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Turbulent Transport of Plasma Edge Impurities

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Introduction

Both bulk particles as well as impurities have their main sources at the edge of magnetic fusion devices but their profiles are often found to be peaked toward the center and only sometimes to be hollow [1]. Non-hollow profiles indicate inward and up-gradient transport, expressed by introducing besides a diffusion coefficient an effective convective pinch velocity. Neo-classical pinches are usually too weak to explain the observed profiles and anomalous pinch effects need to be invoked. Experimentally the details of the transport process are difficult to assess, and most of the insight which has been gained on anomalous transport is due to the use of large scale first principles numerical simulations. These usually take advantage of the wide separation of spatial and temporal scales in a plasma, restricting the role of the turbulence to work on a static background. This rules out the interaction of the turbulence – including the flows the turbulence might generate – with the pressure gradient. In this paper we try to maximise the amount of information on impurity transport that can be achieved from fluctuation based turbulence simulations. Passive tracer dynamics has no backreaction on the turbulence, but we need not to resort to the usual assumptions on separation between scales.

How can particles and densities be passive?

The question on when a particle population in a plasma can be described as passive is not at all easy to answer. Certainly the passive tracer particle density n_{imp} needs to be small compared with the bulk plasma density $n_{imp}/n \ll 1$. The impurity contribution to quasineutrality must everywhere be smaller than each of the other species contribution to quasi-neutrality which arise from their fluctuations. Thus, we have to fulfill a more strict relationship: A passive density is everywhere smaller then the bulk current divergence building up in a characteristic time, e.g., for drift-wave turbulence with a characteristic time given by ρ_s/c_s:

$$Z_{imp} n_{imp} \ll \rho_s/c_s \sum_{i,e} \nabla \cdot (n V_{i,e}) \, .$$

Using drift wave scaling we can reformulate for fluctuations on scale ρ_s. In dimensionless quantities we obtain

$$Z_{imp} n_{imp} \ll \min(\tilde{n} V_{i,e}) \, .$$

This strict condition cannot be guaranteed to be fulfilled in a real plasma at any time, as this demands a correlation of the impurity densities with the bulk fluctuating quantities. Nevertheless we can investigate passive tracer transport as it can reveal tendencies of transport in a given flow field with realistic properties. Furthermore for a number of situations it was shown, that the bulk transport and the one derived from the relative diffusion of passive test particles are in agreement with each other [2, 3]. Deviations between passive tracer transport and bulk transport can only be resolved in turbulence simulations of a multi-species plasma with consistently evolving profiles.

Results

The transport of impurities through the edge plasma turbulence relates to trace tritium experiments recently performed at JET [4] and to the question how cold impurities pass through the edge region of a tokamak towards the core. We consider drift-Alfvén turbulence in flux tube geometry [5].

$$\frac{\partial \omega}{\partial t} + \{\phi, \omega\} = \mathcal{K}(n) + \nabla_{\parallel} J + \mu_\omega \nabla_\perp^2 \omega, \tag{1a}$$

$$\frac{\partial n}{\partial t} + \{\phi, n_{EQ} + n\} = \mathcal{K}(n - \phi) + \nabla_{\parallel}(J - u) + \mu_n \nabla_\perp^2 n, \tag{1b}$$

$$\frac{\partial}{\partial t}\left(\widehat{\beta} A_{\parallel} + \widehat{\mu} J\right) + \widehat{\mu}\{\phi, J\} = \nabla_{\parallel}(n_{EQ} + n - \phi) - CJ, \tag{1c}$$

$$\widehat{\varepsilon}\left(\frac{\partial u}{\partial t} + \{\phi, u\}\right) = -\nabla_{\parallel}(n_{EQ} + n). \tag{1d}$$

The evolution of the impurity density, is given as:

$$d_t \theta = (\zeta/\widehat{\varepsilon}) \nabla_\perp \cdot (\theta d_t \nabla_\perp \phi) - \theta \mathcal{K}(\phi) - \nabla_{\parallel}(\theta u) - \mu_\theta \nabla_\perp^2 \theta. \tag{2}$$

Standard parameters for simulation runs were $\widehat{\mu} = 5$, $q = 3$, magnetic shear $\widehat{s} = 1$, and $\omega_B = 0.05$, with $\mu_\omega = \mu_n = 0.025$, corresponding to typical edge parameters of large fusion devices. Simulations were performed on a grid with $128 \times 512 \times 32$ points and dimensions $64 \times 256 \times 2\pi$ in x, y, s corresponding to a typical approximate dimensional size of 2.5 cm $\times$ 10 cm$\times$ 30 m [6]. We present results from a low $\hat{\beta} = 0.1$ run with $C = 11.5$ and set the effective mass to zero (for finite mass effects see contribution by M. Priego Wood, this conference).

In Fig. 1 the dynamical evolution of the impurity density is exemplified. The flux Γ of the impurity ion species can in lowest order be expressed by the standard parameters used in modeling and in evaluation of transport experiments [7]: a diffusion coefficient D and a velocity V, which is associated to a pinch effect,

$$\Gamma_y(s) = -D(s) \partial_x \langle \theta \rangle_y + V(s) \langle \theta \rangle_y . \tag{3}$$

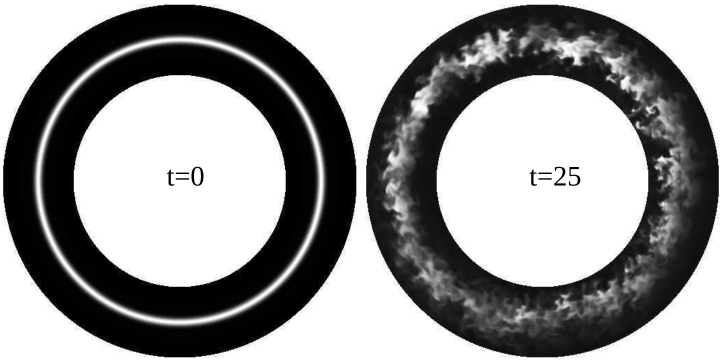

Figure 1: Impurity distribution projected onto a poloidal cross-section (radial dimension not to scale). Initial distribution (left) and after 25 time units (right).

From scatter plots of $\Gamma(r)/\langle n\rangle_y$ versus $\partial_x \ln\langle n\rangle_y$, values for $D(s)$ and $V(s)$ are obtained [8]. The poloidal (coordinate s) dependence of D and V is rather strong and shown in Fig. 2. The effective advective velocity $V(s)$ changes sign and is at the high field side directed outwards, that is the pinch velocity is always directed towards the center of the torus. This pinching velocity is due to curvature and can be consistently explained in the framework of Turbulent EquiPartition (TEP) [9, 10]: In the absence of parallel advection, finite mass effects and diffusion, Eq. (2) has the approximate Lagrangian invariant

$$L(s) = \ln\theta + \omega_B x\cos(s) - \omega_B y\sin(s)\ . \tag{4}$$

TEP assumes the spatial homogenization of L by effective turbulent mixing. As parallel transport is weak, each drift plane $s =$ const. homogenizes independently. This leads to profiles $\langle L(s)\rangle_y = \text{const.}(s)$. At the outboard midplane ($s = 0$) the impurites are advected radially inward leading to an impurity profile ($\langle\ln\theta\rangle_y \propto const. - \omega_B x$), while at the high field side (inboard) they are advected outward ($\langle\ln\theta\rangle_y \propto const. + \omega_B x$). The strength of the “pinch” effect is proportional to the mixing properties of the turbulence and scales with the measured effective turbulent diffusivity:

$$V(s) = -\omega_B \cos(s) D(s)\ . \tag{5}$$

Ballooning in the turbulence level causes the inward flow on the outboard midplane to be stronger than the effective outflow on the high-field side. Therefore, averaged over a flux surface and assuming a poloidally constant impurity density, a net impurity inflow results. This net pinch is proportional to the diffusion coefficient D in agreement with experimental observations [11].

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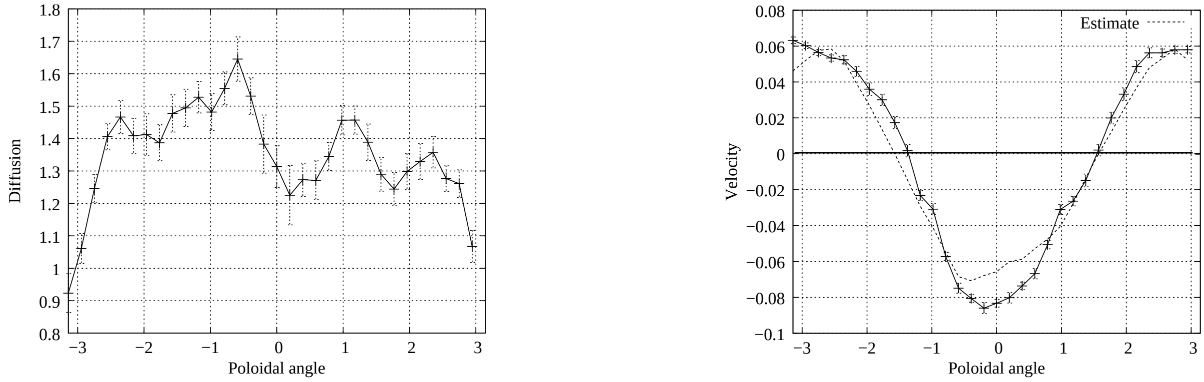

Figure 2: Impurity diffusion D (left) and pinch velocity V (right) over poloidal angle with error-bars. The pinch velocity is compared to $\omega_b * \cos(s) * D(s)$ (dashed line).

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