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ABSTRACT.

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 are a key element to understand impurity transport and plasma recycling [2]. Furthermore, plasma flows are an important ingredient to access to 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×B and B × grad B drifts [3]. Pfirsch-Schlüter flows have been proposed to explain parallel flow reversal measured in the JT-60U tokamak [4]. 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 [5] are 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.

This paper 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.

1. EXPERIMENTAL SET-UP

The dynamical coupling between turbulent transport and parallel flows has been investigated, using an experimental set-up which allows to measure simultaneously both the electrostatic turbulent transport and the parallel Mach number.

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. 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) [5].

Plasma turbulence and parallel flows have been characterized in terms of Probability Density Functions (PDFs). Plasmas studied in this paper were produced in X-point plasma configurations ohmic plasmas with toroidal magnetic fields B = (1.5 − 2) T, I_p = 2MA. Figure 1 shows the time evolution of E×B turbulent transport and parallel flows.

2. EXPERIMENTAL RESULTS

Radial profiles of the poloidal velocity of fluctuations and parallel flows have been investigated in the plasma boundary region of the JET tokamak. A change in both perpendicular and parallel velocities have been found in the proximity of the Last Closed Flux Surface (LCFS). It should be noted that our knowledge of the LCFS position usually relies on code calculations and is usually uncetain by at least ±1cm. The shear in the poloidal flow is close to the inverse time of the correlation of fluctuations ($dv_\theta/dr \approx 1/\tau$) and the shear in the parallel flow is close to $d\, v_{parallel} / dr \approx c_s / L_n$, where c_s and L_n are the sound speed and the density scale length (Fig.2), suggesting a proximity to the threshold of Kelvin-Helmhotz instabilities [6]. Evidence of sheared parallel flow linked to poloidal shear flow has been previously reported in the proximity of the LCFS in tokamak and stellarator plasmas [7-10].

The interplay between the statistical properties of turbulent transport and parallel flows has been investigated at different time scales. 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. Figure 3 shows PDF of turbulent fluxes after averaging the original time series ΔN in the range 2-80μs. 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×B turbulent transport events increases.

The shape of PDFs of transport are significantly modified as the averaging parameter (N) increases: negative transport events are reduced and the shape of the tail of the distribution changes. As time scale increases (i.e. ΔN increases) the dynamical coupling between transport and parallel flows also changes. In particular, for measurements at $r - r_{LCFS} \approx 0.5$cm the expected value of parallel flows shows a stronger increasing with the size E×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 LCFS. Furthermore, the dynamical coupling between transport and flows shows differences at different plasma radius (Fig.3): one has a cusp at zero flux ($r-r_{LCFS} \approx 2$cm); the other has a broad parabolic minimum ($r-r_{LCFS} \approx 0.5$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 [11]. The simultaneous measurements of fluctuations in parallel flows and turbulent particle transport allow to identify, not only significant different differences in their PDFs (being the turbulent transport PDFs much bursty than parallel flows PDFs as shown in figure1), 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 does not necessarily imply a causal and direct link between them. Actually, parallel flows can be directly coupled to transport via Reynolds stresses [12, 13]. Finally, it should be noted that parallel flows might be subject to parallel flow instability [5] which can lead to more transport and therefore providing an additional mechanism to couple transport and parallel flows. Recently the radial structure of parallel flows and turbulence has been investigated in reversed B field configurations. A comparative study of the scaling properties of turbulence and flows in standard and reversed-B field configurations is in progress.

CONCLUSIONS

On the basis of the present results, we conclude that the bursty and strongly non-gaussian behaviour 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. 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. In particular, these findings suggest that turbulent mechanism is an ingredient to explain the generation of parallel flows in the plasma boundary region and the onset of spontaneous rotation in tokamak plasmas [14, 15]. Present measurements show the power and importance of multi-field power density function measurements to unravel the overall picture connecting radial transport and flows in fusion plasmas.

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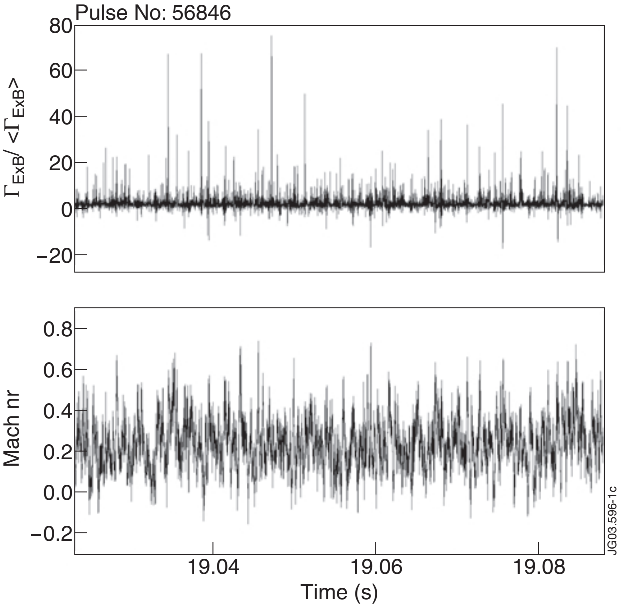

Figure 1: Time evolution of E×B transport and parallel flows.

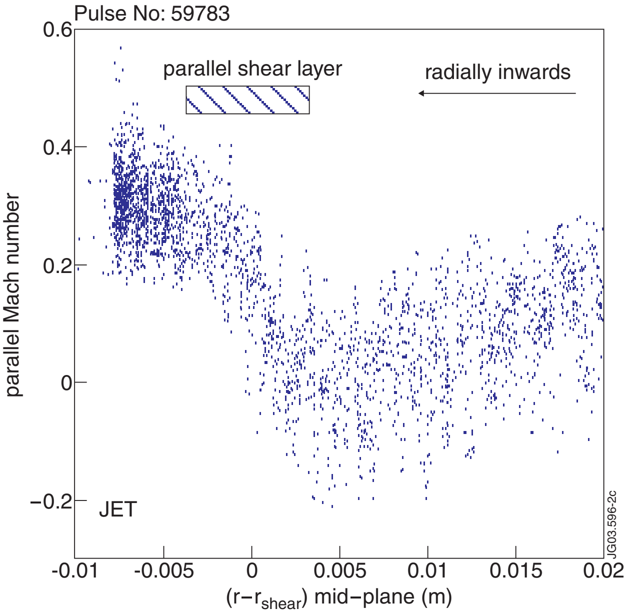

Figure 2: Radial profile of parallel Mach number in the proximity of the LCFS.

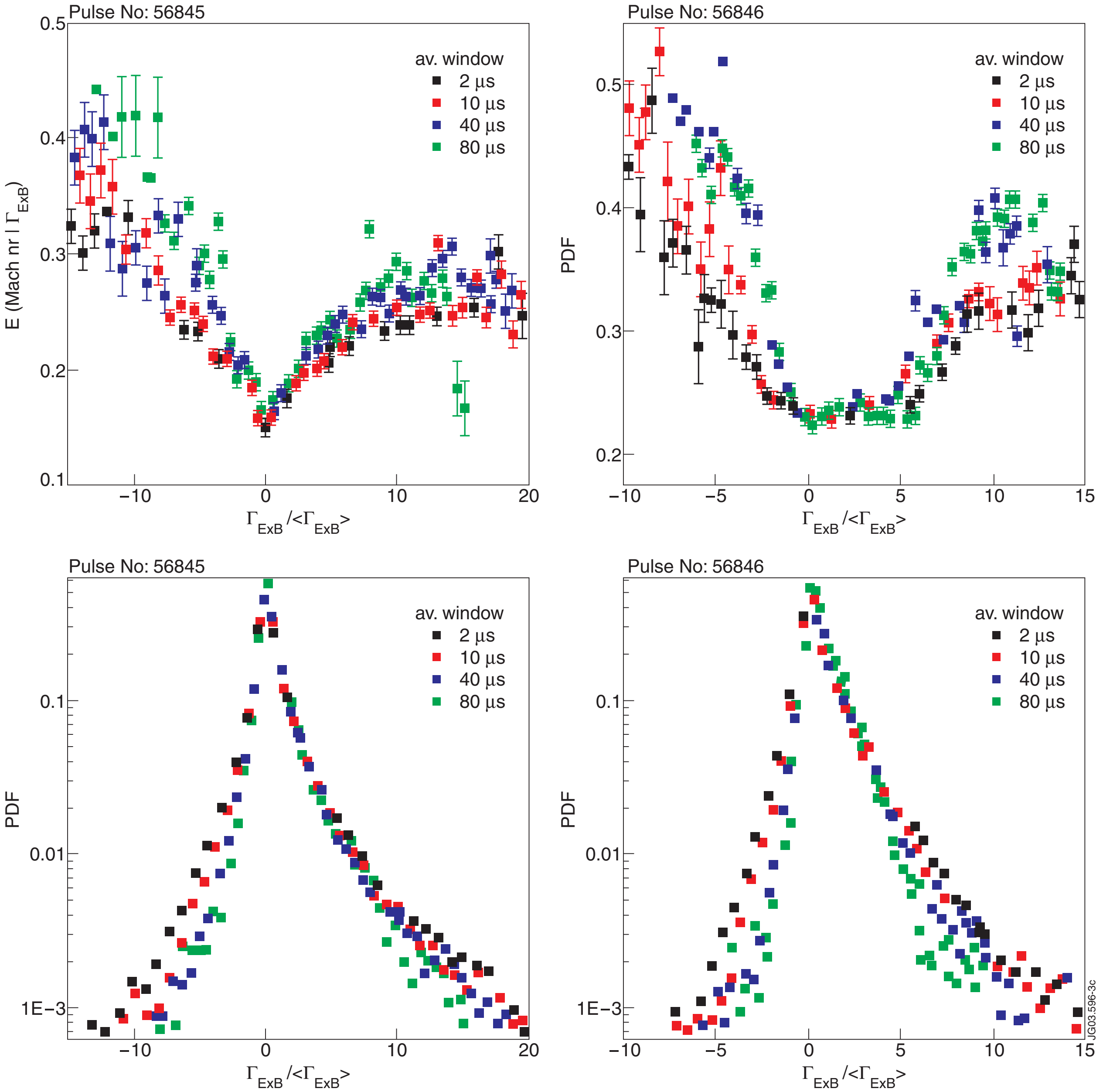

Figure 3: PDFs of parallel Mach numbers versus turbulent transport computed at different time scales (2–80µs). Measurements were taken at $r - r_{LCFS} \approx 0.5$cm (Pulse No: 56846) and $r - r_{LCFS} \approx 2$cm (Pulse No: 56845)