Turbulent impurity transport in fusion plasmas

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Introduction

The 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], and with QL fluid simulations [3]. The results are quantitative and qualitative assessments of the transport properties of several impurity species, and the dependence thereof on various plasma parameters.

Theoretical background

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

$$\Gamma_Z = -D_Z \nabla n_Z + n_Z V_Z \Leftrightarrow \frac{R\Gamma}{n_Z} = D_Z \frac{R}{L_{n_Z}} + RV_Z, \qquad (1)$$

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:

$$-\nabla n_Z / n_Z = 1/L_{n_Z}. \qquad (2)$$

Equation (1) 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:

$$PF_0 = \frac{-RV_Z}{D_Z}\Big|_{\Gamma=0}. \qquad (3)$$

Thus PF_0 is interpeted as the *gradient of zero flux*. This is illustrated in figure 4.

Equation (1) can be derived from the equations of the Weiland multi-fluid model [3]:

$$\frac{\partial n_j}{\partial t} + \nabla\cdot(n_j \boldsymbol{v}_j) = 0, \qquad (4)$$

$$m_{i,Z} n_{i,Z} \frac{\partial v_{\|i,Z}}{\partial t} + \nabla_{\|}(n_{i,Z} T_{i,Z}) + n_{i,Z} q_j \nabla_{\|}\varphi = 0, \qquad (5)$$

$$\frac{3}{2} n_j \frac{\mathrm{d}T_j}{\mathrm{d}t} + n_j T_j \nabla\cdot\boldsymbol{v}_j + \nabla\cdot\boldsymbol{q}_j = 0, \qquad (6)$$

for each included species ($j = i, te, Z$ – Deuterium ions, trapped electrons, and trace impurities). Going to the trace impurity limit $(Zf_Z \to 0)$ in the quasineutrality condition (7),

$$\frac{\delta n_e}{n_e} = (1 - Zf_Z)\frac{\delta n_i}{n_i} + Zf_Z \frac{\delta n_Z}{n_Z}, \quad f_Z = \frac{n_Z}{n_e}, \qquad (7)$$

an eigenvalue equation for ITG and TE modes, is obtained. The impurity transport equation (1) is now derived from

$$\Gamma_{nj} = \langle \delta n_j \boldsymbol{v}_{\boldsymbol{E}\times\boldsymbol{B}} \rangle, \qquad (8)$$

where $\langle\cdot\rangle$ represents a spatial averaging [4].

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.

In *gyrokinetics* an averaging is performed over the gyro orbit, so that one velocity space coordinate is removed and phase space reduced from 6 to 5 dimensions.

An example numerical experiment

As an illustration, the derivation of D_Z and V_Z from NL GENE data is presented below for ITG mode dominated L-mode JET discharge #67730, with *Molybdenum* (Mo; $Z = 42$) impurity in a *Deuterium* (D) plasma. Snapshots taken at $t \approx 300\, c_s/R$; error-bars mark two estimated standard deviations.

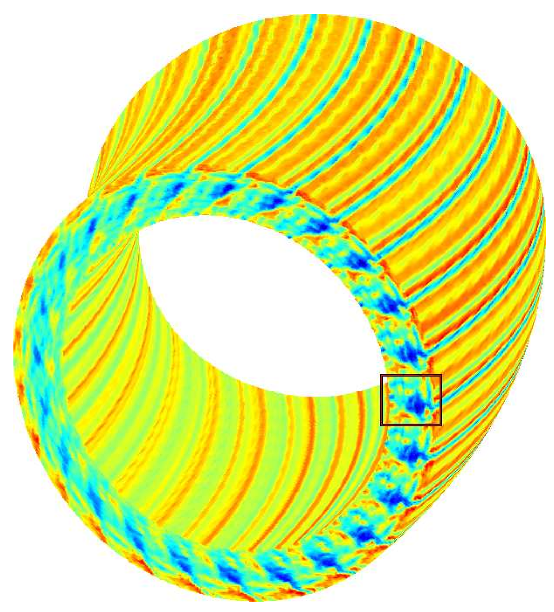

Figure 1: One eighth of the **toroidal annulus** made up of the flux tube as it twists around the torus following the $\boldsymbol{B}$ field, showing the fluctuation of n_D, the density of background ions. Marked area corresponds to the **cross-section in figure 2**.

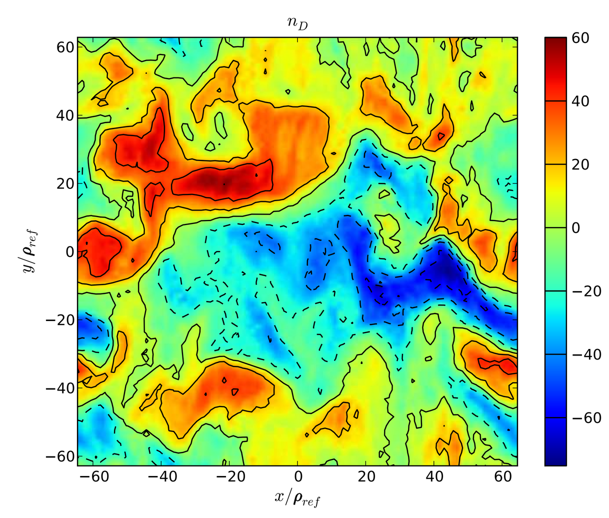

Figure 2: **Cross-section of the flux tube** showing the scale of the turbulent fluctuations in n_D, the density of background ions. Scale ρ_{ref} is the main ion cylcotron radius; note the periodic boundary conditions. Corresponds to **marked area in figure 1**.

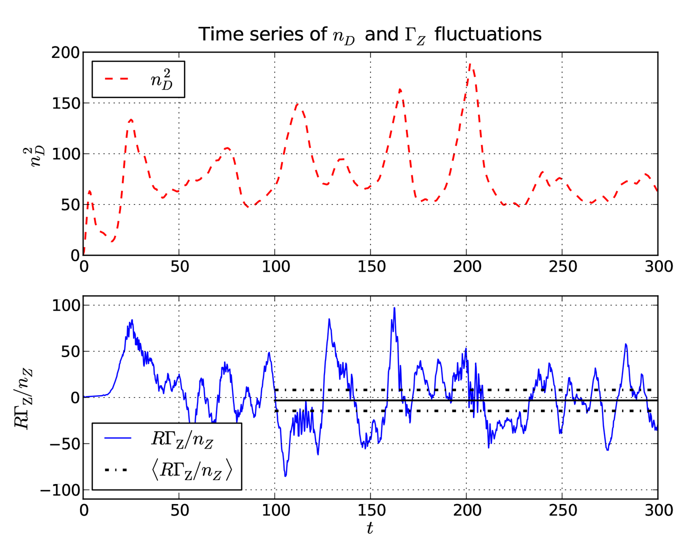

Figure 3: **Integrating over the simulation domain in figures 1 and 2** yields time-series of scalar quantities. Fluctuations of main ion density (n_D; – –) and impurity flux (Γ_Z; —) are shown, along with average impurity flux with estimated error (· – ·), corresponding to the **third data point in figure 4**.

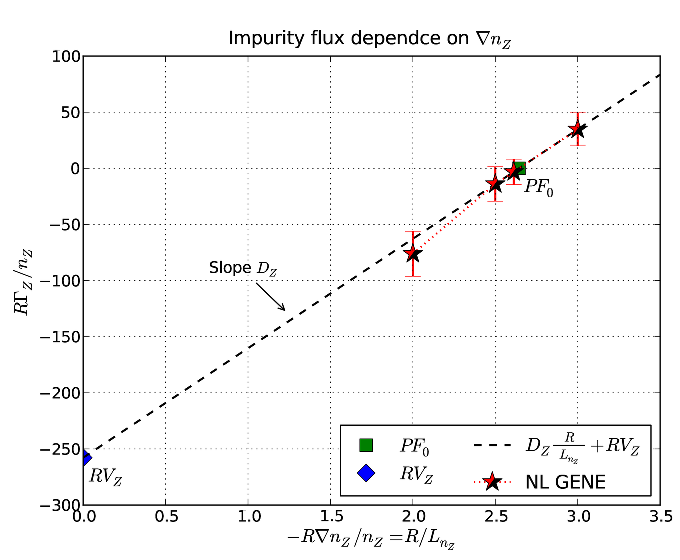

Figure 4: **Impurity flux dependence on** ∇n_z, illustrating PF_0 and the validity of the linearity assumption (1) of $\Gamma_Z|_{\nabla n_Z \approx 0}$ for trace impurities. Parameters of **equation** (1) are estimated from the three samples closest to $\Gamma_Z = 0$.

Results

The difference between the ITG and TE mode dominated cases shown in figure 5 can be understood from convective velocity V_Z in (1), which contains two important terms: [4]

- thermodiffusion:
  - $V_{T_Z} \sim \frac{1}{Z}\frac{R}{L_{T_Z}}$
  - outward for ITG $(V_{T_Z} > 0)$, inward for TE $(V_{T_Z} < 0)$
- parallel impurity compression:
  - $V_{p_Z} \sim \frac{Z}{A_Z} k_{\|}^2 \sim \frac{Z}{A_Z q^2}$
  - inward for ITG $(V_{p_Z} < 0)$, outward for TE $(V_{p_Z} > 0)$

This yields the high and low Z behaviours observed in the simulations.

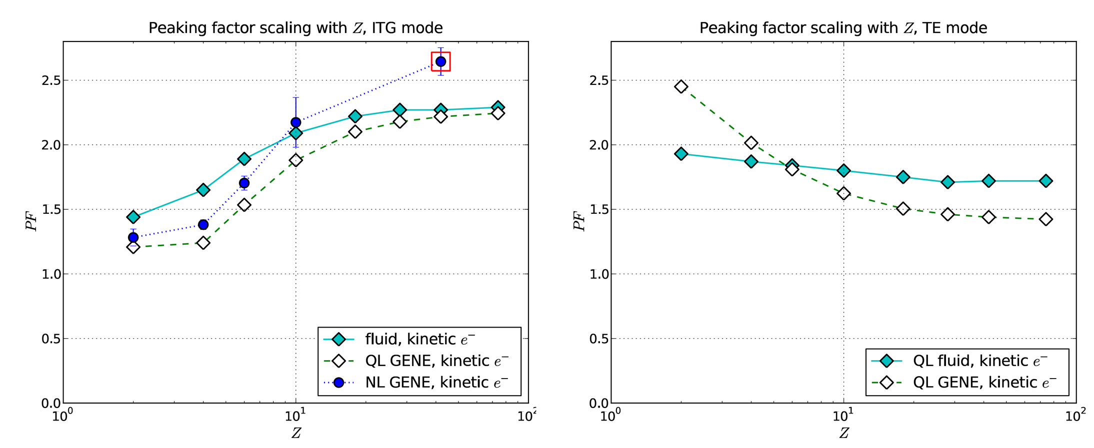

Figure 5: **Scaling of** PF_0 **with impurity charge** Z for ITG and TE mode cases; comparison of NL GENE, and QL GENE and fluid results with $k\rho_s = 0.3$. Error-bars for non-linear results mark two estimated standard deviations. The sample for the Mo impurity acquired from the data **illustrated in figures 1–4** is highlighted (□).

Scaling of PF_0 with temperature gradients (figure 6) is weak, despite strong influence on eigenvalues and fluctuation levels, as expected from theory [6].

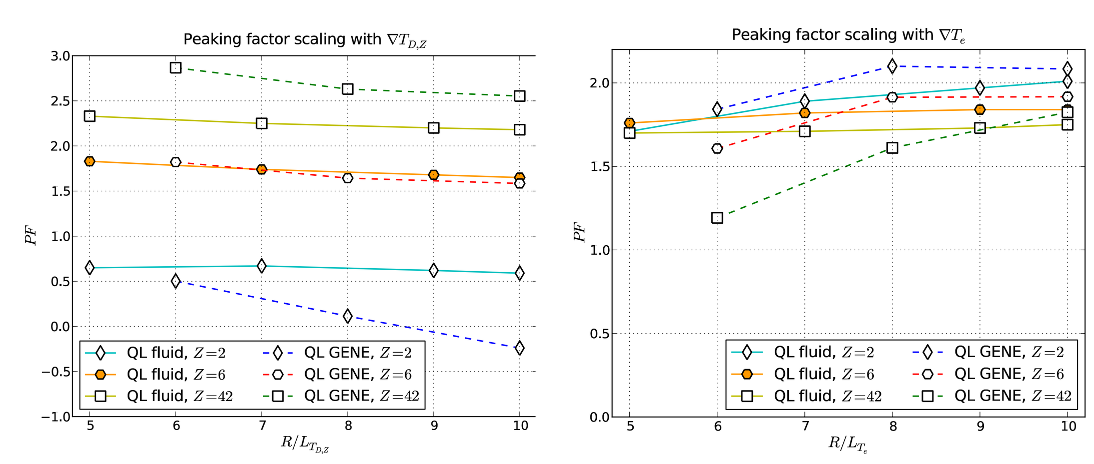

Figure 6: Scaling of PF_0 with temperature gradients $\nabla T_{D,Z}$ and ∇T_e; comparison of QL GENE and fluid results with $k\rho_s = 0.3$.

Conclusions and outlook

- PF_0 increases with the impurity charge Z for ITG mode dominated transport
- For TE mode dominated transport, the opposite holds
- Gyrokinetic results agree well with fluid results
- Simulations agree well with JET experiments for injected impurities (Ne, Ar, Ni)
- Turbulent peaking factors are much smaller than neoclassical predictions for high Z
- Future work will focus on more direct comparisons with experiments, including more details in the physics description and realistic magnetic geometry

References

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