Impurity transport in ITG and TE mode dominated turbulence

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Introduction

The transport properties of impurities is of high relevance for the performance and optimisation of magnetic fusion devices. For instance, if impurities from the plasma-facing surfaces accumulate in the core, wall-impurities of relatively low density suffice to dilute the plasma and lead to unacceptable energy losses in the form of radiation.

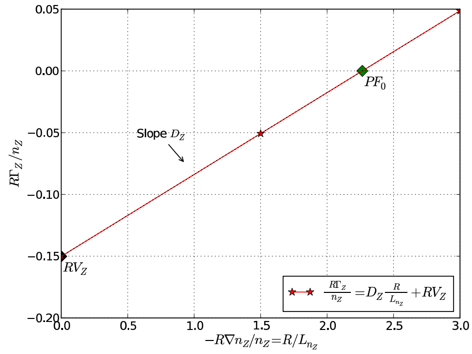


Figure 1: Illustration of PF_0 and the linearity of $\Gamma_Z\,(\nabla n_Z)$; ITG dominated quasi-linear GENE result for Ne with $k\rho = 0.3$

In the present study, turbulent impurity transport in Deuterium tokamak plasmas, driven by Ion Temperature Gradient (ITG) and Trapped Electron (TE) modes, has been investigated using fluid and gyrokinetic models. The impurity diffusivity (D_Z) and convective velocity (V_Z) are calculated, and from these the zero-flux peaking factor (PF_0) is derived. This quantity expresses the impurity density gradient at which the convective and diffusive transport of impurities are exactly balanced. The sign of PF_0 is of special interest, as it determines whether the impurities are subject to an inward ($PF_0 > 0$) or outward ($PF_0 < 0$) pinch.

Quasilinear results obtained from the GENE code [1, 2] are compared with two-fluid results [3] for both ITG and TE mode dominated turbulence. Scalings of PF_0 with impurity charge (Z) and various plasma parameters, such as magnetic shear ($\hat{s}$), are studied. Of particular interest are conditions favouring an outward convective impurity flux.

Theoretical background

The transport of a trace impurity species can locally be described by a *diffusive* and a *convective* part. The former is characterized by the diffusion coefficient D_Z, the latter by a convective velocity or "pinch" V_Z, see equation (1) [4]. From these, the *zero flux peaking factor* is defined as $PF_0 = \frac{-RV_Z}{D_Z}|_{\Gamma=0}$, see figure 1. PF_0 is important in reactor design, as it quantifies the balance of convective and diffusive transport. This can be seen from equation (1), where Γ_Z is the impurity flux, n_Z the density of the impurity species and R the major radius of the tokamak.

For the domain studied – a narrow flux tube – the gradient of the impurity density is constant: $\nabla n_Z/n_Z = 1/L_{n_Z}$. Setting $\Gamma_Z = 0$ in equation (1) yields the interpretation of PF_0 as the gradient of zero impurity flux.

$$\Gamma_Z = -D_Z\nabla n_Z + n_Z V_Z \Leftrightarrow \frac{R\Gamma}{n_Z} = -D_Z\frac{R}{L_{n_Z}} + RV_Z \tag{1}$$

Fluid model

Though the main results presented in this study have been obtained using quasilinear gyrokinetic simulations, their physical meaning is interpreted by comparing with the Weiland multi-fluid model [3]. The fluid equations for each included species ($j = i,\ te,\ Z$, representing Deuterium ions, trapped electrons, and trace impurities) are:

$$\frac{\partial n_j}{\partial t} + \nabla\cdot(n_j\boldsymbol{v}_j) = 0 \tag{2}$$

$$m_{i,Z}n_{i,Z}\frac{\partial v_{||i,Z}}{\partial t} + \nabla_{||}\left(n_{i,Z}T_{i,Z}\right) + n_{i,Z}e\nabla_{||}\varphi = 0 \tag{3}$$

$$\frac{3}{2}n_j\frac{\mathrm{d}T_j}{\mathrm{d}t} + n_jT_j\nabla\cdot\boldsymbol{v}_j + \nabla\cdot\boldsymbol{q}_j = 0 \tag{4}$$

Here $\boldsymbol{q}_j$ is the diamagnetic heat flux, and $\boldsymbol{v_j}$ is the sum of the $\boldsymbol{E}\times\boldsymbol{B}$, diamagnetic drift, polarization drift, and stress-tensor drift velocities. To solve the equations, it is assumed that $\boldsymbol{q}_j$ is the only heat flux for all species, that passing electrons are adiabatic, and that quasineutraility (equation (5)) holds. Going to the trace limit for the impurities, i.e. letting $Zf_Z \to 0$ in equation (5), an eigenvalue equation for ITG and TE modes is obtained. The impurity particle flux in equation (1) is then obtained from $\Gamma_{nj} = \langle\delta n_j\boldsymbol{v}_{\boldsymbol{E}\times\boldsymbol{B}}\rangle$, where the averaging is performed over all unstable modes for a fixed length scale $k\rho$ of the turbulence.

$$\frac{\delta n_e}{n_e} = (1 - Zf_Z)\frac{\delta n_i}{n_i} + Zf_Z\frac{\delta n_Z}{n_Z},\ \ f_Z = \frac{n_Z}{n_e} \tag{5}$$

Quasilinear gyrokinetic simulations

GENE is a parallel gyrokinetic code employing a fixed grid in five dimensional phase space and a flux-tube geometry [1]. The simulations were performed on the *HPC-FF* cluster[1] with GENE running in eigenvalue mode. Growth rates and impurity fluxes were thus computed for ITG and TE mode dominated cases, for which a number of parameters were varied and trends observed. The main parameters used are presented in table 1.

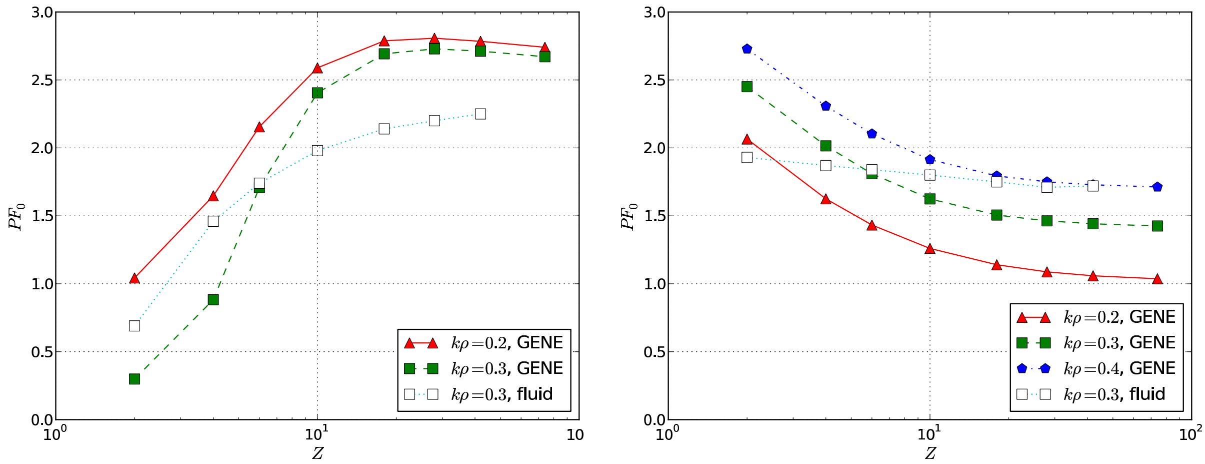
[1]HPC-FF (*High Performance Computing For Fusion*) is an EFDA funded computer situated at Forschungszentrum Jülich. Germany, dedicated to fusion research

Table 1: Parameters used in all simulations

	ITG:	TEM:
T_D/T_e:	1.0	1.0
$\hat{s}$:	0.8	0.8
q_0:	1.4	1.4
ε:	0.14	0.14
$R/L_{T_D}, R/L_{T_Z}$:	7.0	3.0
R/L_{T_e}:	3.0	7.0
$N_x \times N_{ky} \times N_z$:	$5 \times 1 \times 24$	$4 \times 1 \times 24$
$N_{v_{\|\|}} \times N_\mu$:	64×12	64×12

Results

Impurity charge Z: The main results obtained are the scalings of the peaking factor with the charge of the impurity species. These are presented in figures 2(a) and 2(b), showing ITG and TE mode dominated turbulence respectively.



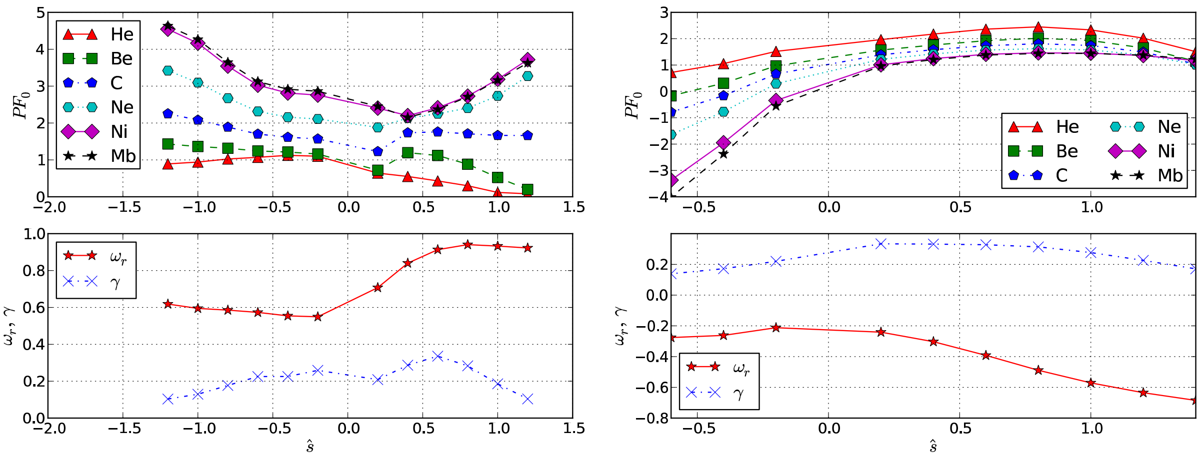
(a) ITG mode dominated case

(b) TEM dominated case

Figure 2: Scalings of PF_0 with impurity charge Z; quasilinear GENE and fluid results

The difference between figure 2(a) and 2(b) can be understood from the properties of the convective velocity in (1). V_Z contains a thermodiffusive term $V_{T_Z} \sim \frac{1}{Z}\frac{R}{L_{T_Z}}$ and a parallel impurity compression term $V_{pZ} \sim \frac{Z}{A_Z} k_{||}^2 \sim \frac{Z}{A_Z q^2}$. The former is generally outward ($V_{T_Z} > 0$) for ITG and inward ($V_{T_Z} < 0$) for TE mode dominated transport, whereas for the latter the opposite is generally the case.

Magnetic shear $\hat{s}$: The effect of magnetic shear on the peaking factor is shown in figures 3(a) and 3(b). It is worth noting that a flux reversal, i.e. a change of sign in PF_0, owing to a change in sign of V_Z, occurs for negative $\hat{s}$ for $Z \gtrsim 6$ in the TE mode dominated case, indicating a net outward transport of the heavier elements. Similar trends are not seen in fluid simulations, and this warrants further investigation.



(a) ITG mode dominated case

(b) TEM dominated case

Figure 3: Scalings of PF_0 with magnetic shearing $\hat{s}$; quasilinear GENE results with $k\rho = 0.3$

Other parameters: Scans of the dependence PF_0 on other parameters, such as $k\rho$ and L_T, have also been carried out. The results are similar to those reported in [5], [6] and [7] respectively. In most cases, only a weak dependence of PF_0 is observed.

Conclusions and outlook

Quasilinear GENE simulations and fluid results show that peaking factor increases with impurity charge Z for ITG mode dominated transport, whereas the opposite holds for TE mode dominated transport. In both cases PF_0 saturates for high Z.

For magnetic shear, a flux reversal is observed for negative magnetic shear in the TEM dominated case. This is not seen in fluid simulations, and will be a focus of future studies.

For other parameters investigated, weak scalings for PF_0 are observed, in agreement with previous work.

References

[1] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers. Electron temperature gradient driven turbulence. *Physics of Plasmas*, 7(5):1904–10, May 2000.

[2] F. Merz. *Gyrokinetic Simulation of Multimode Plasma Turbulence*. Monography, Westfälischen Wilhelms-Universität Münster, 2008.

[3] J. Weiland. *Collective Modes in Inhomogeneous Plasma*. Institute of Physics Publishing, London, UK, 2000.

[4] C. Angioni and A. G. Peeters. Direction of impurity pinch and auxiliary heating in tokamak plasmas. *PRL*, 96:095003–1–4, 2006.

[5] T. Dannert. *Gyrokinetische Simulation von Plasmaturbulenz mit gefangenen Teilchen und elektromagnetischen Effekten*. Monography, Technischen Universität München, January 2005.

[6] H. Nordman, R. Singh, and T. Fülöp et al. Influence of the radio frequency ponderomotive force on anomalous impurity transport in tokamaks. *PoP*, 15:042316–1–5, 2007.

[7] T. Fülöp and H. Nordman. Turbulent and neoclassical impurity transport in tokamak plasmas. *PoP*, 16:032306–1–8, 2009.

This work benefited from an allocation on the EFDA HPC-FF computer.