a saturation of $PF \sim 2$. This is in contrast to the QL growth rate γ, which increases uniformly. We note that the impurity peaking is substantially weaker than that of the background, for $R/L_{n_e} \gtrsim 2$, and that a *flux reversal* is observed for very flat profiles ($R/L_{n_e} \sim 2$).

It has been observed in [3] that for $R/L_{n_e} \lesssim R/L_{T_e}$, temperature gradient driven TEM turbulence dominates. Our results indicate a smooth transition from density gradient driven TEM, though the bump in ω_r may be a result of the mode change.

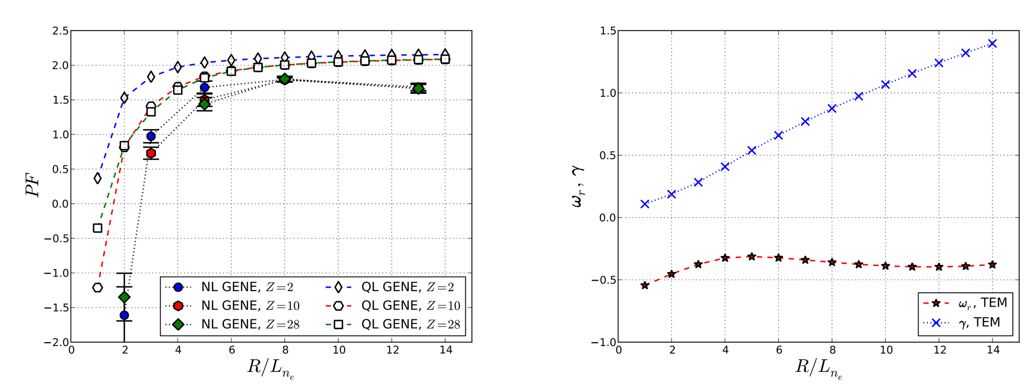

FIGURE 3: Scaling of PF_Z with **electron density gradient** (R/L_{n_e}) shows saturation for peaked profiles, despite increased QL growthrate. A flux reversal is observed with both QL and NL for flat background density profiles.

Background ion flux levels: The PF_p for the background protons can be found by similar means to that of PF_Z. Our results, however, indicate that for $R/L_{T_e} = 5.0$, lower density gradients only result in $\Gamma_p \to 0$, not in flux reversal. This means that the pinch $V_p = 0 \Rightarrow PF_p = 0$.

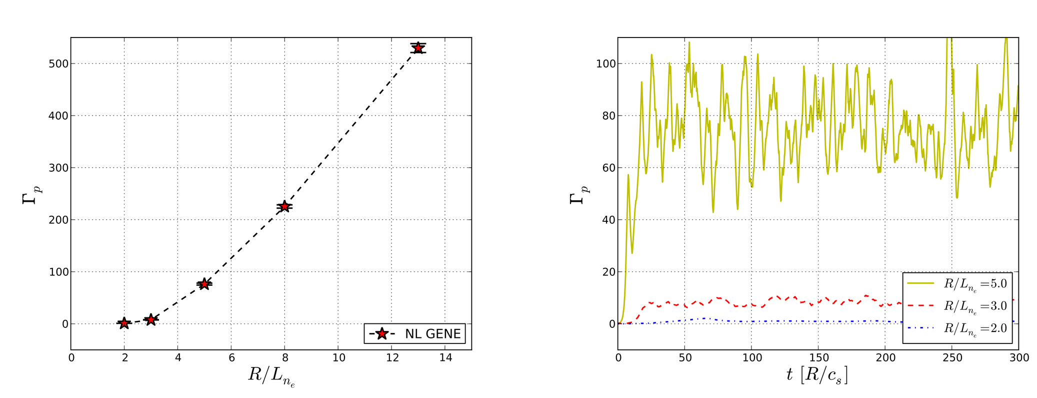

FIGURE 4: Scaling of **main ion flux** with R/L_{n_e} shows that for $R/L_{T_e} = 5.0$ a background pinch is not observed.

Multiple gradients and resolution: Since PF_Z is much lower than the driving R/L_{n_e}, the simulation required a correspondingly smaller ∇n_Z. An observed effect of this, was that the $k_\perp$ spectra of the impurities were shifted toward larger k. As the effect was persistent, despite changes in resolution, this is not thought to be a purely numerical artifact.

This observation meant that, in order to investigate systems with trace species in steep driving gradients, precautions had to be taken to ensure that the trace dynamics were properly resolved.

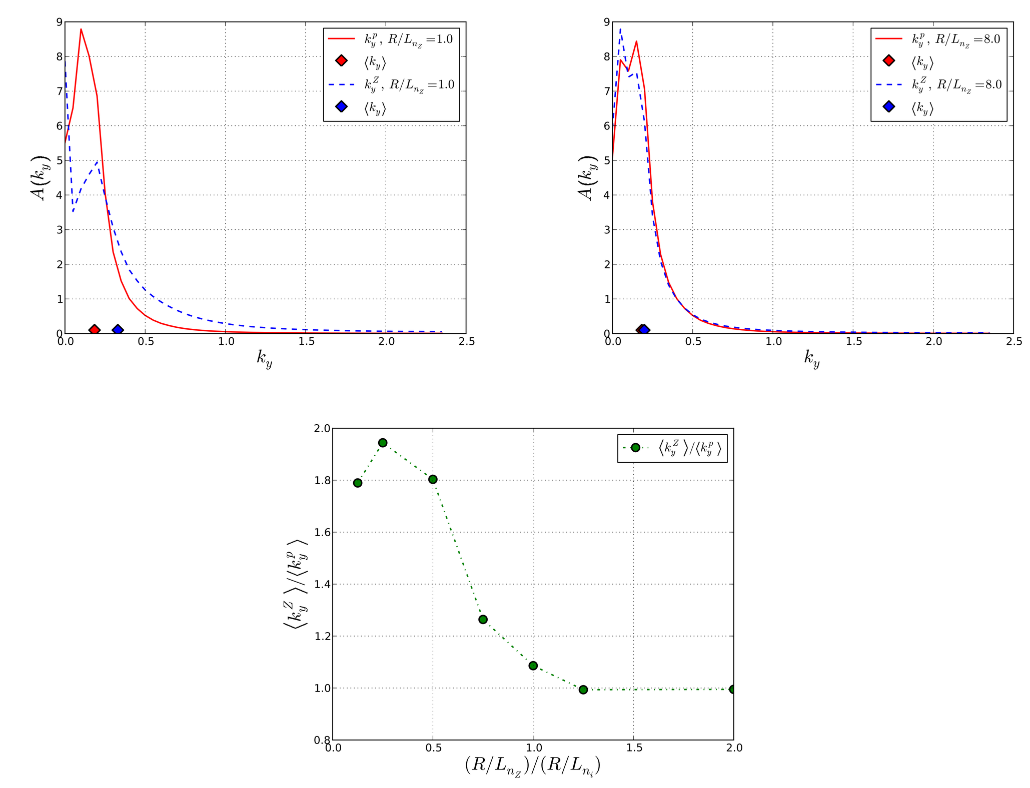

FIGURE 5: The $k_\perp$ spectra of the impurities show a shift toward larger k, when $R/L_{n_Z} < R/L_{n_e}$. The trend is investigated by measuring the quotient between the mean k_y of impurity and main ions, as a function of $(R/L_{n_Z})/(R/L_{n_e})$.

Conclusions and outlook

- PF_Z decreases with the impurity charge Z for TE mode dominated transport
- QL simulations over-estimate PF compared to NL, as seen in previous studies [6]
- Turbulent peaking factors are much smaller than neoclassical predictions for high Z
- Peaking of impurities is much smaller than for the background in th high ∇n_e regime
- An impurity flux reversal is observed for flat background densities ($R/L_{n_e} \sim 2$)
- The numerical resolution needed to be increased when studying species with different density profiles
- Future work will focus on more direct comparisons with experiments, including more details in the physics description and realistic magnetic geometry, and on self consistent studies of simultaneous background and impurity peaking

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The simulations were performed on resources provided on the Lindgren [7] and HPC-FF [8] high performance computers, by the Swedish National Infrastructure for Computing (SNIC) at Paralleldatorcentrum (PDC) and the European Fusion Development Agreement (EFDA), respectively.

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