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Statistical description of the radial structure of turbulence in the JET plasma boundary region

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Abstract

The statistical properties of the radial structure of fluctuations and $E \times B$ turbulent transport have been investigated in the plasma boundary of the JET tokamak. PDFs of fluctuations and turbulent transport have shown evidence of multiple radial scale lengths in the plasma boundary region. Radial effective velocities and turbulence radial coherence are modified in the presence of sheared poloidal flows which remains near marginal stability. These findings show a link between the structure of SOL profiles, sheared flows and turbulence statistical properties.

PACS: Plasma confinement; Electric fields; Plasma turbulence
Keywords: Radial electric fields; Turbulence; Fluctuations; Langmuir probe; JET

1. Introduction

Transport modelling of density profiles in fusion plasmas is usually described in terms of an effective diffusivity and a drift velocity. Effective particle diffusivities are anomalous and it is usually accepted that anomalous transport is due to plasma turbulence. Evidence of anomalous inward drift velocities much larger than the value predicted by neoclassical theory has been recently reported in tokamak plasmas [1,2].

The importance of the statistical description of transport processes in fusion plasmas as an alternative approach to the traditional way to characterize transport based on the computation of effective transport coefficients and on average quantities has been recently emphasized [3–7]. It was shown that the radial velocity of transport events ranges from about 20 m/s for events implying a small deviation from the most probable gradient, up to 500 m/s for large transport events, suggesting a link between the size of transport events and the properties of intermittent transport [8–11]. The characterization of the naturally occurring edge velocity shear layer suggests that $E \times B$ sheared flows and fluctuations organize themselves to be closed to marginal stability in the proximity of the last closed flux surface (LCFS) [6]. This paper reports results on the statistical properties in the radial propagation and spatial structure of transport events and their relation with edge profiles and sheared flows.

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2. Sheared flows plasma density and statistical description of transport

Plasma profiles and turbulence have been investigated in the JET plasma boundary region using a fast reciprocating Langmuir probe system located on the top of the device. The experimental set-up consists of arrays of Langmuir probes radially separated 0.5 cm, allowing the simultaneous investigation of the radial structure of fluctuations and electrostatic driven turbulent transport. The plasmas studied were produced in X-point plasma configurations with toroidal magnetic fields $B = 1–2$ T, $I_p = 1–2$ MA and ohmic heating. The local time resolved radial $E \times B$ turbulent induced fluxes, $\tilde{\Gamma}(t) \propto \langle \tilde{n}(t)\tilde{E}_\theta(t)\rangle/B$, (where $\tilde{n}$ and $\tilde{E}_\theta$ are the fluctuating density and poloidal electric field, respectively) were calculated from the correlation between E_θ and n_e fluctuations neglecting the influence of electron temperature. An effective radial velocity ($v_r^{\rm eff}$) was defined as the normalized $E \times B$ turbulent particle transport to the local density, $v_r^{\rm eff} = \langle \tilde{I}_s\tilde{E}_\theta\rangle/I_sB_T$, where I_s is the ion saturation current of the inner probe. This quantity takes into account the correlation between the fluctuations in n_e and E_θ and therefore represents the propagation velocity of turbulent events. This coefficient is not affected by uncertainties in the probe area providing a convenient way to investigate the statistical properties of the radial propagation in the scrape-off-layer (SOL).

A velocity shear layer has been observed near the location of the LCFS in JET in agreement with previous experiments in fusion plasmas. The poloidal phase velocity of fluctuations ($v_{\rm phase}$) increases in the electron drift direction up to 2000 m/s, in the proximity of the separatrix and the radial gradient in $v_{\rm phase}$ is in the range of 10^5 s^{-1}, which is comparable to the inverse of the correlation time of fluctuations, $\tau \approx 10$ μs [6]. Observations in TJ-II stellarator have shown that the development of the naturally occurring velocity shear layer in the proximity of the LCFS has a density threshold above which the $v_{\rm phase}$ reverses, being the increase in the shearing rate correlated with the increase in turbulent velocity fluctuations [12]. These results suggest that, both in tokamaks and stellarators, spontaneous sheared poloidal flows and fluctuations remains near marginal stability.

Fig. 1 shows the measured ion saturation and floating potential profiles in JET plasmas in which the probe was radially shifted shot by shot from the SOL up to the velocity shear layer location with good reproducibility in the measured radial profiles.

Multiple relaxation mechanisms can play a role in fusion plasmas. Those related with collective transport behaviour in the presence of fluctuating electric and magnetic fields are termed as anomalous mechanisms whereas those related with particle orbit in non-homogeneous magnetic field are termed neoclassical transport. These mechanisms may be described in terms of probability distribution functions (PDFs). The PDF of turbulent transport can be described by an effective radial velocity ($v_r^{\rm eff}$) being the resulting $v_r^{\rm eff}$-PDF clearly asymmetric with tails (outward transport). For the individual particle motion PDF, in which E_θ fluctuations lead to a radial acceleration of particles (e.g. electron/impurities), the resulting $v_{E\times B}$-PDF is rather symmetric. The differences between $v_r^{\rm eff}$-transport PDF (with tails) and $v_{E\times B}$ (quasi-gaussian) PDFs reflect the strong temporal correlation between n_e and E_θ fluctuations (Fig. 2). The PDF of $v_r^{\rm eff}$ has been estimated from time records of $v_{\rm eff}$ with a time resolution of 100 μs ($\Delta N = 50$), by averaging over blocks of ΔN elements from the original time series (50–70 ms, i.e. about 30000 points) to compute the averaged turbulent transport ($\Gamma_{E\times B}$) and the ion saturation current (I_s).

Fig. 3 shows $v_r^{\rm eff}$-PDFs at different radial positions for reproducible discharges with different magnetic fields. In the SOL region $v_r^{\rm eff}$-PDFs show clear non-gaussian features with both positive (radially outwards transport) and negative (radially inwards transport) events. Although the most probable radial velocity is in the order of 10 m/s, experimental evidence of intermittent events propagating radially with velocities in the range of 100–400 m/s is clearly observed, in agreement with previous experiments [6], illustrating the presence

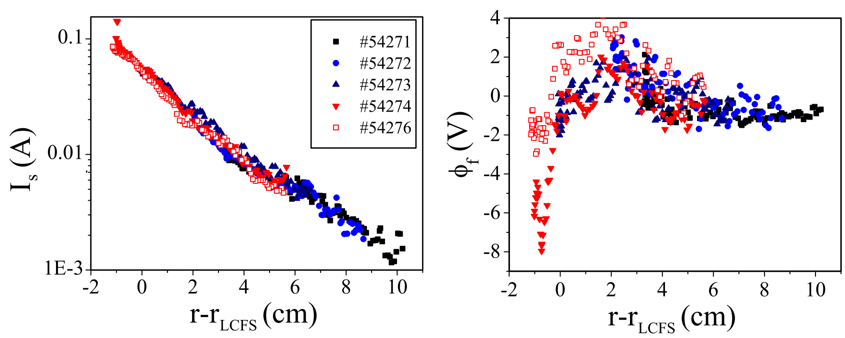

Fig. 1. Radial profiles of ion saturation current and floating potential in the JET boundary region (ohmic plasmas).

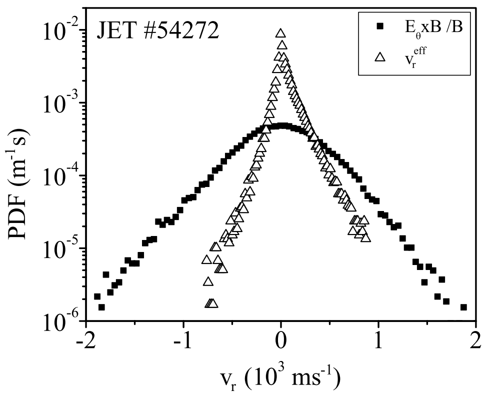

Fig. 2. PDFs of radial effective velocities and $E \times B$ drift velocities.

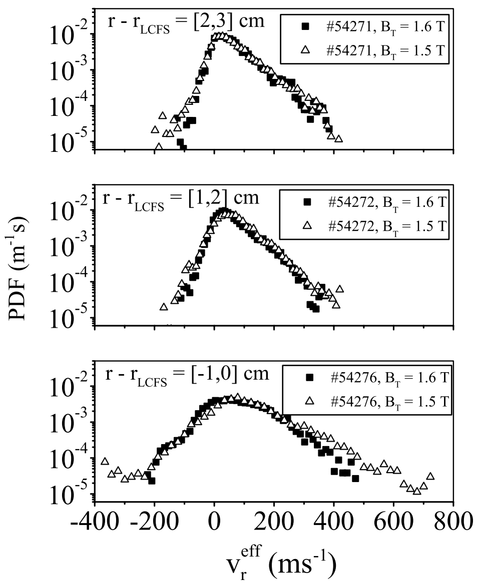

Fig. 3. PDFs of radial effective velocity in the JET plasma boundary region.

of large and sporadic transport (velocity) events. A clear modification in v_r^{eff}-PDFs takes place near the shear location: v_r^{eff}-PDFs become broader and more gaussian and about 20% of the particles move radially inwards with averaged radial velocities of about 50 m/s. This modification can be interpreted in terms of the turbulence decorrelation effects induced by sheared flows near marginal stability ($\mathrm{d}v_{phase}/\mathrm{d}r \approx 1/\tau$).

Similar conclusions can be drawn from Fig. 4 which shows the PDF for fluctuations in gradients, and the expected value of the radial effective velocity for a given density gradient ($E[v_r^{eff}|\nabla_r I_S]$) measured at different radial locations, from the SOL region ($r - r_{LCFS} \approx 3$ cm) up to the proximity of the velocity shear layer

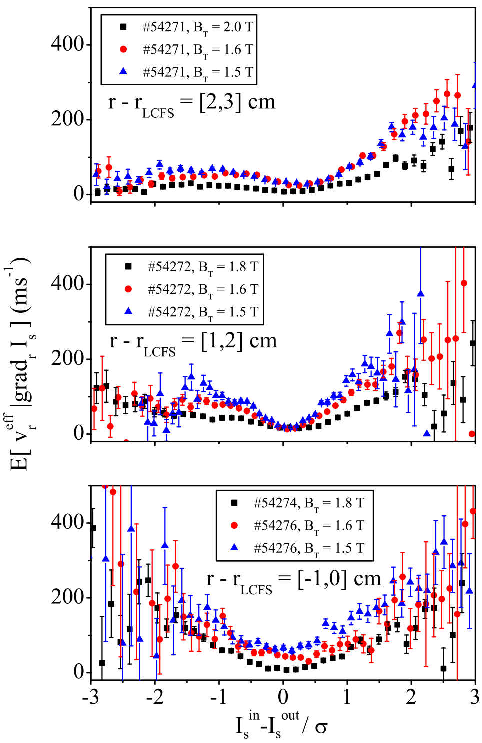

Fig. 4. Radial effective velocity versus fluctuations in gradients in the JET boundary region.

($r - r_{LCFS} \approx -1$ cm) in JET ohmic plasmas. Most of the time the plasma is at its average gradient and the effective velocity of the transport events is close to the diffusive values ($v_r^{eff} \approx 10$–$20\ \mathrm{ms}^{-1}$). Large amplitude transport events propagating with high effective velocity ($v_r^{eff} \approx 200$–$300\ \mathrm{ms}^{-1}$) take place when the plasma displaces from the most probable gradient value. The functional dependence between v_r^{eff} and gradients is strongly affected as moving from the SOL to the location of the velocity shear layer. In the SOL region ($r - r_{LCFS} \approx 3$ cm) the radial velocity is small as the plasma is at or below its average gradients. However, the expected value of the radial effective velocity increases strongly as the gradient increases above its most probable value (i.e. $\nabla\tilde{I}_s/\sigma > 0$) [4,6]. Furthermore, the radial velocity increases linearly with the size of transport events, consistently with a recent investigation of the radial propagation of ELMs events also suggesting an increase in the radial velocity with the ELM amplitude [5]. On the contrary, in the proximity of the velocity shear layer the size of transport events is rather similar above and below the most probable radial gradient. These results illustrate the impact of sheared flows in the relationship between fluctuations in gradients and transport.

Evidence of anomalous inward particle pinch in full non-inductive plasmas driven by lower hybrid waves

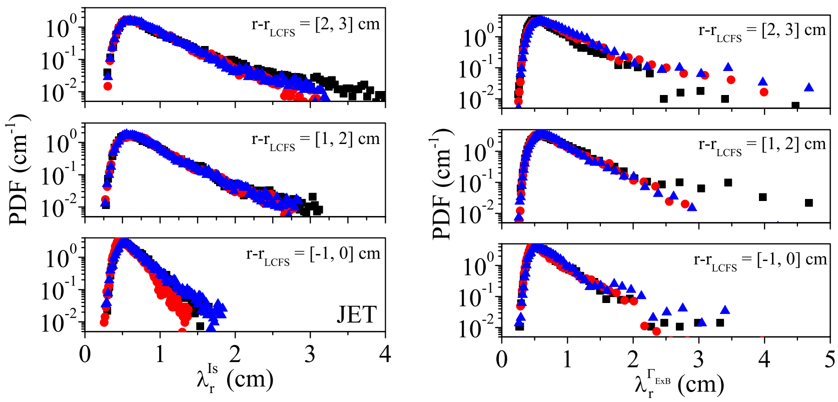

Fig. 5. PDFs of the radial correlation length of: (a) the floating potential fluctuations; (b) $E \times B$ transport in the JET boundary region.

has been reported on Tore Supra [1]. Peaked density profiles have been also reported in stellarator plasmas showing evidence of convective inward particle transport [13]. Observations in the plasma boundary of CHS stellarator have shown that a reversal in the turbulent particle flux is correlated with the formation of a region with a positive radial electric field shear [14], and experiments in the TJ-II stellarator have shown the impact of rational surfaces to modify transport (from radially outwards to radially inwards) [15]. Theoretically it has been argued that, in some cases, turbulence can give rise to a fully inward anomalous transport [16]. Radially peaked profiles might be also explained on the basis of a description of turbulent transport in tokamaks by invariants [17]. The magnitude of the required inward velocity to explain density profiles is in the range 0.1–10 m/s, increasing at the plasma edge. Present results suggest an alternative interpretation of radially peaked profiles both in tokamaks and stellarators based on the modification of PDFs in the radial velocity of turbulence in the presence of $E \times B$ sheared flows near marginal stability. The generation of internal and edge transport barriers is linked to plasma regions with a unique magnetic topology [18]. Experimental results have shown the impact of rational surfaces in the generation of internal transport [19] and $E \times B$ sheared flows [20]. Based on these results it can be argued that sheared flows are connected to the magnetic topology (e.g. rationals, LCFS). In the framework of this interpretation, peaked density profiles would be linked with gradient in q (e.g. density of low order rationals) [2].

3. Evidence of multiple radial scales on edge transport

The statistical properties of the radial coherence of fluctuations and transport have been computed from the cross correlation of $\Gamma_{E \times B}$ signals and floating potential signals radially separated 0.5 cm. The correlation length (λ_r) was computed assuming an exponential decay of the correlation between two probes radially separated (Fig. 5). The investigation of PDFs of the radial scale length of electrostatic turbulent transport has shown evidence of multiple radial scale lengths in the JET plasma boundary region, both in ohmic and L-mode plasmas. The PDF of the radial correlation length of $E \times B$ transport shows tails (i.e. sporadic events with high radial coherence). PDFs of the radial coherence of fluctuations are wider than those corresponding to the $E \times B$ turbulent flux. Tails in radial-PDFs are modified in the presence of sheared poloidal flows. In the SOL side of the shear location, radial correlation of the fluctuations exhibits a wide PDF that covers a large range of radial scales. When approaching the shear layer the PDF becomes narrower. This result can be interpreted on the basis of the influence of sheared flows on the radial scale of fluctuations and transport.

4. Conclusions

The PDF of radial velocities of turbulence and the radial and poloidal correlation of the floating potential fluctuations and $E \times B$ transport has been investigated in JET and evidences of multiple radial scale lengths in the plasma boundary region were found. PDFs of turbulence radial coherence and radial velocities are modified in the proximity to the velocity shear layer, which remains near marginal stability in the proximity of the LCFS. These results suggest an interpretation of radially peaked profiles both in tokamaks and stellarators based on the modification of PDFs in the radial velocity of turbulence in the presence of $E \times B$ sheared flows self-organized near marginal stability. The present findings show the importance of the statistical characterization of the radial scales of transport and fluctuations to improve our understanding of the physics underlying transport processes in fusion plasmas and highlight the necessity to incorporate these results into numerical simulations.

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