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ABSTRACT
The statistical properties of the radial structure of fluctuations and E×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.

1. INTRODUCTION
Transport modelling of density profiles is usually described in terms of two coefficients in fusion plasmas: an effective diffusivity (D) and a drift velocity (V). 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 (Ware pinch and thermo-diffusion) 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 (i.e. diffusion coefficients and convected velocities) and on average quantities (i.e., average correlation lengths) has been recently emphasized [3,4,5,6,7]. In particular, this approach has shown the resulting radial velocity of transport events ranges from about 20m/s for events implying a small deviation from the most probable gradient, up to 500m/s for large transport events. This result suggest a link between the size of transport events and the properties of intermittent transport observed in tokamaks [8,9,10,11]. Furthermore, the characterization of the naturally occurring edge velocity shear layer suggests that E×B sheared flows and fluctuations organized themselves to be closed to marginal stability in the proximity of the last closed flux surface [6]. This opens the possibility to investigate the impact of critical sheared flows on the statistical properties of both radial propagation and radial scale of transport events using Lagmuir probes keeping in mind the presently favoured view that the probes do not perturb the plasma. However, it should be remarked that, in view of recent results [12], some caution should be taken in the interpretation of probe results since it acts as a carbon source and may locally perturb the plasma.

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. The paper has been organized as follows. The experimental set-up and analysis tools are described in section 2. The impact of sheared flows in the probability distribution function of radial velocities is discussed in section 3. Evidence of multiple radial scales on edge transport is discussed in section 4. Finally conclusions are presented in section 5.

2. EXPERIMENTAL SET-UP
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 0.5cm, allowing the simultaneous investigation of the radial structure of fluctuations and electrostatic driven turbulent transport. Plasmas studied in this paper were produced in X-point plasma configurations with toroidal magnetic fields B = 1 – 2. T, Ip = 1 - 2MA ohmic plasmas in the JET tokamak. The local time resolved radial E×B turbulent induced fluxes, Γ (t) $\propto \langle \tilde{n}(t)\, E_\theta (t) \rangle / B$, (where ñ and E_θ are the fluctuating density and poloidal electric field, respecfively) were cãlculated neglecting the influence of electron temperature from the correlation between poloidal electric fields and density fluctuations. An effective radial velocity (v_r^{eff}) was defined as the normalized E×B turbulent particle transport to the local density.

A velocity shear layer has been observed near the location of the Last Closed Flux Surface (LCFS) in the JET tokamak in agreement with previous experiments in fusion plasmas. As previously reported the poloidal phase velocity of fluctuations (v_{phase}) increases in the electron drift direction up to 2000m/s, in the proximity of the separatrix and the radial gradient in vphase is in the range of $10^5\ s^{-1}$, which turns out to be comparable to the inverse of the correlation time of fluctuations, in the range of $\tau \approx$ 10ms [6]. Recent observations made in TJ-II stellarator have shown that the development of the naturally occurring velocity shear layer in the proximity of the Last Closed Flux Surface requires a minimum plasma density above which the poloidal phase velocity reverses and that the increasing in the shearing rate is also correlated with the increase in turbulent velocity fluctuations in the plasma [13]. These results suggest that, both in tokamaks and stellarators, spontaneous sheared poloidal flows and fluctuations remains near marginal stability.

Figure 1 shows the measured ion saturation and floating potential profiles in plasmas in which the reciprocating probe was radially shifted shot by shot from the Scrape-Off-Layer (SOL) up to the velocity shear layer location in JET. The reproducibility in the measured radial profiles is very good.

3. SHEARED FLOWS PLASMA DENSITY AND STATISTICAL DESCRIPTION OF TRANSPORT

In principle, multiple relaxation mechanisms can play a role in magnetically confined plasmas. Those related with particle orbit in non-homogeneous magnetic field are termed neoclassical transport whereas those related with collective transport behaviour in the presence of fluctuating electric and magnetic fields are termed as anomalous mechanisms. Each of these mechanisms might be described in terms of Probability Distribution Functions (PDFs). The PDF of transport can be described by an effective radial velocity (v_r). The resulting v_r-PDF of transport is clearly asymmetric with tails (outward transport). It should be noted that for the individual particle motion PDF, in which poloidal electric field 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-transport PDF (with tails) and $v_{E\times B}$ (quasi-gaussian) PDFs reflect the strong temporal correlation between density and poloidal electric field fluctuations (Fig.2).

The distribution function of the effective radial velocity of fluctuations has been estimated by,

$$\mathrm{PDF}\,(v_{eff}) = N v_{eff} / N\,W, \qquad (1)$$

where Nv_{eff} is the number of data values that fall within the range $v_{eff} \pm W/2$, W is a narrow interval centred at v_{eff} and N is the total number of data values. We have constructed time records of v_{eff} with a time resolution $\Delta N = 100$ms, by averaging over blocks of ΔN elements from the original time series to compute the averaged turbulent transport ($\Gamma_{E\times B}$) and the ion saturation current (Is) and using expression (1). The original time series has about 50 – 70ms (i.e. about 30.000 points). The radial evolution of v_{eff} - PDFs has been investigated at two different magnetic fields in reproducible discharges. Figure 3 shows v_{eff}–PDFs. In the SOL region v_{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 10m/s, experimental evidence of intermittent events propagating radially with velocities in the range of 100 – 400m/s is clearly observed, in agreement with previous experiments [6]. This result illustrates the presence of large and sporadic transport (velocity) events. A clear modification in v_{eff}-PDFs takes place near the shear location: v_{eff}-PDFs become broader and more gaussian and about 20% of the particles move radially inwards with averaged radial velocities of about 50m/s. This modification in radial velocity-PDFs can be interpreted in terms of the turbulence decorrelation effects induced by sheared flows near marginal stability ($dv_{phase}/dr \approx 1/\tau$).

Similar conclusions can be drawn from figure 4 which shows the Probability Density Function (PDF) for fluctuations in gradients, and the expected value of the radial effective velocity for a given density gradient ($E[v_r^{eff} \mid \nabla_r I_S]$) measured at different radial locations, from the SOL region ($r-r_{LCFS} \approx 3$cm) up to the proximity of the velocity shear layer ($r-r_{LCFS} \approx -1$ cm) in JET ohmic plasmas. The results show that 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 ($v_r^{eff} \approx 10\text{-}20\,ms^{-1}$). Large amplitude transport events which propagate with high effective velocity ($v_r^{eff} \approx 200\text{-}300\ ms^{-1}$) take place when the plasma displaces from the most probable gradient value. However the functional dependence between radial effective velocity 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. $\nabla \tilde{I}_s / s > 0$), in agreement with previous experiments [4, 6]. Furthermore, the radial velocity increases linearly with the size of transport events. This conclusion is consistent with a recent investigation of the radial propagation of ELMs events which also suggest an increase in the radial velocity of ELM events with their 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 near marginal stability in the relationship between fluctuations in gradients and transport. Evident anomalous inward particle pinch in full non-inductive plasmas driven by lower hybrid waves has been reported on Tore Supra [1]. Peaked density profiles have been also reported in stellarator plasmas showing evidence of convective inward particle transport [14]. Radially inward turbulent velocities have also been observed in the plasma boundary region of fusion plasmas. In particular, experiments carried out 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 [15], and experiments in the TJ-II stellarator have shown the impact of rational surfaces to modify transport (from radially outwards to radially inwards) [16]. From the theoretical point of view is has been argued that, in some cases, turbulence can give rise to a fully inward anomalous transport [17]. Radially peaked profiles might be also explained on the basis of a description of turbulent transport in tokamaks by invariants [18]. The magnitude of the required inward velocity to explain density profiles is in the range 0.1 – 10m/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×B sheared flows near marginal stability is suggested. The generation of internal and edge transport barriers is linked to plasma regions with a unique magnetic topology [19]. In particular, experimental results have shown the impact of rational surfaces in the generation of internal transport [20] and E×B sheared flows [21]. Based on these results it can be argued that sheared flows (near marginal stability) 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].

4. 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 $G_{E\times B}$ signals and floating potential signals radially separated 0.5cm. PDFs of the veff and radial scale (L_r) of fluctuations and turbulent transport have been computed at different time scales. The correlation length (λr) was computed assuming an exponential decay of the correlation between two probes radially separated 5mm (Figure 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 as previously indicated [22]. As shown in figure 5 the PDF of the radial correlation length of E×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×B turbulent flux. Furthermore, tails in radial-PDFs are modified in the presence of sheared poloidal flows in the plasma boundary region. 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 narrowed. This result can be interpreted on the basis of the influence of sheared flows near marginal stability on the radial scale of fluctuations and transport.

Present findings highlight the importance of considering the inclusion of statistical descriptions on numerical simulations. First attempts to simulate impurity transport based on experimental measurements of radial velocity probability density function were made recently [23]. A Monte Carlo Code (DIVIMP) was used to follow the individual ions in time using either diffuse assumption, in which the change if radial location of an ion is prescribed by an effective diffusion coefficient (D), or using a velocity density distribution function supplied from experimental measurements. However, these first attempts led to unphysical results. The results have shown that besides the importance of the statistical description of transport (through turbulence correlation time), the numerical codes should also take into account the spatial collective transport behaviour (correlation lengths) remaining as an open question how to include these “ingredients of transport” in a Monte Carlo simulation of transport.

CONCLUSIONS

The PDF of radial velocities of turbulence and the radial and poloidal correlation of the floating potential fluctuations and ExB transport has been investigated in the JET and the following conclusions have been reached:

1) Evidences of multiple radial scale lengths in the JET plasma boundary region were observed.
2) 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 last closed flux surface. 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×B sheared flows self-organized near marginal stability.
3) 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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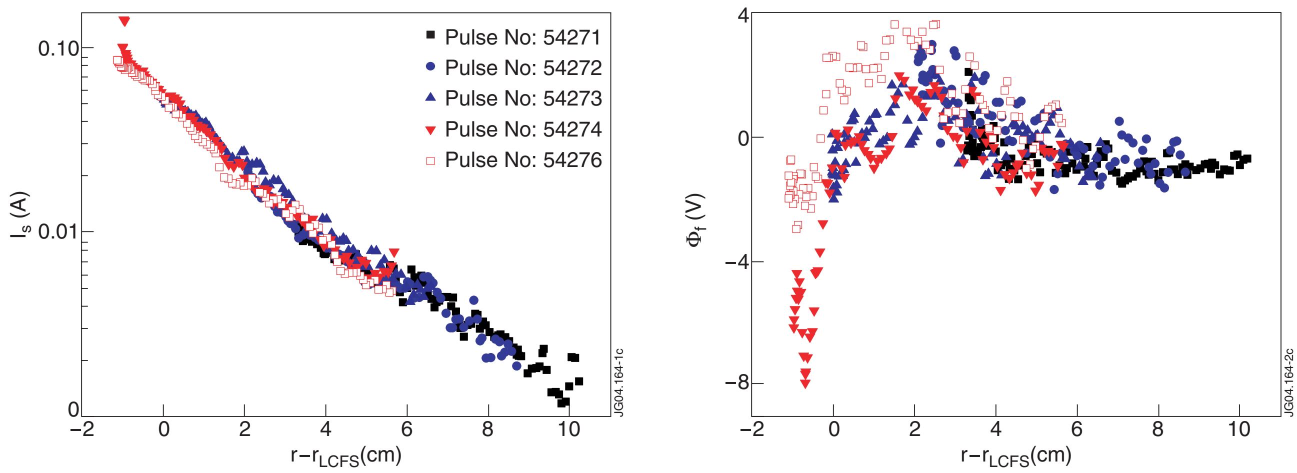

Figure 1: Radial profiles of ion saturation current and floating potential in the JET boundary region (ohmic plasmas) in reproducible discharges.

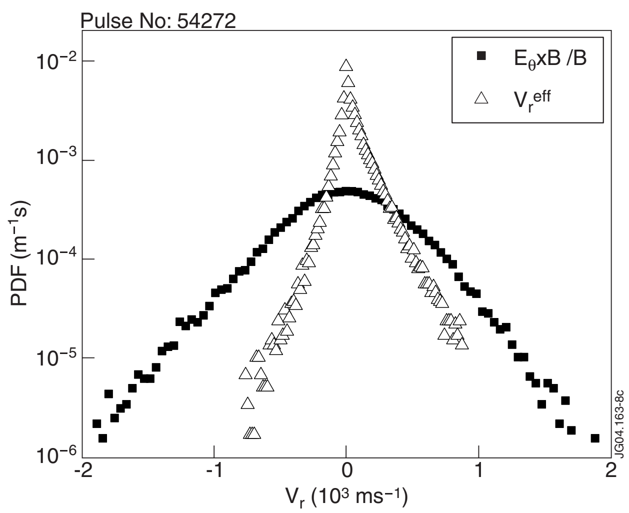

Figure 2: PDFs of radial effective velocities and E×B drift velocities

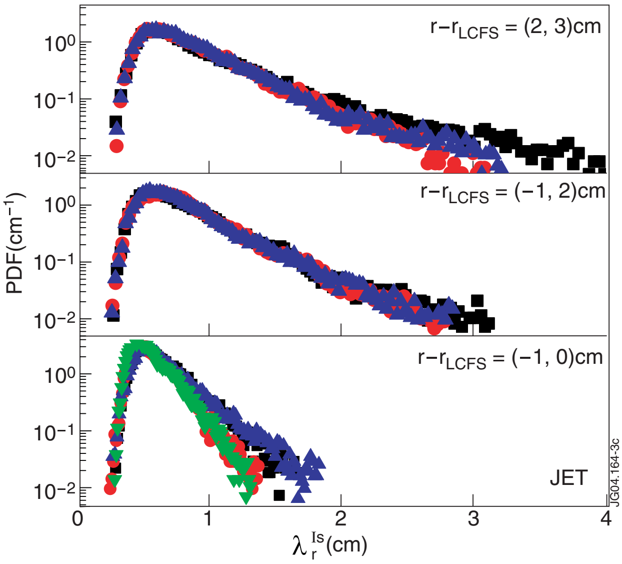

Figure 3: PDFs of radial effective velocity in the JET plasma boundary region.

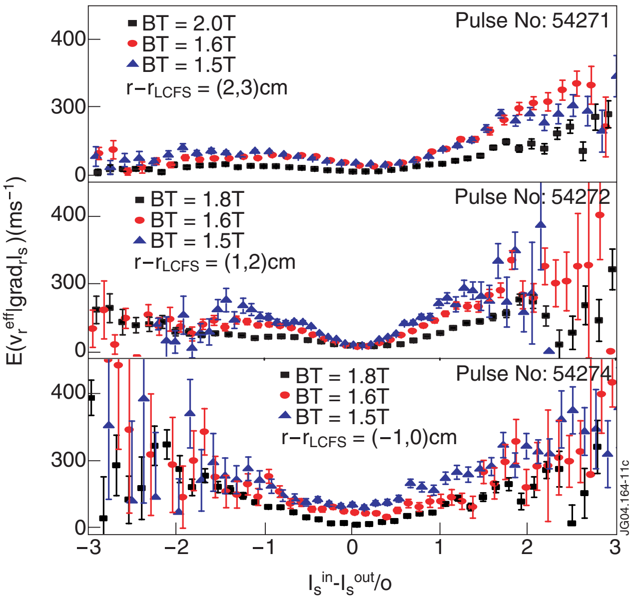

Figure 4: Radial effective velocity versus fluctuations in gradients in the JET boundary region.

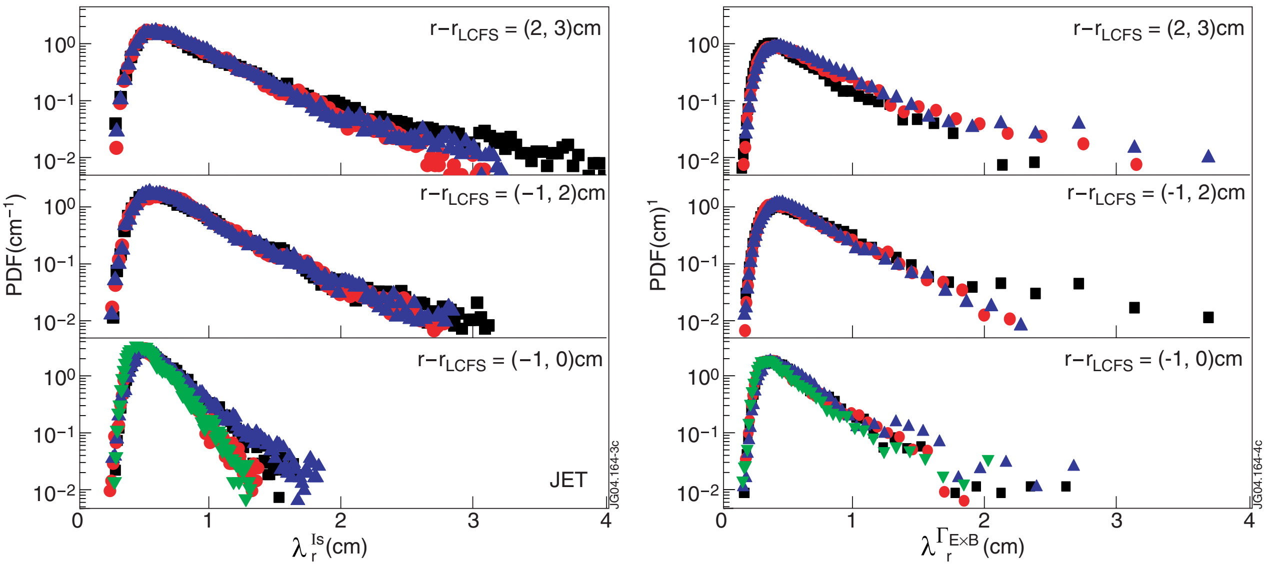

Figure 5: PDFs of the radial correlation length of the floating potential fluctuations in the JET boundary region (a). PDFs of the radial correlation length of E×B transport in the JET boundary region (b).