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Experimental evidence of fluctuations and flows near marginal stability and dynamical interplay between gradients and transport in the JET plasma boundary region

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Abstract

The structure of the naturally occurring velocity shear layer and the dynamical coupling between gradients and transport have been investigated in the JET plasma boundary region. The velocity shear layer appears to organize 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 $E \times B$ sheared flows organized themselves to be close to marginal stability (i.e. $\omega_{E\times B} \approx 1/\tau$). The size of turbulent events increases when the plasma deviates from the average gradient. The resulting radial velocity of fluctuations is of the order of 20 m/s for transport events implying a small deviation from the most probable gradient. This value is consistent with a diffusive modeling with B2-Eirene. The radial velocity increases up to 500 m/s for large transport events.

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1. Introduction

Broadband electrostatic and magnetic fluctuations have been observed in the boundary region of magnetically confined devices. The electrostatic fluctuations produce a fluctuating radial velocity given by $\tilde{v}_r = \widetilde{E}_\theta/B$, $\widetilde{E}_\theta$ being the fluctuating poloidal electric field and B is the toroidal magnetic field and the resulting electrostatic fluctuation driven radial particle flux is given by $\Gamma_{E\times B}(t) = \tilde{n}(t)\widetilde{E}_\theta(t)/B$. Ignoring poloidal and toroidal asymmetries the total electrostatic fluctuation driven particle fluxes have been measured in the plasma boundary region of tokamaks, stellarators and reversed fields pinches. It has been experimentally shown that in some cases the fluctuating flux can account for an important part of the total particle flux in the edge region [1,2]. However, it should be noted that in some cases fluctuation fluxes appear too high to be consistent with global particle balance [3]. At present, this disagreement still remains as an open question [4]. It has been recently suggested the importance of the statistical description of transport processes, based on probability density functions, as an alternative approach to the study of transport based on the computation of effective transport coefficients [5]. This approach would be useful to clarify the underlying physics of turbulent driven transport in fusion plasmas.

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One of the important achievements of the fusion research community in the last years has been the development of techniques to control plasma turbulence based on the $E \times B$ shear stabilization mechanism. Several mechanisms have been proposed as responsible for the generation of shear flow [6–8 and references therein]. Understanding the physics of sheared flows is a crucial issue to explain the transition to improved confinement regimes and the generation of transport barriers in fusion plasmas.

This paper reports results on the characterization of the statistical properties of turbulence and the physics of $E \times B$ sheared flows in the JET plasma boundary region. The paper has been organized as follows. Section 2 presents the experimental set-up and analysis tools. Experimental evidence of sheared flows and fluctuations near marginal stability in the edge region of JET tokamak is presented in Section 3. The investigation of the coupling between transport, fluctuations in gradients and the effective radial velocity of transport is discussed in Section 4. Finally conclusions are presented in Section 5.

2. Experimental set-up and analysis tools

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. Plasma fluctuations are investigated using standard signal processing techniques and 500 kHz digitizers. Plasmas studied in this paper were produced in X-point plasma configurations with toroidal magnetic fields $B = 1$–2.5 T, $I_p = 1$–2 MA, $P_{NBI} = 0$–5 MW (ohmic and L-mode plasmas).

The mean velocity of fluctuations perpendicular to B_T 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 [9] using floating probes separated 0.5 cm in the poloidal direction in the JET 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, $E_\theta = \Delta\tilde{\Phi}_f/\Delta\theta$ with $\Delta\theta \approx 0.5$ cm. Fluctuations in the radial component of ion saturation current gradients have been computed as $\nabla\tilde{I}_s(t) = [\tilde{I}_s^{inner}(t) - \tilde{I}_s^{outer}(t)]$ with $\langle\Delta\tilde{I}_s\rangle = 0$, 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 0.5 cm.

An effective radial velocity has been defined as the normalized $E \times B$ turbulent particle transport to the local density: $v_{eff} = \langle\tilde{I}_s\tilde{E}_\theta\rangle/I_s B_T$, where I_s is the ion saturation current of the inner probe [10]. 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.

3. The naturally occurring velocity shear layer and L–H transition physics

3.1. The velocity shear layer

A velocity shear layer has been observed near the location of the LCFS (as determined from magnetic measurements-EFIT). In divertor plasmas, the poloidal phase velocity of fluctuations (v_{phase}) increases in the electron drift direction up to 2000 m/s, in the proximity of the separatrix. This change can be explained in terms of $E \times B$ drifts (Fig. 1). The resulting radial gradient in v_{phase} 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 μs (Fig. 2). This result is verified in ohmic plasmas with $I_p = 1$ MA/$B = 1$ T, in which the power threshold for the L–H transition is about 1 MW. A more detailed quantitative analysis of the experimental results would require to take into account the influence of plasma rotation in the correlation time [11]. It should be noted that the present results are consistent with previous observations in tokamaks [11], stellarators [12] and reversed field pinches [13] 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. Whereas this property is consistent with turbulent driven fluctuating radial elec-

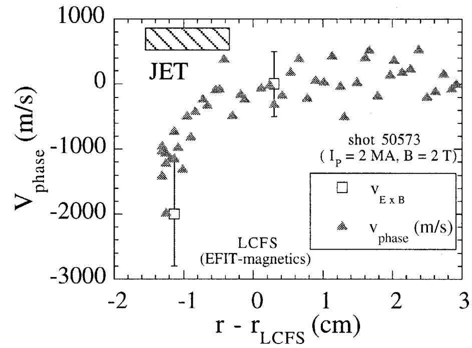

Fig. 1. Phase velocity of fluctuations and $E \times B$ drift. The $E \times B$ drift has been deduced from the radial profile of plasma potential (Φ_p). This profile was computed from electron temperature and floating potential profiles using $\Phi_p = \Phi_f + 2.5T_e$.

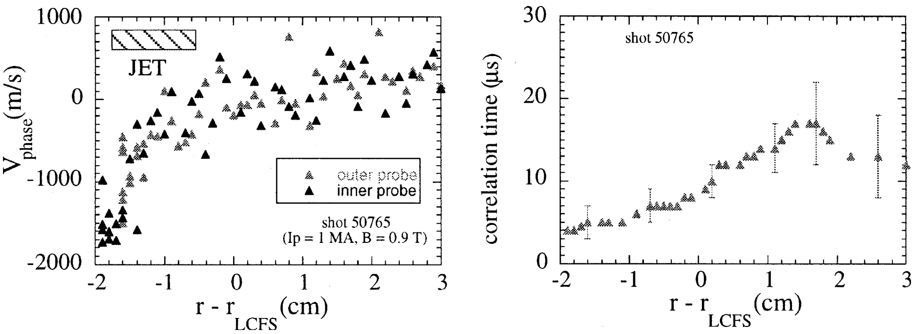

Fig. 2. Phase velocity of fluctuations and auto-correlation times.

tric field [14], 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.

3.2. Flows near marginal stability and L–H transition physics

Previous results are consistent with the paradigm of turbulent transport self-regulated via fluctuations. In this section we discuss the impact of these findings in the properties of turbulent transport and in the power threshold for the transition to H-mode regimes.

Once turbulence driven sheared electric fields (e.g. Reynolds stress, anomalous stringer spin-up) reach the critical value to modify fluctuations, a negative feedback mechanism will be established which will keep the plasma near the condition $\omega_{E\times B}$ critical. However, this feedback mechanism might not allow the transition to the improved confinement regime unless a $E\times B$ shear positive feedback mechanism is triggered by the Reynolds stress. This positive feedback mechanism might be provided by the ∇P_i contribution to the $E\times B$ shear flow [7]. In the framework of the interpretation, the following condition should be verified to reach the L–H transition,

$$\omega_{E\times B}^{\text{critical}} \approx \frac{1}{Z_i e}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{1}{n_i B}\nabla P_i\right),$$

where Z_i is the ion charge, n_i the ion density and P_i is the ion pressure and B is the toroidal magnetic field [6]. Considering that the ion heat flux can be related to the pressure gradient through an effective diffusivity (χ_i) and neglecting $\mathrm{d}B/\mathrm{d}r$ and $\partial^2 P_i/\partial r^2$, it follows

$$\omega_{E\times B}^{\text{critical}} \approx \frac{1}{Z_i B n_i^2}\frac{\mathrm{d}n_i}{\mathrm{d}r}\nabla P_i \approx \frac{L_n^{-1}}{Z_i e B n}\frac{Q_i}{\chi_i}.$$

Thus the transition to the improved confinement regime will be characterized by a critical heat flux,

$$Q_i \approx Z_i e \omega_{E\times B}^{\text{critical}} L_n \chi_i B n. \qquad (1)$$

Using typical JET edge plasma parameters for the L–H transition, $\omega_{E\times B}^{\text{critical}} \approx 10^5\ \mathrm{s}^{-1}$, $Bn_{\text{L–H}} \approx 10^{20}\ \mathrm{m}^{-3}\ \mathrm{T}$, $\chi_i \approx 1$–$10\ \mathrm{m}^2/\mathrm{s}$, $L_n^{-1} \approx 10^{-2}$ m, it follows that $Q_i \approx (0.01$–$0.1)$ $\mathrm{MW\,m}^{-2}$. This value is close to the L–H power threshold values reported in JET [15]. Expression (1) shows that the critical heat flux depends on the plasma density and magnetic field, which resembles the parametric dependences of the power threshold reported in tokamak plasmas [16] ($P_{\text{th}} \propto n^{\alpha}B^{\beta}(\alpha \approx \beta \approx 1)$). Expression (1) also shows that the critical heat flux depends on transport (e.g. χ_i) and Z_i (the ion charge). The dependence with the ion charge (Z_i) would be consistent with the increase of the power threshold in He plasmas as compared with D plasmas ($P_{\text{th L–H}}(\text{He}_4)/P_{\text{th L–H}}(D) \approx 1.5$). Finally, it should be noted that, in the framework of the proposed synergy between fluctuation driven flows (e.g. Reynolds stress) and pressure gradients, the characteristic time for the L–H transition would determined by the time scale of the energy transfer between different turbulent scales (i.e. the turbulence correlation time) [7].

4. Dynamical interplay between fluctuations in gradients and $E\times B$ transport

Turbulent transport and effective radial velocities of turbulent events have been characterized in terms of probability distribution function (PDF). The joint probability P_{ij} of the two variables X and Y, meaning 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 $(X_i, X_i + \Delta X)$ and $(Y_i, Y_i + \Delta Y)$ and N the time series dimension. ΔX and ΔY are the bin dimension of X and Y time series, respectively, where the indices stands for ith (or jth) bin average value. The expected value of X at a given value of Y_j is defined as

$$E[X|Y_j] = \frac{\sum_i P_{ij} X_i}{\sum_i P_{ij}}$$

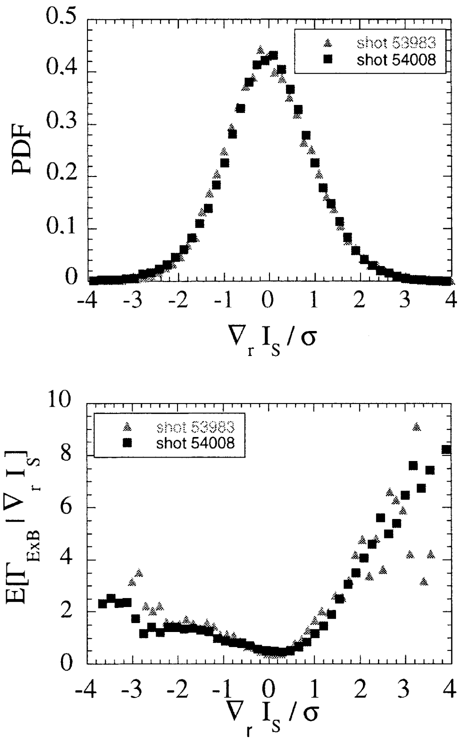

Fig. 3. PDF fluctuations in radial gradients and amplitude for the expected value of the $E \times B$ turbulent versus $\nabla\tilde{I}_s/\sigma$.

and represents the average value of the probability distribution of X at a given value of Y.

Fig. 3 shows the PDF for fluctuations in gradients, and the expected value of the $E \times B$ flux for a given density gradient ($E[\Gamma_{E\times B}|\nabla_r I_s]$) in L-mode 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 ($\Gamma_{E\times B}/\langle\Gamma_{E\times B}\rangle \approx 0.5$). Large amplitude transport events ($\Gamma_{E\times B}/\langle\Gamma_{E\times B}\rangle \approx 3$–$8$) take place when the plasma displaces from the most probable gradient value. The expected value of $E \times B$ turbulent transport events increases strongly as the gradient increases above its most probable value (i.e. $\nabla\tilde{I}_s/\sigma > 0$).

The present experimental results show that the bursty and strongly non-gaussian behaviour of turbulent transport is strongly coupled with fluctuations in gradients. As the density gradient increases above the most probable gradient the $E \times B$ turbulent driven transport increases and the system perform a relaxation which tends to drive the plasma back to the marginal stable situation which minimized the size of transport events. The increase in the size of transport events as gradient increases is consistent with the self-regulation of turbulent transport and gradients near marginal stability in the plasma boundary region. However, the non-monotonic dynamical relation between $E \times B$ transport ($\Gamma_{E\times B}$) and gradients ($\nabla\tilde{I}_s$) may be also partially due to the direct link between $\Gamma_{E\times B}$ and $\nabla\tilde{I}_s$ through density fluctuations.

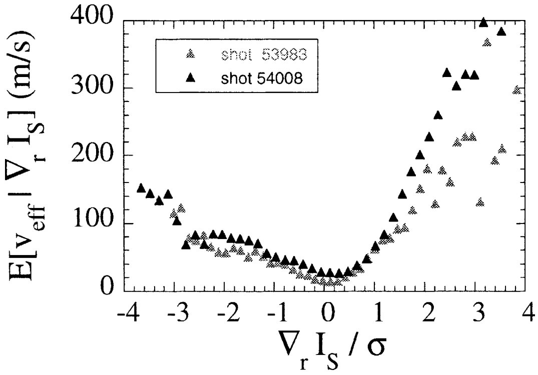

Fig. 4. Expected value of the radial effective velocity versus $\nabla\tilde{I}_s/\sigma$.

Fig. 4 shows the expected value of the effective radial velocity of fluctuations for a given density gradient ($E[v_{\text{eff}}|\nabla_r I_s]$). The radial velocity is close to 20 m/s for small deviations from the averaged gradient but increases up to 500 m/s for large transport events implying a strong deviation from the most probable radial gradient. Experimental evidence of intermittent events

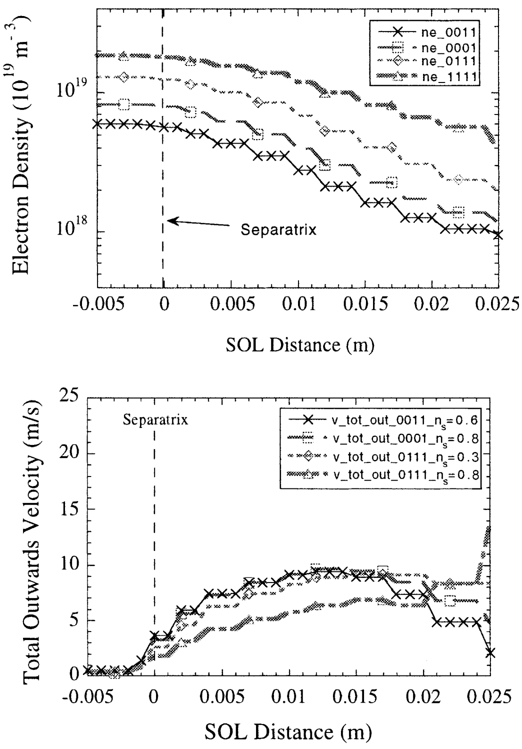

Fig. 5. Density and effective radial velocities from simulations with B2-Eirene for JET ohmic conditions.

propagating radially with velocities in the range of 1000 m/s have been previously reported [17–19].

It is interesting to compare the present experimental results with predictions from a diffusive modeling of the plasma boundary in JET [20]. Fig. 5 shows the results from simulations with B2-Eirene for JET ohmic conditions. This simplified model assumes that particle transport can be characterized by a diffusion coefficient $D_{perp} = 0.1$ m^2/s with a density decay length of about 1 cm and neglecting the influence of drifts. The resulting typical effective radial velocity is of the order of 10 m/s. This radial velocity turns out to be rather close to the experimental values for the radial velocity of transport events implying a small deviations from the most probable gradient; however, it is very far away from the several 100 m/s of the large transport events.

5. Conclusions

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

(a) 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 there is no continuous increase of the $E \times B$ flow when approaching the critical power threshold for the transition to improved confinement regimes and that $E \times B$ sheared flows appears to organize themselves to be close to marginal stability (i.e. $\omega_{E\times B} \approx 1/\tau$). A synergy between fluctuation driven flows (e.g. Reynolds stress) and pressure gradient driven flows is suggested to trigger the L–H transition.

(b) 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.

(c) Transport event, related with small departures from the most probable local gradient, propagates radially with an effective velocity of about 20 m/s, which is consistent with simplified simulations of diffusive transport in the SOL region. On the contrary, large transport events, related to significant departures from the most probable gradient, propagates radially with an effective velocity up to 500 m/s. These results suggest a link between the size of transport events and the nature of transport in the plasma boundary region.

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