Experimental Investigation of Dynamical Coupling between Turbulent Transport and Parallel Flows in the JET Plasma-Boundary Region

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The dynamical coupling between turbulent transport and parallel flows has been investigated in the plasma boundary region of the Joint European Torus tokamak. Experimental results show that there is a dynamical relationship between transport and parallel flows. As the size of transport events increases, parallel flows also increase. These results show that turbulent transport can drive parallel flows in the plasma boundary of fusion plasmas. This new type of measurement is an important element to unravel the overall picture connecting radial transport and flows in fusion plasmas.

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The mechanisms underlying the generation of plasma flows play a crucial role to understand transport in magnetically confined plasmas [1]. In the scrape-off layer (SOL) region flows along the field line is a key element to understand impurity transport and plasma recycling [2]. Furthermore, plasma flows are an important ingredient to access improved confinement regimes, both in edge and core plasma transport barriers [1]. Simulations of plasma flows have been previously investigated, including the effects of diamagnetic, $E \times B$ and $B \times \mathrm{grad}B$ drifts [3–5]. Pfirsch-Schlüter flows have been proposed to explain parallel flow reversal measured in the JT-60U tokamak [6]. In general, calculated SOL flow profiles can qualitatively reproduce the radial shape of the experimentally measured radial profile of parallel flows. However, the amplitude of measured parallel flow [7] is significantly larger than those resulting from simulations [3]. These findings might suggest that there is a missing ingredient in previous simulations to explain the generation of parallel flows in the plasma boundary region.

The importance of plasma broadband turbulence in the plasma boundary region in magnetically confined plasmas is well known since decades ago [8]. Fluctuations are usually dominated by frequencies below 500 kHz, with large fluctuation levels in density and potential. As a consequence, turbulent radial transport can account, in some cases, for an important part of the particle flux in the plasma boundary region. However, it should be noted that in some cases fluctuation fluxes appear too high to be consistent with global particle balance. At present, this disagreement still remains as an open question [9].

Turbulence can also modify transport affecting the radial structure of poloidal flows [1,8]. This mechanism can explain the property of sheared poloidal flows, and fluctuations organize themselves near marginal stability reported in the edge of tokamaks and stellarator devices [10].

Recently a new approach to study the relation between gradients and transport, based on the investigation of the dynamical coupling between turbulent transport and gradients, has been proposed [10,11]. This approach had emphasized the importance of the statistical description of turbulent transport in terms of probability density functions (PDFs).

This Letter reports experimental evidence of parallel flows dynamically coupled to radial turbulent transport, showing that turbulence can drive parallel flows in the plasma boundary region of magnetically confined plasmas.

Plasma profiles and turbulence have been investigated in the Joint European Torus (JET) boundary region using a fast reciprocating Langmuir probe system located on the top of the device. The experimental setup consists of arrays of Langmuir probes allowing the simultaneous investigation of the radial structure of fluctuations and parallel Mach numbers. Plasma fluctuations are investigated using 500 kHz digitizers. Plasmas studied in this Letter were produced in X-point plasma configuration, Ohmic plasmas with toroidal magnetic fields $B = 2$ T and plasma current $Ip = 2$ MA.

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. The poloidal electric field has been estimated from floating potential signals measured by poloidally separated probes, $E_\theta = \Delta\tilde{\Phi}_f/\Delta\theta$. The Mach number has been computed as $M = 0.4\ln(I^{ct}/I^{co})$ where I^{co} and I^{ct} represent the ion saturation current measured at each side of the Mach probe (i.e., *co* and counter direction magnetic field) [7].

In order to study the coupling between probability distribution functions of transport and parallel flows, we have computed the joint probability P_{ij} of the two variables X (e.g., turbulent transport) and Y (e.g., parallel

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flows). The probability that at a given instant X and Y occur simultaneously is given by $P_{ij} = P(X_i, Y_j) = N_{ij}/N$ where N_{ij} is 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 dimensions of X and Y time series, respectively, where the indices stand for ith (or jth) bin average value. The expected value of X at a given value of Y_j is defined as $E[X|Y_j] = \sum_i P_{ij} X_i / \sum_i P_{ij}$ and represents the average value of the probability distribution of X at a given value of Y.

Figure 1 shows the time evolution of $E \times B$ turbulent transport and parallel flows in the JET scrape-off-layer region. From the raw data it can be seen that PDFs for parallel flows and transport are quite different. Whereas PDFs for transport show clear non-Gaussian features with a large and sporadic burst, PDFs of parallel flows look, at first sight, rather Gaussian.

Figure 2 shows the expected value of the parallel Mach number for a given turbulent transport in the SOL region ($r - r_{\rm LCFS} = 0.5$–2 cm). In the present experiments parallel Mach numbers are close to 0.3, but values up to 0.5 are not untypical [7]. The results show that turbulent transport and parallel flows are dynamically coupled. The expected value of parallel flows significantly increases as the size of $E \times B$ turbulent transport events increases.

The interplay between the statistical properties of turbulent transport and parallel flows has also been investigated at different time scales. In order to do this, we have constructed time records with a time resolution $\Delta N \times$ sampling time, by averaging over blocks of ΔN elements from the original time series. The original time series has about 80 ms (i.e., about 40 000 points). Figure 3 shows PDF of turbulent fluxes after averaging the original time series ΔN in the range 2–80 μs. The shape of PDFs of transport are significantly modified as the averaging parameter (ΔN) increases: negative transport events are reduced and the shape of the tail of the distribution changes. As the time scale increases (i.e., ΔN increases), the dynamical coupling between transport and parallel flows also changes. In particular, for measurements at $r - r_{\rm LCFS} \approx 0.5$ cm the expected value of parallel flows shows a stronger increasing with the size $E \times B$ turbulent transport at longer time scales. This result suggests that low frequencies have a dominant effect on the link between parallel flows and turbulent transport in the proximity of the last closed flux surface (LCFS). Longer time records would be needed to quantify the importance of different time scales in the coupling between transport and parallel flows.

Furthermore, the dynamical coupling between transport and flows shows differences at different plasma radii (Fig. 3): one has a cusp at zero flux ($r - r_{\rm LCFS} \approx 2$ cm); the other has a broad parabolic minimum ($r - r_{\rm LCFS} \approx 0.5$ cm). This result reflects that the coupling between transport and flows depends on the proximity to the naturally occurring velocity shear layer observed near the LCFS in JET [10].

The simultaneous measurements of fluctuations in parallel flows and turbulent particle transport allow one to identify, not only significant differences in their PDFs (with the turbulent transport PDFs much more bursty than parallel flow PDFs as shown in Fig. 1), but also significant *skewness* (i.e., asymmetries) in the transport-parallel flow joint probability functions (Fig. 3).

The fact that the parallel Mach number increases with the size of turbulent transport is an important element to clarify the overall picture connecting radial transport and flows. As shown by the present experimental results, as the amplitude of transport events increases (e.g., in the presence of turbulent blobs) it is possible to correlate experimentally turbulent cross-field transport and parallel flows. However, in the case of fine scale cross-field transport (e.g., small amplitude transport events) it might be more difficult to detect a link between them.

In this context it must be noted that the observed connection between turbulent transport and parallel flows

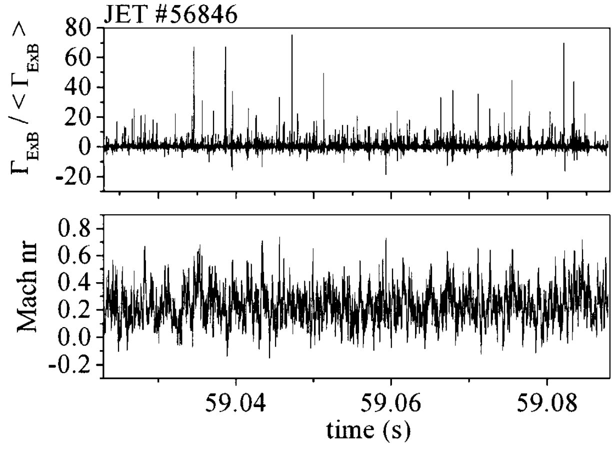

FIG. 1. Time evolution of $E \times B$ turbulent transport and parallel flows in the JET scrape-off-layer region ($r - r_{\rm LCFS} \approx 2$ cm, midplane).

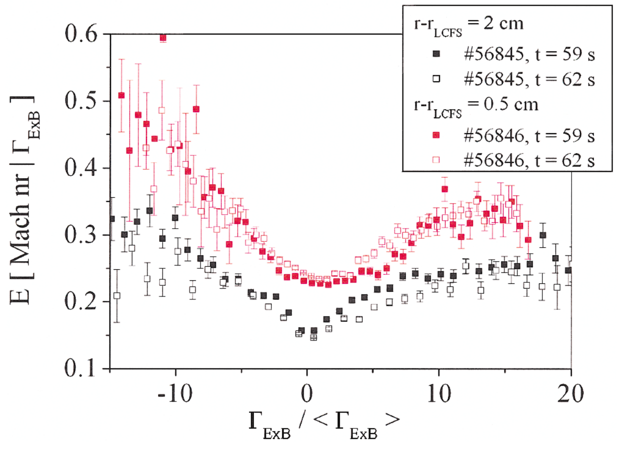

FIG. 2 (color). Expected number of the parallel Mach number versus local turbulent transport ($r - r_{\rm LCFS} \approx 0.5$–$2$ cm, midplane).

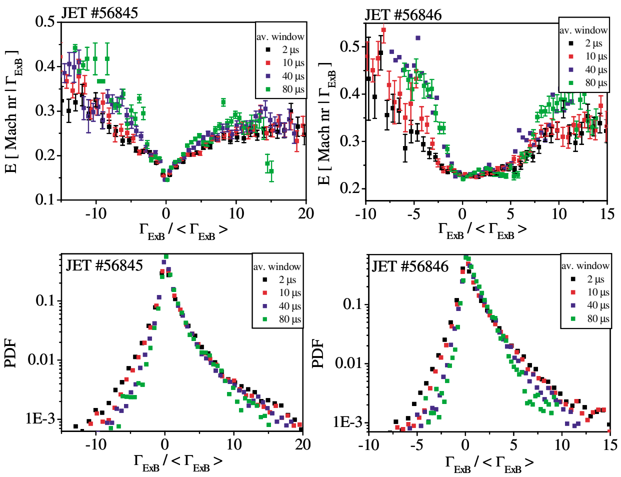

FIG. 3 (color). PDFs of parallel Mach numbers versus turbulent transport computed at different time scales (2–80 μs). Measurements were taken at $r - r_{\mathrm{LCFS}} \approx 0.5$ cm (shot 56846) and $r - r_{\mathrm{LCFS}} \approx 2$ cm (shot 56845).

does not necessarily imply a causal and direct link between them. Actually, parallel flows can be directly coupled to transport via Reynolds stresses, which provide a (nonlocal) energy transfer between high and low wave numbers [12,13]. In the framework of this interpretation the observed radial variation in the dynamical coupling between flows and radial transport could be related with the role of Reynolds stress in rearranging the momentum profile, which allows sheared flows and fluctuations to organize themselves near marginal stability as reported in the edge of JET tokamak [10]. It remains as a challenge for experimentalists to compare the burstiness in the turbulent particle flux and in Reynolds stresses to quantify the importance of this mechanism [14,15] and to clarify the role of turbulent momentum transport as a mechanism providing a link between turbulent transport and flows. Finally, it should be noted that parallel flows might be subject to parallel flow instability [16] which can lead to more transport and therefore providing an additional mechanism to couple transport and parallel flows.

On the basis of the present results, we have to conclude that the bursty and strongly non-Gaussian behavior of turbulent transport is strongly coupled with fluctuations in parallel flows. This dynamical coupling reflects that parallel flows are, at least partially, driven by turbulence mechanisms. Then, turbulent transport is an important ingredient to explain the generation of parallel flows in the plasma boundary region in fusion plasmas [7]. This observation is consistent with a recent model which has pointed out the possible role of turbulence on toroidal momentum transport [17] to explain the onset of spontaneous rotation in tokamak plasmas [18]. Present measurements show the importance of multifield power density function measurements to unravel the overall picture connecting radial transport and flows in fusion plasmas.

Considering that significant plasma turbulence has been observed both in the edge and core plasma regions, the present results might have a strong impact in our understanding of parallel momentum transport in fusion plasmas. Particularly interesting will be the investigation of the link between magnetic topology (i.e., rational surfaces) and parallel flows driven by turbulence. Because fluctuations are expected to show maximum amplitude at the rational surface, a significant radial variation in the magnitude of parallel flows would be expected on the basis of the results reported in this Letter. This mechanism can provide sheared parallel flows linked to the location of rational surfaces which could be an ingredient to explain the spontaneous formation of transport barriers near rational surfaces in fusion plasmas [19].

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