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Experimental Evidence of Fluctuations and Flows Near Marginal Stability in the Plasma Boundary Region of Fusion Plasmas

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ABSTRACT.

Electrostatic turbulence has been investigated in the plasma boundary region in the JET tokamak and in the TJ-II stellarator. In both devices the naturally occurring velocity shear layer organizes itself to reach a condition in which the radial gradient in the poloidal phase velocity of fluctuations is comparable to the inverse of the correlation time of fluctuations (1/t). This result suggests that E¥B sheared flows organized themselves to be close to marginal stability (i.e. $w_{\text{E¥B}}$ ~1/t). The investigation of the dynamical interplay between fluctuation in gradients, turbulent transport and radial electric fields has shown that these parameters are strongly coupled both in tokamak and stellarator plasmas. The bursty behaviour of turbulent transport is linked with a departure from the most probable radial gradient. The dynamical relation between fluctuations in gradients and transport is strongly affected by the presence of sheared poloidal flows, heating power and the proximity to instability thresholds: the size of large transport events decreases in the proximity of sheared flows and increases with heating power and in the proximity of instability thresholds.These results are consistent with the concept of turbulent transport self-regulated via fluctuations near marginal stability.

1. INTRODUCTION

Understanding the mechanisms which control the relation between transport, gradients and electric fields remains as a crucial physics issue in magnetic fusion research. Non-linear relations between heat and particle fluxes and gradients play a key role to explain confinement properties, such as confinement degradation with heating power and the transition to improved confinement regimes [1]. Recently a new approach to study the relation between gradients and transport, based on the investigation of the dynamical coupling between transport and gradients, has been proposed [2, 3]. Based on this approach it has been shown that transport events propagating with radial velocities up to 1000m/s are particularly significant when the radial gradient increases above its average value in the Scrape-Off-Layer (SOL) region. Comparative studies of plasma turbulence in different magnetic confinement devices have led to conclude that turbulence displays, as in many other dynamical systems, universal features [4, 5, 6].

This paper reports an investigation of the influence of sheared poloidal flows, the proximity to instability thresholds and the heating power in the dynamical coupling between turbulent transport and density gradients in the plasma boundary of tokamak (JET) and stellarator (TJ-II) devices.

The paper has been organized as follows. The experimental set-up and analysis tools are described in section 2. The structure of sheared flows in the plasma boundary of tokamak and stellarator devices is presented in section 3. The role of sheared flows, instability thresholds and heating power on the dynamical interplay between gradients and transport are described in section 4, 5 and 6 respectively. Experimental evidence of non-gaussian features in PDFs of gradients is reported in section 7. Finally, conclusions are presented in section 8.

2. EXPERIMENTAL SET-UP AND ANALYSIS TOOLS

Plasma profiles and turbulence have been investigated in the JET and TJ-II 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. Plasma fluctuations are investigated using 500 kHz digitisers. Plasmas studied in this paper were produced in X-point plasma configurations with toroidal magnetic fields $B = 1-2.5T$, $Ip = 1-2MA$, $P_{NBI} = 0-5MW$ (ohmic and L-mode plasmas) in the JET tokamak and in ECRH plasmas (300 kW) in the TJ-II stellarator.

The mean velocity of fluctuations perpendicular to BT has been computed as $v_{phase} = \Sigma\, S(k,\omega)\,(k,\omega) / \Sigma\, S(k,\omega)$, from the wave number and frequency spectra $S(k,\omega)$, computed from the two point correlation technique using floating probes poloidally separated (Δ_θ) 0.5cm and 0.3cm respectively in the JET and TJ-II plasma boundary region.

Turbulent particle transport and fluctuations have been calculated, neglecting the influence of electron temperature fluctuations, from the correlation between poloidal electric fields and density fluctuations at the inner probe position. The poloidal electric field has been estimated from floating potential signals measured by poloidally separated probes, $E_\theta = \Delta\tilde{\Phi}_f / \Delta\theta$. Fluctuations in the radial component of ion saturation current gradients have been computed, $\tilde{\nabla} I_s\,(t) = [\tilde{I}_s^{inner}\,(t) - \tilde{I}_s^{outer}\,(t)]$ with $< \Delta\tilde{I}_s > = 0$, where $\tilde{I}_s^{inner}$ and $\tilde{I}_s^{outer}$ are the ion saturation current fluctuations simultaneously measured at two different plasma locations radially separated 0.5cm. Figure 1 shows the time evolution of ion saturation current gradients and the turbulent transport in the JET plasma boundary region. From the raw data it can be seen that Probability Density Functions (PDFs) for gradients and transport are quite different. Whereas PDFs for transport show clear non-gaussian features, with large and sporadic burst, PDFs of gradients look, at first sight, rather gaussian.

In order to study the coupling between probability distribution functions of transport and gradients, we have computed the joint probability Pij of the two variables X and Y. The probability that at a given instant X and Y occur simultaneously, is given by $P_{ij} = P(X_i, X_j) = N_{ij}/N$ where N_{ij} the number of events that occur in the interval $(X_i, X_i + DX)$ and $(Y_i, Y_i + DY)$ and N the time series dimension. DX and DY are the bin dimension of X and Y time series, respectively, where the indices stands for i-th (or j-th) bin average value. The expected value of X at a given value of Y_j is defined as $E[X\,|Y_j] = \sum_i P_{ij}\, x_i / \sum_i P_{ij}$ and represents the average value of the probability distribution of X at a given value of Y.

An effective radial velocity has been defined as the normalized ExB turbulent particle transport to the local density, $v_{eff} = < \tilde{I}_s\, \tilde{E}_\theta > / I_s\, B_T$ where Is is the ion saturation current of the inner probe. As this coefficient is not affected by uncertainties in the effective probe area, it provides a convenient way to compare experimental results with edge code simulations. The coupling between the effective velocity of transport events and fluctuations in gradients has been investigated.

3. THE NATURALLY OCCURRING VELOCITY SHEAR LAYER

A velocity shear layer has been observed near the location of the Last Closed Flux surface (LCFS) in the TJ-II stellarator and in the JET tokamak in agreement with previous experiments in fusion plasmas [7]. In JET divertor plasmas, the poloidal phase velocity of fluctuations (v_{phase}) increases in the electron drift direction up to 2000m/s, in the proximity of the separatrix. This change can be explained in terms of E×B drifts. Both in TJ-II and JET devices 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 $5-10\mu s$ (Fig. 2). This result is verified in ohmic plasmas with $I_p = 1MA / B = 1T$, in which the power threshold for the L-H transition is about 1MW. A more detailed quantitative analysis of the experimental results would require to take into account the influence of plasma rotation in the correlation time.

It should be noted that the present results are consistent with previous observations in tokamaks, stellarators and reversed field pinches which have shown that the shearing rate of the naturally occurring velocity shear layer is close to the inverse time of fluctuations in different devices [7]. Whereas this property is consistent with turbulent driven fluctuating radial electric field, it is difficult to understand in which way other mechanisms, like those based on ion orbit losses mechanisms, can allow sheared flows and fluctuations to reach marginal stability. Recent numerical simulations have shown that turbulent driven fluctuating radial electric field via Reynolds stress has the property to get wExB critical [8].

4. DYNAMICAL COUPLING BETWEEN FLUCTUATIONS IN GRADIENTS AND TRANSPORT: INFLUENCE OF THE VELOCITY SHEAR LAYER

The influence of sheared poloidal flows in the dynamical coupling between transport and gradients have been investigated in JET ohmic plasmas. Figure 3 shows radial profiles of floating and ion saturation current measured in a series of discharges in which the reciprocating probe moves radially from the Scrape-Off-Layer (SOL) region up to proximity of the velocity shear layer. Near the velocity shear layer the floating potential becomes negative and the density gradient is steeper.

Figure 4 shows the probability density function (PDF) for fluctuations in gradients, and the expected value of the ExB flux for a given density gradient ($E[\Gamma_{E\times B} \mid \nabla_r I_S]$) measured at different radial locations, from the SOL region ($r-r_{LCFS} \approx 3cm$) up to the proximity of the velocity shear layer ($r-r_{LCFS} \approx 3cm$) in JET ohmic plasmas. The results show that most of the time the plasma is at its average gradient and the size of transport events has minimum amplitude ($\Gamma_{E\times B} / <\Gamma_{E\times B}> \approx 0.5$). Large amplitude transport events ($\Gamma_{E\times B} / <\Gamma_{E\times B}> \approx 3 - 8$) take place when the plasma displaces from the most probable gradient value. However the functional dependence between fluxes and gradients is strongly afected as moving from the SOL to the location of the velocity shear layer.

In the SOL region ($r-r_{LCFS} \approx 3cm$) the amplitude of transport events is small (($\Gamma_{E\times B} / <\Gamma_{E\times B}> \approx 0.5 - 1$) as the plasma is at or below its average gradients. However, the expected value of turbulent transport increases strongly as the gradient increases above its most probable value (i.e. $\nabla_r \tilde{I}_S / \sigma > 0$), in agreement with previous experiments [2,3]. 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 near marginal stability is the relationship between fluctuations in gradients and transport.

5. DYNAMICAL COUPLING BETWEEN FLUCTUATIONS IN GRADIENTS AND TRANSPORT: INFLUENCE OF HEATING POWER.

The influence of heating power in the dynamical relation between transport and gradients has been investigated comparing ohmic plasmas ($B = 2T / I_p = 2MA$) and L-mode plasmas ($B = 2T / I_p = 2$ MA, $P_{NBI} = 5MW$). Because sheared flows plays an important role on the dynamical relation between transport and gradients, the location of the velocity shear layer has been used as a point of reference to compare plasmas with different heating power.

Figure 5 shows the radial profiles of ion saturation current, floating potential and poloidal phase velocity of fluctuations measured in ohmic and L-mode discharges in JET. As expected the ion saturation current increases in L-mode as compared with ohmic plasmas. However, at the inner probe position ($r\text{-}r_{LCFS} \approx -1$cm) the floating is negative (about – 20V) and the poloidal phase velocity of fluctuations increases up to 500 m/s, both in ohmic and L-mode plasmas. These findings illustrate that both measurements are taken at to SOL side of the velocity shear location.

Figure 6 shows PDFs of fluctuations in radial Is gradients, the amplitude for the expected value of transport and the effective velocity of transport versus fluctuations in gradients. As heating power and density increases, the relation between fluctuations in gradients and transport becomes much steeper and the effective radial velocity of transport events also increases up to 600m/s for $\nabla\tilde{I}_S / \sigma > 0$. 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 [9].

6. DYNAMICAL COUPLING BETWEEN FLUCTUATIONS IN GRADIENTS AND TRANSPORT: INFLUENCE OF INSTABILITY THRESHOLDS.

The influence of the level of fluctuations in the radial structure of parallel flows has been investigated making used of the TJ-II flexibility to modify magnetic well. Plasma stability is provided in TJ-II through the existence of a magnetic well in the whole plasma radius (magnetic well depth is defined as $W = 100 \times [U(\rho)\text{-}U(0)]/ U(0)$, where $U(\rho)$ is the specific volume at a given effective radius ρ; $\rho = 0$ refers to the magnetic axis). Previous magneto hydrodynamic (MHD) studies have examined the stability properties of the device and have shown the characteristics of the magnetic well term for ideal and resistive interchange modes, finding that the presence of magnetic well is the main stabilising mechanism in TJ-II. Experimental evidence of the influence of the magnetic well in regulating the fluctuations in the plasma edge region of the TJ-II stellarator has been recently reported [7]. Making use of the flexibility of the TJ-II magnetic configuration, three different magnetic configurations with very similar iota profiles and magnetic well 2.4, 1.6 and 0.9% have been investigated. In the magnetic configuration with magnetic well 0.9%, a region having magnetic well in the plasma core can coexist with a region having magnetic hill in the plasma edge. Measurements reported in TJ-II were carried out at the plasma bulk side of the velocity shear location ($r\text{-}r_{LCFS} \approx -2$cm).

Figure 7 shows the probability density function for fluctuations in gradients and the expected value of the E×B flux, taking the magnetic well as a parameter. From the upper graph it can be deduced that the density gradient PDF is rather gaussian around the average gradient and that level of edge plasma fluctuations increases when the magnetic well is reduced, in agreement with previous findings.

A significant fraction of the total E×B turbulent flux can be assigned to large and sporadic transport bursts whose amplitude increase as well depth is decreased. This bursty behaviour of turbulent transport is strongly coupled with fluctuations in density gradients. As the density gradient increases above the most probable value the E×B turbulent driven transport increases until the system relaxes back to the initial marginally stable situation. It should be noted as the plasma becomes more unstable (i.e. magnetic well 0.9%) the size of turbulence events increases significantly as density increases above the most probable value.

7. NON-GAUSSIAN FEATURES IN FLUCTUATIONS IN GRADIENTS

PDFs of turbulent transport show much stronger non-Gaussian features than PDFs of fluctuations in gradients, as pointed out in section 2 (see figure 1). However, a detailed investigation of the statistical properties of fluctuations in gradients has reveiled the existence of non-gaussian features. This result is illustrated in figure 8 which shows PDFs of gradients and the effective radial velocities measured at different magnetic fields in the JET SOL region. A small, but significant departure from the gaussian distribution is observed. The trigger of large transport events propagating at high radial speeds (200 – 600m/s) takes place well above the most probable radial gradient suggesting that the system remain subcritical.

8. CONCLUSIONS

The structure of the naturally occurring velocity shear layer and the dynamical coupling between gradients and transport have been investigated in the JET and TJ-II plasma boundary region and the following conclusions have been reached:

In both devices, the naturally occurring velocity shear layer organizes itself to reach a condition in which the radial gradient in the poloidal phase velocity of fluctuations is comparable to the inverse of the correlation time of fluctuations ($1/\tau$). This result suggests that ExB sheared flows appears to organize themselves to be close to marginal stability (i.e. $\omega_{ExB} \approx 1/\tau$). Whereas this property is consistent with turbulent driven fluctuating radial electric fields, it looks difficult to explain in which way other mechanims, like those based in the concept of ion orbit losses, can allow poloidal sheared flows and fluctuations to reach marginal stability.

The investigation of the dynamical interplay between fluctuations in gradients and turbulent transport has shown that their PDFs are strongly coupled. The bursty behaviour of turbulent transport is linked with a departure from the most probable radial gradient. The dynamical relation between fluctuations in gradients and transport is strongly affected by the presence of sheared poloidal flows, heating power and the proximity to instability thresholds: the size of large transport events decreases in the proximity of sheared flows and increases with heating power and in the proximity of instability thresholds. These results are consistent with the concept of turbulent transport self-regulated via fluctuations near marginal stability.

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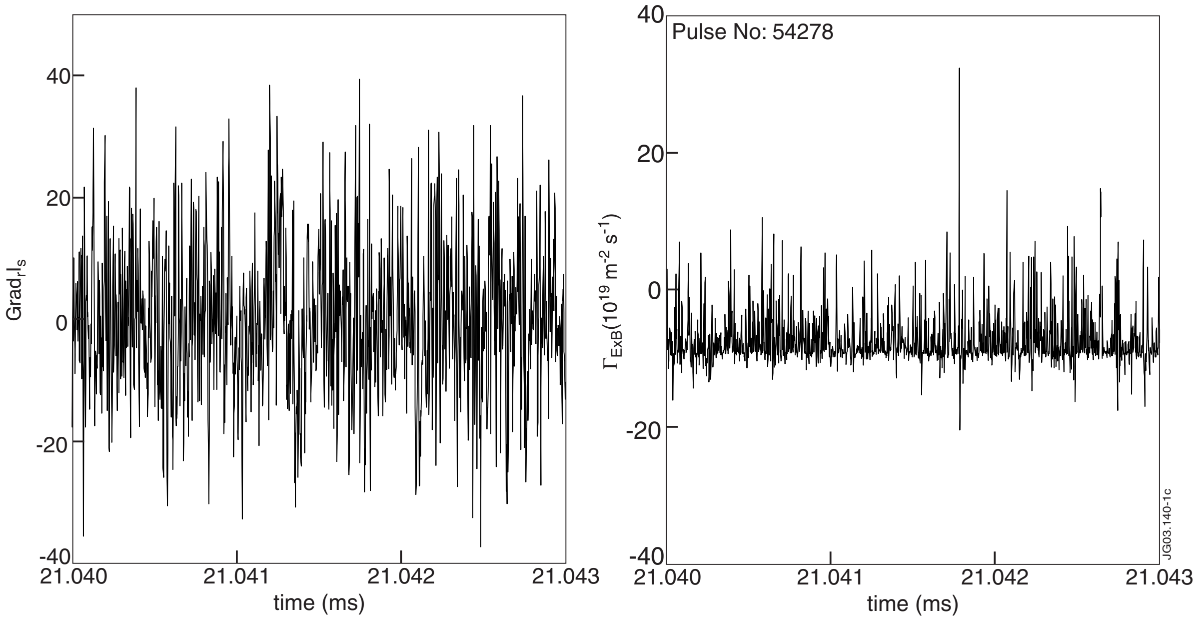

Figure 1: Time evolution of the radial gradients and turbulent transport in the JET plasma boundary region.

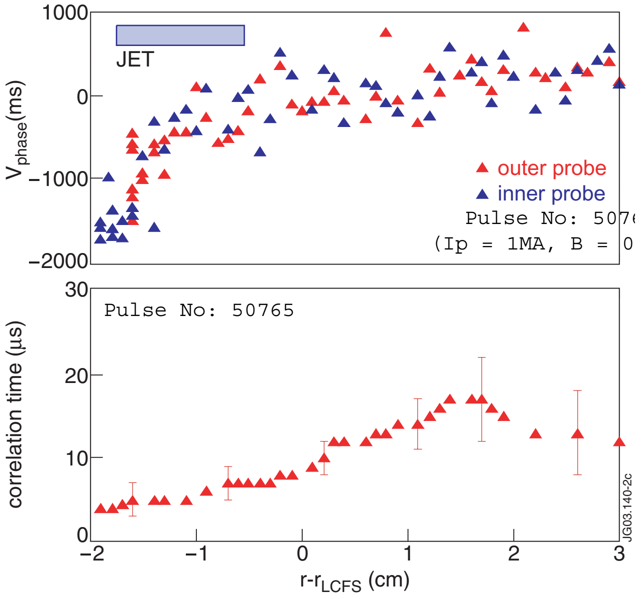

Figure 2: Radial profiles of poloidal phase velocity of fluctuations and autocorrelation times in JET.

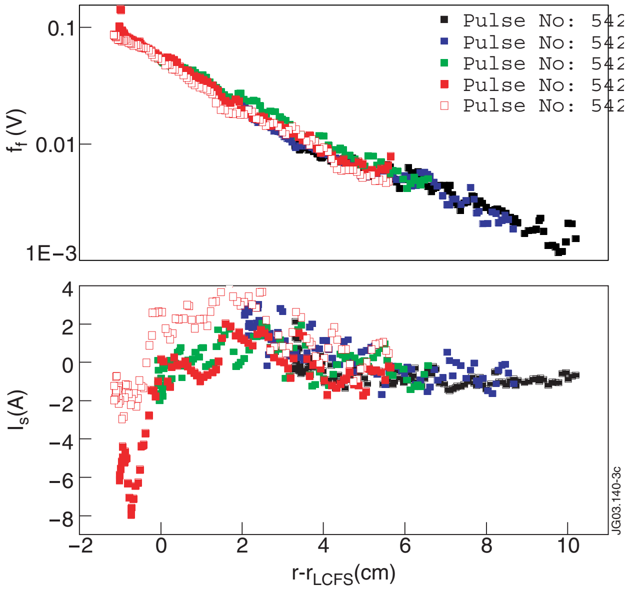

Figure 3: Radial profiles of ion saturation current and floating potential in the JET boundary region (ohmic plasmas).

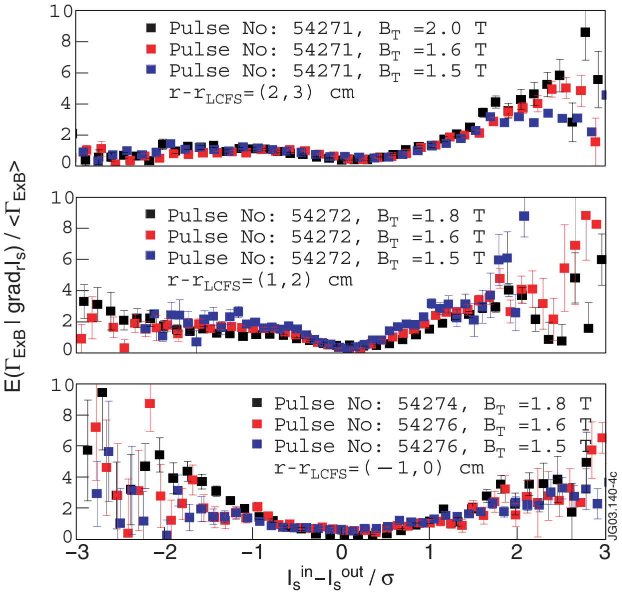

Figure 4: Radial transport versus fluctuations in gradients in the JET boundary region.

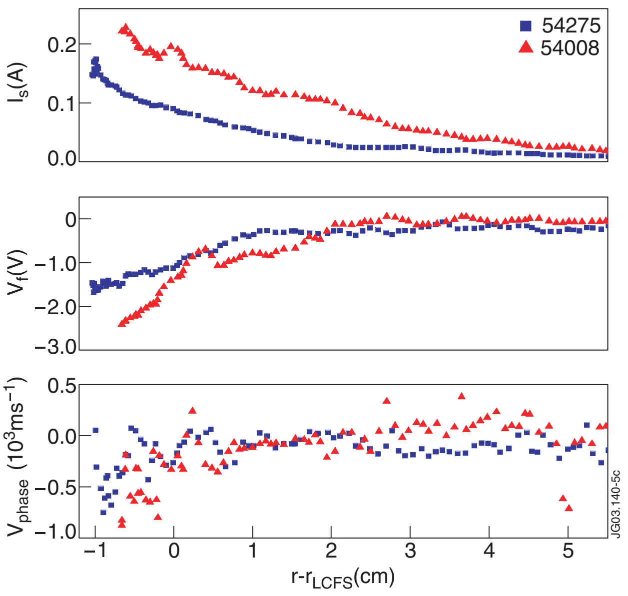

Figure 5: Radial profiles in JET ohmic (Pulse No: 54275) and L-mode (Pulse No: 54008) plasmas.

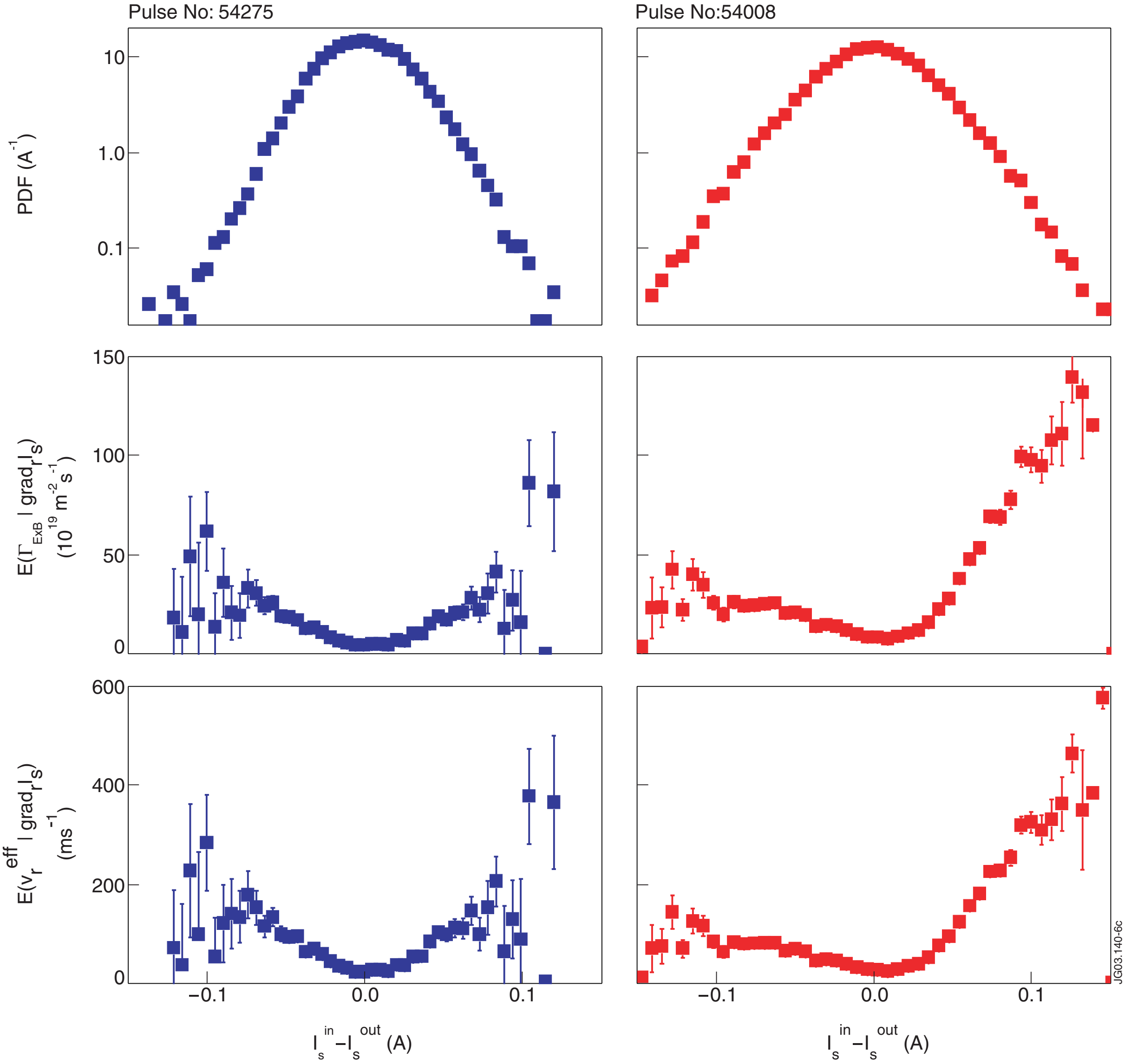

Figure 6: PDFs od gradients, transport and radial effective velocity in ohmic (Pulse No: 54275) and L-mode plasmas (Pulse No: 54008) in the JET plasma plasma boundary region.

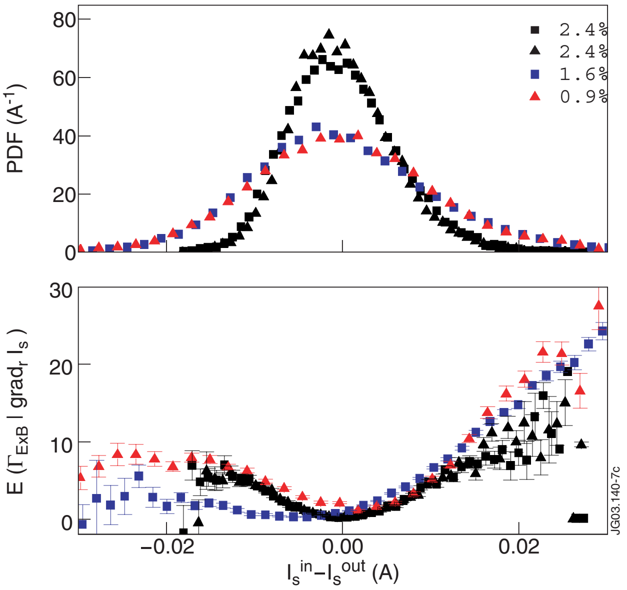

Figure 7:. PDFs of gradients and turbulent transport varying the magnetic well (0.9 – 2.4%) in the TJ-II stellarator.

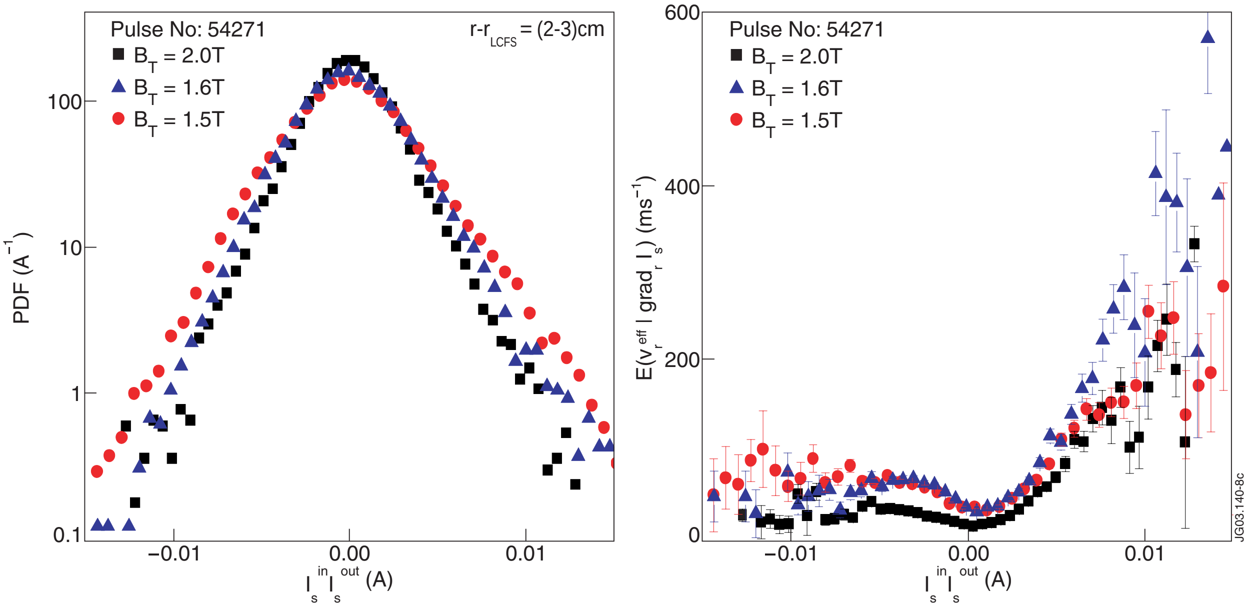

Figure 8: PDFs of gradients and effective radial velocities measured in the JET plasma boundary region.