Turbulent Transport and Mixing of Impurities in the Edge Plasma

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We have investigate the turbulent transport and mixing of impurities in the scrape-off-layer (SOL) by employing the Risø ESEL-code. The impurity density is assumed to be low and impurity ions are described as particles that are passively advected by the turbulent ExB-velocity. The code is based on a model for interchange turbulence in a local slab geometry at the outboard mid-plane of a toroidally magnetized plasma [1, 2]. The model includes the self-consistent evolution of the full thermodynamic and flow profiles. The geometry comprises distinct production and loss regions, corresponding to the edge and SOL of magnetized plasmas. The separation of these two regions defines an effective last closed flux surface (LCFS). In the edge region, where the sources of particles and heat are located, strong pressure gradients maintain a state of turbulent convection. The driving instability is the interchange mode due to an inhomogeneous magnetic field. In the SOL the parallel losses are accounted for by damping terms. This model is capable of reproducing the main features observed in the edge and SOL of various magnetically confined plasmas [3]. The turbulence and transport is strongly intermittent and involves large outbreaks of hot plasma. Associated with these bursts are blob-like structures, which are formed near LCFS and penetrate far into the SOL.

In the simulations presented here we use parameters relevant for SOL plasmas as described
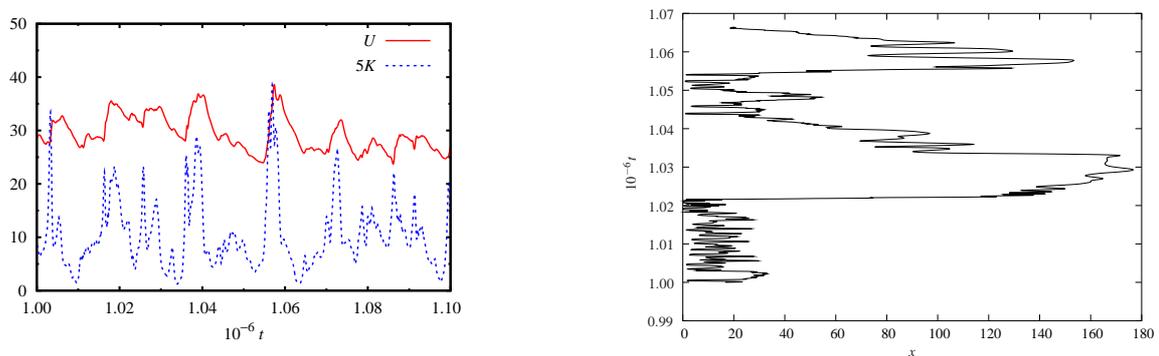

Figure 1: Evolution of the kinetic energy contained in the fluctuating motions, K, and the poloidally mean flows, U (left panel). Typical evolution of the radial position of a particle released in the plasma edge region, inside LCFS (right panel).

in Ref. [2]. The dimension of the two dimensional simulation domain is $L_x = 2L_y = 200$ and the LCFS is located at $x_{\text{LCFS}} = 50$, where x corresponds to the radial and y to the poloidal coordinate. Spatial scales are normalized by $\rho_s = c_s/\omega_{ci}$ and time is normalized by $1/\omega_{ci}$, where ω_{ci} is the ion cyclotron frequency and c_s is the acoustic speed.

Generally, we observe that the turbulent flux is strongly intermittent [1, 2]: quite periods are interrupted by strong bursts during which particles and heat are lost from the edge into the SOL region. This global dynamics is caused by a self-regulation mechanism in which kinetic energy is transferred from the fluctuating to the mean components of the flows, and subsequently damped by collisional dissipation (cf. Fig. 1). The thermal energy ejected into the SOL region, will eventually be lost by transport along open field lines. The bursts are correlated with localized structures in the form of blobs propagating radially far into the scrape-off-layer (SOL). The characteristics time between the bursts is related to the viscous diffusion, for the present case this time is around $\tau_{\text{burst}} = 10^4$ with a rather large spread [2].

It is of interest to investigate how the strongly intermittent dynamics in the edge and the SOL will influence the transport and spreading of impurity ions. The dynamics of impurities is modelled by means of the passive tracer particle approach, assuming that the impurity particle density is much lower than the plasma particle density [4, 5]. We thus follow tracer particles that are passively advected by the inherently turbulent motions, but do not back-react on the turbulence. The trajectories of tracers are calculated by integrating their equation of motion, $d\mathbf{x}/dt = \mathbf{v} = \hat{\mathbf{z}} \times \nabla\phi/B(x)$, where the tracer velocity is taken to be the electric drift. Thus, we have neglected the effect of finite inertia on the tracer dynamics and limit ourself to tracer ions having a mass to charge ratio comparable to that of the plasma ions. The electric drift is compressible due to the spatial dependence of the magnetic field. We have employed a bi-cubic interpolation scheme to provide the velocity at the exact particle position [6].

A large number of tracers, typically of the order 10^6, were released uniformly over space. In Fig. 1 we show the evolution of the radial coordinate of a typical trajectory for a tracer released inside the LCFS during a quiet period. The tracer is randomly oscillating inside the LCFS until it is captured by a structure and perform a long flight to the far SOL. However, the tracer is subsequently transported back into the edge region. Long flights may be found both in the radially outgoing and ingoing direction. Correspondingly, the PDF of the radial step size is strongly non-Gaussian, see Fig. 2. In the left panel we show the PDF of the radial step size, Δx, measured over a time interval of $\Delta t = 50$ and averaged over all particles. The mean value of Δx is close to zero ($\langle \Delta x \rangle = -0.08$), and the standard deviation, $\sigma = 1.02$. The PDF is slightly skewed with a positive skewness, $S = 0.4$, and has a kurtosis, $K = 10.7$, signifying
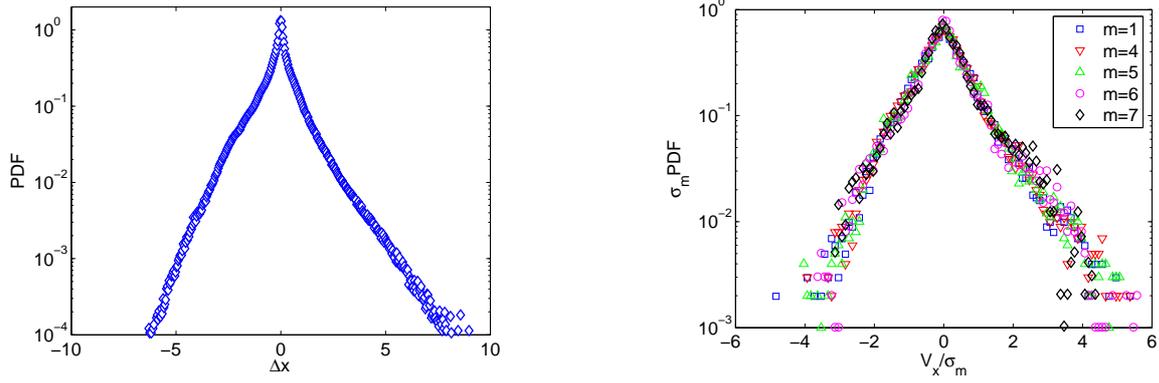
Figure 2: The PDF of the radial displacement, Δx, measured over $\Delta t = 50$ of all particles (left panel). The re-scaled PDF of the radial particle velocity coarse grained over time intervals $\Delta t = 50 \times 2^{m-1}$ for particles released inside the LCFS (left panel).
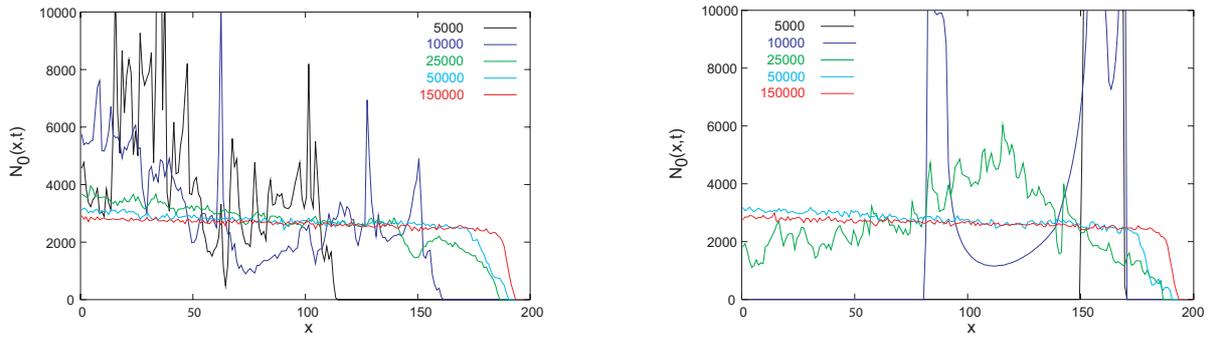

Figure 3: Evolution of the impurity density N_0 averaged over the y-direction. Impurities are released in a narrow band around $x = 40$ (left panel) and $x = 160$ (right panel).

broad tails, which are observed to be exponentially decaying. The tails are near symmetric, *i.e.,* long steps are almost equally probable in both in- and outgoing directions. The step size PDF is found to be self-similar with respect to the time interval Δt, this is consistent with the observation in the right panel in Fig. 2. Here we show the PDF's for the radial velocity component, V_x, of particles released inside the LCFS (at $x = L_x/12$) for increasing values of Δt. The PDF's are re-scaled as $\sigma_m \text{PDF}(V_x/\sigma_m)$, where σ_m is the standard deviation of the coarse grained velocity fluctuations, and they are observed to fall into coincidence. These PDF's are hardly distinguishable from the PDF's obtained by averaging over particles released uniformly in the whole domain. Furthermore, the particle velocity PDF is comparable to the re-scaled PDF of the electric drift velocity, which have the same functional form throughout the whole simulation domain [2].

In Fig. 3 we present the evolution of the impurity density, N_0, averaged over the periodic direction y for the cases where the impurities are released inside the LCFS (left panel) and far into the SOL (right panel). The particles are rapidly mixed and after a time of the order of τ_{burst}, the particles released inside LCFS already penetrate far into the SOL. The velocity of the front of the particles is larger than 0.1, which is more than twice the typical blob speed [2]. The particles released in the SOL are mixing at a slower rate, but after a time of only a couple of burst periods they penetrate inside the LCFS. Ultimately the impurity density profile ends up following the same functional shape as the inhomogeneous magnetic field. This final profile is independent of where the particles are released. The transport is certainly not governed by a standard "Fickian" diffusive process. It can be described by an effective pinch, which may be understood by considering the continuity equation for the impurity particle density N [4, 7],

$$\left(\frac{\partial}{\partial t} + \frac{1}{B}\widehat{\mathbf{z}} \times \nabla\phi \cdot \nabla\right)\frac{N}{B} = 0,$$

which implies that N/B is a Lagrangian invariant advected by the compressible electric drift $\widehat{\mathbf{z}} \times \nabla\phi/B$. Now, assuming that the impurities are effectively mixed by the turbulent velocity fluctuations, this invariant will be uniformly distributed in space and the poloidally averaged impurity density $N_0(x)$ varies like $B(x)$. Thus, impurities are effectively mixed within a few burst periods and even if originating far out in the SOL they will quickly penetrate across the LCFS into the edge plasma. This corresponds to the the so-called inward (curvature) pinch.

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