INSTITUTE OF PHYSICS PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION

Plasma Phys. Control. Fusion **44** (2002) 1557–1564 PII: S0741-3335(02)35634-3

Empirical similarity in the probability density function of turbulent transport in the edge plasma region in fusion plasmas

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Received 9 April 2002
Published 22 July 2002
Online at stacks.iop.org/PPCF/44/1557

Abstract

The probability density function (PDF) of turbulent transport has been investigated in the plasma edge region of tokamak (JET) and stellarator (TJ-II) fusion devices. PDFs can be re-scaled using a functional form, $\mathrm{PDF}(\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}) = L^{-1}g(\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}/L)$, where L is directly related with the level of fluctuations in the turbulent flux. This kind of re-scaling holds at different timescales in which the functional form of the PDF changes. The empirical similarity in the PDF of turbulent transport in the edge region in both the JET tokamak and the TJ-II stellarator supports the view that turbulent transport displays universality in fusion plasmas. These results emphasize 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 on average quantities (i.e. average correlation lengths).

1. Introduction

Comparative studies of the structure of plasma turbulence carried out in different magnetic confinement devices have led to insights furthering the understanding of the underlying physics of turbulent transport in fusion plasmas [1–4]. The overall similarity in the structure in the statistical properties of fluctuations [1, 2], in the phase velocity of fluctuations in the plasma edge region [3] and the empirical similarity in frequency spectra [4] has led to the conclusion that plasma turbulence in magnetically confined plasmas, as in many other dynamic systems, displays universal characteristics.

Dimensionless scaling investigations have been used to reveal the physical dependences of plasma transport on fusion plasmas [5]. The dimensionless parameter ρ^* (gyro-radius normalized to the plasma minor radius) plays a major role in determining the transport processes (e.g. Bohm versus gyro-Bohm-type processes). In particular, if the radial scale length of turbulence is of the order of the gyro-radius, a gyro-Bohm-type transport follows, whereas the existence of radially elongated structures would imply Bohm-type transport coefficients. Self-organized critical (SOC) models predict large-scale and sporadic avalanches connecting remote parts of the plasma, which might be a key ingredient in explaining Bohm-like transport [6, 7]. These results emphasize the importance of systematic investigations of the statistical properties of turbulent transport and its radial structure in fusion plasmas.

The characterization of fluctuation-driven particle and energy fluxes requires experimental techniques to measure the time evolution in plasma parameters such as density and electric fields with good temporal and spatial resolution. With the present state of the art in plasma diagnostics this kind of measurement is mostly limited to the plasma edge region. However, it has been recently argued that the correlation between density fluctuations and fluctuations in the radial phase velocity of fluctuations can provide a good estimation of the $\boldsymbol{E} \times \boldsymbol{B}$ turbulent transport in the plasma edge [8, 9]. These findings allow the possibility to investigate the statistical properties of turbulent transport in the plasma core region of fusion plasmas based on measurements of density fluctuations.

In this paper, we present experimental evidence of an empirical similarity in the statistical properties of turbulent transport in the plasma boundary of JET tokamak and TJ-II stellarator.

2. Experimental set-up and edge fluctuation levels

2.1. TJ-II stellarator

The TJ-II stellarator ($R = 1.5$ m, $a \leqslant 0.22$ m, $B \leqslant 1.2$ T) has a high degree of magnetic configuration flexibility. In particular, the magnetic well can be changed from -1% to 6%. Since the magnetic well is the main stabilizing term in heliacs [10, 11], this property makes TJ-II an ideal device for studying the onset of fluctuations and related phenomena close to instability thresholds. The absence of magnetic well gives rise in TJ-II stellarator to instabilities at any plasma pressure [10, 11]. A sequence of configurations was selected with well depth ranging from 2.4% down to 0.2%, and having magnetic well in the bulk and magnetic hill at plasma edge, which becomes, thus, unstable. Remarkable similarity exists between different configurations according to their rotational transform profiles as well as to their magnetic surfaces.

Experiments were carried out in ECRH plasmas ($P_{\mathrm{ECRH}} = 300$–600 kW). A fast reciprocating Langmuir probe has been used to investigate the structure of plasma profiles and their fluctuations. Plasma fluctuations are investigated using 500 kHz digitizers.

Fluctuations in the ion saturation current (I_{s}) have been observed to increase when magnetic well is reduced [12]. Figure 1 shows the modification in the level of ion saturation fluctuations as the magnetic well is reduced in the plasma edge region.

2.2. JET tokamak

Plasmas studied in this paper were produced in X-point configurations. 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 position of the last closed flux surface was determined by the equilibrium code EFIT. Plasma fluctuations are investigated

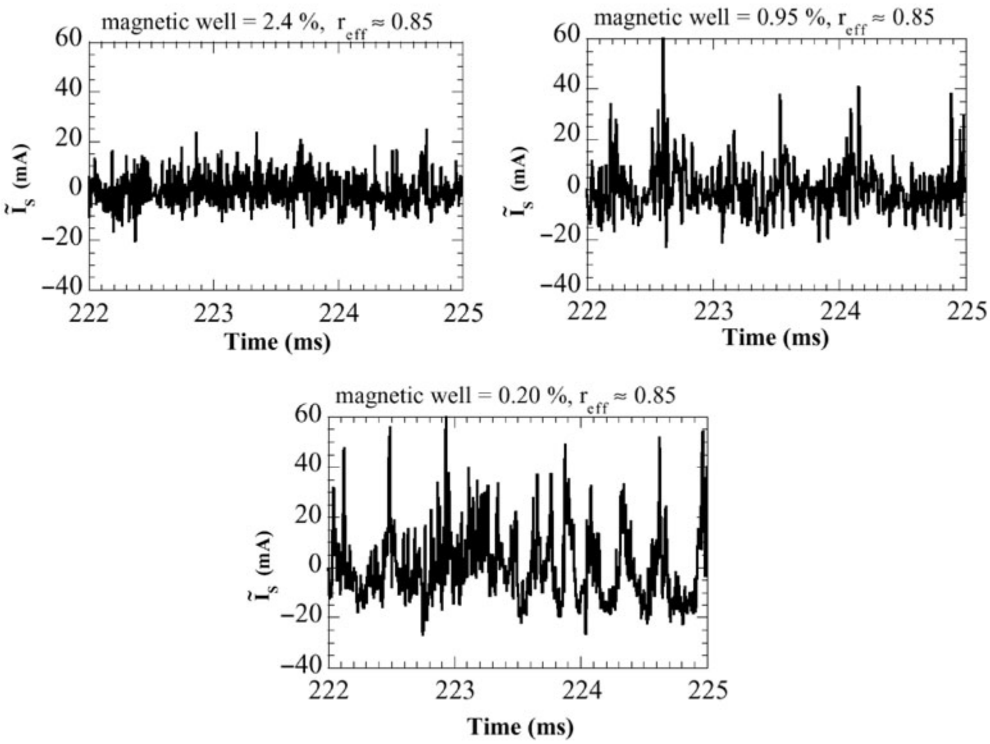

Figure 1. Ion saturation current fluctuation levels versus magnetic well in the plasma edge region of the TJ-II stellarator. The level of fluctuations increases as the magnetic well is reduced [12]. Measurements were taken at the effective radius $r_{\text{eff}} \approx 0.85$.

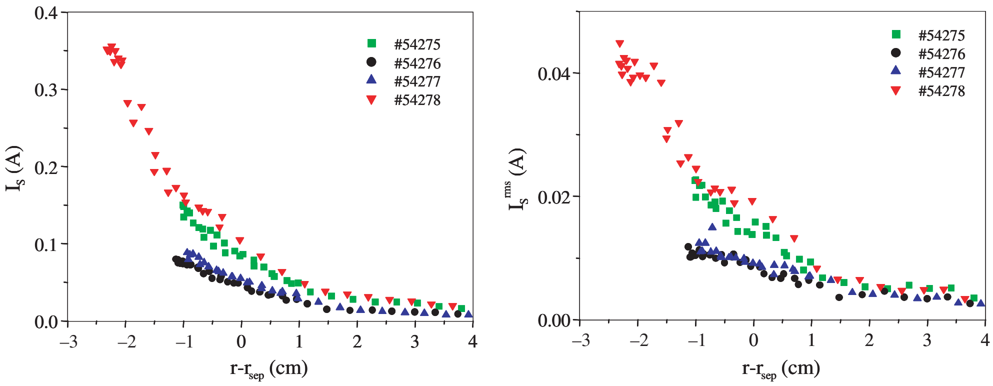

Figure 2. Radial profile of time-averaged ion saturation current (I_s) and radial profile of the corresponding (rms) level of fluctuations in the ion saturation current (I_s^{rms}) in the plasma boundary region in the JET tokamak.

using standard signal processing techniques and 500 kHz digitizers. Figure 2 shows the radial profiles of ion saturation current (I_s) and the root mean square (rms) of ion saturation current fluctuations (I_s^{rms}) in plasmas with $B = 1.8$ T, $I_p = 2$ MA and plasma density in the range $(2.9–6.7) \times 19^{19}\,\text{m}^{-3}$. The rms value of fluctuations systematically increases with increasing the plasma density.

3. Empirical similarity in turbulent fluxes

The local time resolved radial $\boldsymbol{E} \times \boldsymbol{B}$ turbulent induced fluxes, $\tilde{\Gamma}(t) = \tilde{n}(t)\tilde{E}_\theta(t)/B$ (where $\tilde{n}$ and $\tilde{E}_\theta$ are the fluctuating density and poloidal electric field, respectively), were calculated neglecting the influence of electron temperature both on TJ-II and JET devices. The distribution function of the time resolved turbulent transport has been estimated by $\text{PDF}(\Gamma_n) = N_{\Gamma n}/NW$, where $N_{\Gamma n}$ is the number of data values that fall within the range $\Gamma_n \pm W/2$, W is a narrow interval centred at Γ_n and N is the total number of data values.

Figures 3 and 4 show the probability density functions (PDFs) of the $\boldsymbol{E} \times \boldsymbol{B}$ turbulent fluxes for measurements taken in the plasma edge region in the proximity of the last closed flux surface in JET and TJ-II stellarator. In both devices PDFs of fluctuating transport show non-Gaussian features. A significant fraction of the total $\boldsymbol{E} \times \boldsymbol{B}$ turbulent flux can be attributed to the presence of large and sporadic transport burst, whose magnitude is quite sensitive to the plasma conditions. In the case of TJ-II experiments, the size of turbulent flux events strongly increases when magnetic well is reduced, as expected from the increase in density and potential fluctuations as well as in their correlation [12]. An analysis of flux PDFs reflects the increase in the probability of large amplitude flux events when well depth is decreased. In the case of JET experiments, increasing plasma density tends to increase the amplitude of transport events.

The statistical properties of turbulent transport have also been investigated at different timescales using JET data. In order to do this, we have constructed time records with a time resolution ΔN, by averaging over blocks of ΔN elements from the original time series. The original time series is about 50–70 ms (i.e. $\sim$30.000 points). Figure 4 shows PDF of turbulent fluxes after averaging the original time series $\Delta N = 20$ and $40\,\mu$s. The shapes of PDFs of transport are significantly modified as the averaging parameter (ΔN) increases: negative transport events are strongly reduced and the shape of the tail of the distribution changes in agreement with previous observation in stellarator plasmas [13]. As the timescale decreases (e.g. ΔN increases), the PDF of transport is fully dominated by outwards transport events.

The PDFs of transport both in TJ-II and JET devices have an interesting property: they can be re-scaled assuming a 'finite-size scaling' functional form [14, 15]

$$\text{PDF}(\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}) = L^{-1} g\left(\frac{\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}}{L}\right), \tag{1}$$

where L is a scaling factor. As shown in figures 3(*b*) and 5 the re-scaled PDFs of $\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}$ show the same behaviour over the entire amplitude range of transport. The re-scaling functional form given by expression (1) can fit experimental results measured at different timescales $\Delta N = 2$–$40\,\mu$s, both in TJ-II and JET. However, it should be noted that the fitting of the experimental results significantly improves as the timescale decreases (figure 5). Experiments performed in TJ-II in different operational regimes (different magnetic well level) and JET (density scan) showed a linear relation between the scaling factor (L) and the rms value of the turbulent flux (figures 6 and 7).

As shown in figure 8, the form of the scaling function in equation (1) is consistent with a stretched exponential, $g(x) \propto \exp[-(x/x^*)^\alpha]$, having found that α is about 0.5–0.6 for both devices for $\Delta N = 2\,\mu$s and x^* is a fitting parameter. The α parameter increases as ΔN increases. This distribution form has also been found in other physical systems, quite different from fusion plasmas [14, 15].

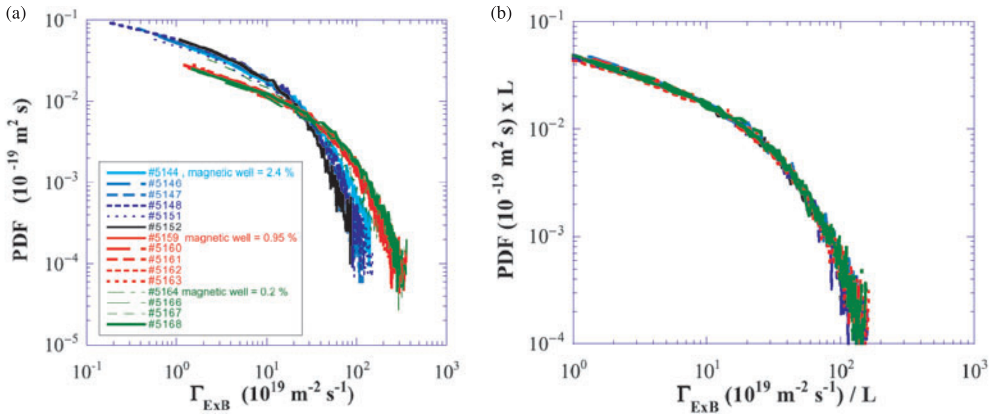

Figure 3. (*a*) PDFs of edge turbulent transport in plasma configurations having different magnetic well in the TJ-II stellarator; (*b*) re-scaled PDFs of turbulent transport using the functional form $\mathrm{PDF}(\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}) = L^{-1}g(\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}/L)$.

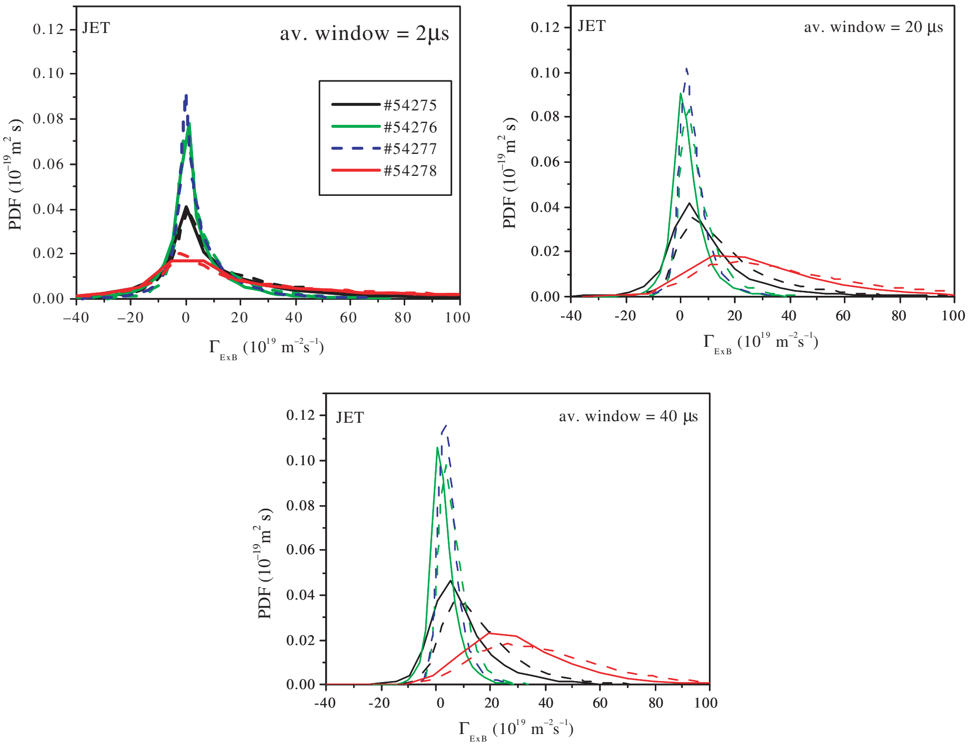

Figure 4. PDFs of edge turbulent transport in density scan experiment in the JET tokamak. PDFs have been computed at different timescales: $\Delta N = 2$–20–40 μs.

4. Discussion and conclusions

The statistical properties of turbulent transport show a striking empirical similarity in the plasma edge region in fusion plasmas. Experimental results show that PDFs of turbulent flux

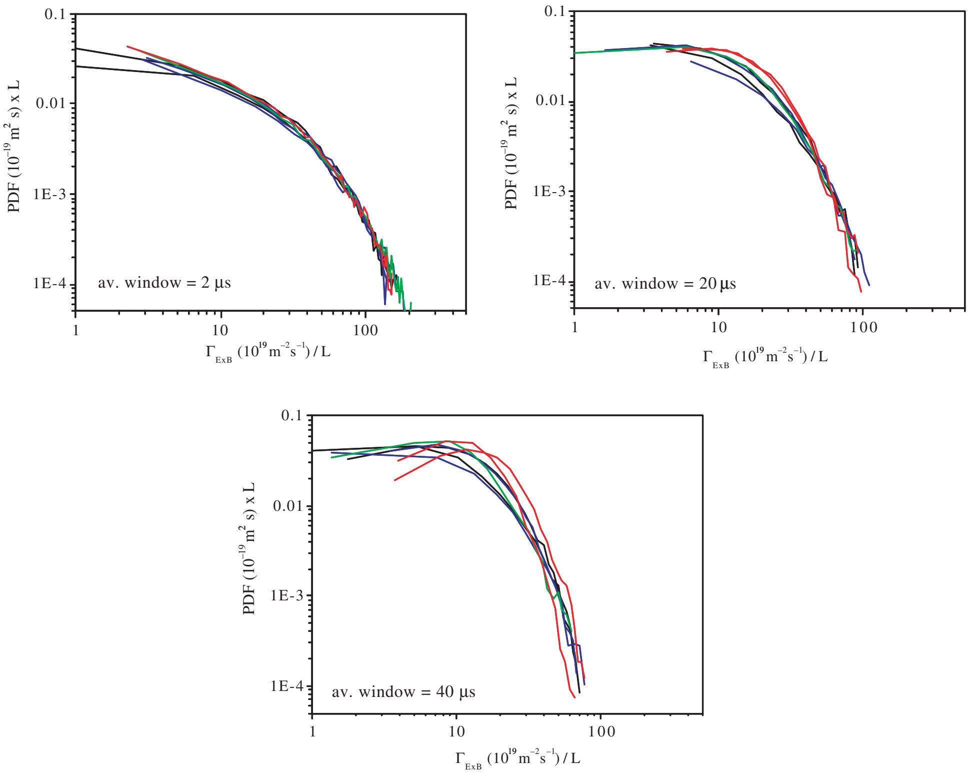

Figure 5. Re-scaled PDFs of edge turbulent transport using the functional form $\mathrm{PDF}(\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}) = L^{-1}g(\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}/L)$ in the JET tokamak.

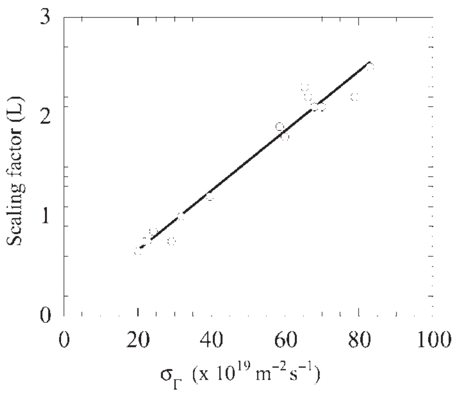

Figure 6. Scaling factor L versus the level of fluctuations (σ_Γ) of turbulent transport in the TJ-II stellarator device.

can be re-scaled using a law which appears in finite-size scaling studies [14]. The fact that this finding has been observed in fusion devices with different magnetic topology and heating supports the view that plasma turbulent transport displays universality. Furthermore, these findings are in agreement with the empirical similarity in the frequency spectra of fluctuations previously reported in different fusion plasmas [4]. Frequency spectra of fluctuations can

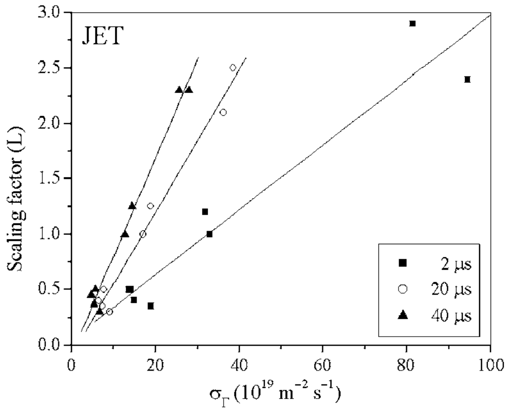

Figure 7. Scaling factor L versus the level of fluctuations (σ_Γ) of turbulent transport in the JET tokamak.

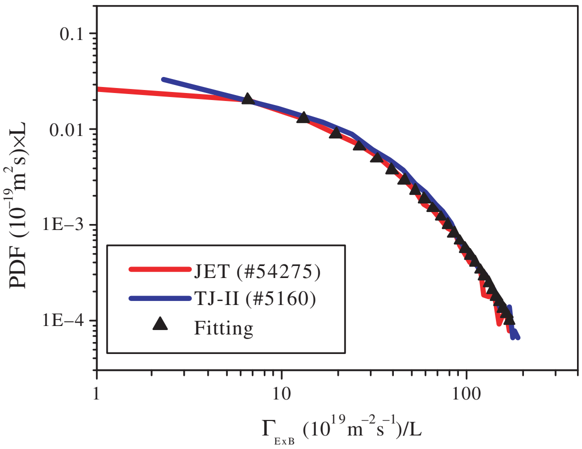

Figure 8. Comparison between the re-scaled PDFs of edge turbulent transport measured in the TJ-II stellarator and in the JET tokamak ($\Delta N = 2\,\mu$s). Re-scaled PDFs are consistent with a stretched exponential, $g(x) \propto \exp[-(x/x^*)^\alpha]$, with $x = \Gamma_{E\times B}/L$ and α is about 0.5–0.6 for both devices. The α parameter increases as ΔN increases.

be re-scaled using the expression, $P(\omega) = P_0 g(\lambda\omega)$ where λ and P_0 are parameters to be determined for each device. The present experiments show that the re-scaling parameter is directly related with the variance of fluctuations in the turbulent transport.

The functional form for the PDF given by expression (1) might be partially explained considering that the flux is a quadratic function of two fluctuating and correlated density and radial velocity fields [13]. On the other hand, this kind of re-scaling holds at different timescales in which the functional form of the PDF changes, and at the longer timescale turbulent transport is fully dominated by the outward flux events. Previous studies have shown that self-similar properties of the PDF of transport changes from the so-called fluctuation timescale to the mesoscale timescale [13].

These findings suggest that turbulent transport evolves into a critical state which shows a similar behaviour in the distribution function of transport events, independently of details of the free energy source driving fluctuations. These results emphasize 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 on average quantities (i.e. average correlation lengths).

A more systematic analysis of the PDF of transport from other confinement devices is needed to clarify the interpretation of the present findings. In particular, it would be very useful to look the properties of PDFs in non-confined plasmas (like linear devices and toroidal devices without rotational transform), where we do not expect to have self-similarity on the structure of edge fluctuations [16]. It would also be interesting to clarify whether this empirical similarity in the PDFs of edge turbulent fluxes is fulfilled in the plasma core region. It has been recently argued that the correlation between density fluctuations and fluctuations in the radial phase velocity of fluctuations provides a good estimation of the $\boldsymbol{E} \times \boldsymbol{B}$ turbulent transport computed from the correlation between density and poloidal electric field fluctuations [8, 9]. These results indicate that statistical properties of turbulent transport might also be computed in the plasma core from measurements of density fluctuations with microwave reflectrometry or beam emission spectroscopy. Experiments are in progress to investigate the validity of 'finite-size scaling laws' of turbulent transport in the plasma core region in fusion plasmas.

Acknowledgment

One of the authors (B Gonçalves) acknowledges support by the Fundaçao para a Ciencia e Tecnologia (Lisbon) under Grant No PRAXIS XXI/BD/15814/98.

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