# Experimental evidence of turbulent transport near marginal stability in the plasma boundary region in the TJ-II stellarator

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## I. Introduction

Several distinct mechanisms have been invoked to explain the connection between turbulent fluxes and gradients that provide a free energy source to drive instabilities in magnetically confined plasmas. Non-linear relations between heat fluxes and gradients, in which heat fluxes increases non-linearly as gradient becomes steeper, can explain the confinement degradation with the heating power reported in magnetically confined fusion plasmas [1]. Instabilities governed by a threshold may lead to a self-organized critical (SOC) system by producing transport events at all scales, called avalanches [2, 3]. In the context of these models, the functional dependence between heat and particle transport is expected to show sharp jumps as the system crosses instability thresholds [4]. The transition to improved regimes implies non-monotonic relations (bifurcations) between gradients and transport [5]. This paper reports experimental evidence of strong dynamical coupling between density gradients and turbulent transport in the boundary region of the TJ-II stellarator.

## II. Experimental set-up and analysis tools

The TJ-II stellarator ($R = 1.5$ m, $a \leq 0.22$ m, $B \leq 1.2$ T) has a high degree of magnetic configuration flexibility. In particular, the magnetic well can be changed from -1 to 6%. Being the magnetic well the main stabilising term in heliacs [6, 7], this property makes TJ-II an ideal device to study the onset of fluctuations and related phenomena close to instability thresholds [8]. In TJ-II stellarator, the absence of magnetic well gives rise to instabilities at any plasma pressure. 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. Experiments were carried out in ECRH plasmas ($P_{ECRH}$ = 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 digitisers.

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 as $\Gamma_{ExB}(t) = \tilde{n}(t)\tilde{E}_q(t)/B$ at the inner probe position. The poloidal electric field has been estimated from floating potential signals measured by poloidally separated probes, $\tilde{E}_\theta = \Delta\tilde{\Phi}_f / \Delta_\theta$ with $\Delta\theta \approx 0.3$ cm and $< \tilde{E}_\theta >= 0$. Fluctuations in the radial component of ion saturation current gradient have been computed as $\nabla \tilde{I}_s(t) = [\tilde{I}_s^{inner}(t) - \tilde{I}_s^{outer}(t)]$ 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 0.8 cm.

The joint probability $P_{ij}$ of the two variables X and Y 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. $\Delta X$ and $\Delta Y$ 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 $E[X \mid Y_j] = \sum_i P_{ij} X_i \Big/ \sum_i P_{ij}$ .

## III. Experimental results and discussion

Figure 1 shows the probability density function (PDF) for fluctuations in gradients and the expected value of the ExB flux for a given density gradient ($E[\Gamma_{ExB} \mid \nabla_r I_S]$) in TJ-II plasmas in a magnetic well scan experiment. The density gradient PDF is rather gaussian around its average gradient. On the contrary, the PDF of turbulent transport is strongly non-gaussian with large and sporadic transport burst (fig. 2). The results show that most of the time the plasma is at its average gradient and the size of transport events has minimum amplitude. Large amplitude transport events ($\Gamma_{ExB} \approx$ 5- 20 $\times 10^{19}$ $m^2 s^1$) take place when the

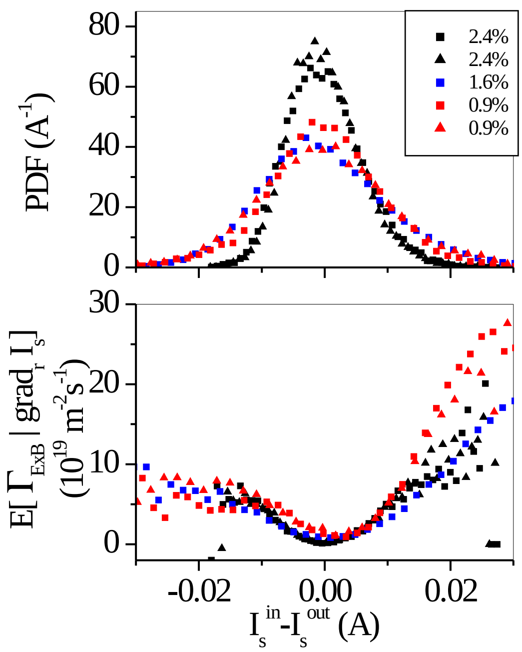


Fig. 1: a) The Probability Density Function of gradient with different magnetic well; b) Expected turbulent flux at a given density gradient. The most probable value of density gradient minimizes flux events amplitude.

plasma displaces from the average gradient. The expected value of ExB turbulent transport events increases strongly as the gradient increases above its most probable value (i.e. $\nabla_r \tilde{I}_S > 0$).

The present experimental results show that the bursty and strongly non-gaussian behavior of turbulent transport is strongly coupled with fluctuations in gradients. As the density gradient increases above the most probable gradient the ExB turbulent driven transport increases and the system performs a relaxation that tends to drive the plasma back to the marginal stable situation minimizing 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, it is important to emphasize that the non-monotonic dynamical relation between ExB transport and gradients may also be partially due to the direct link between gamma and gradients through density fluctuations. In this case, the experimental result might be also consistent with the properties of drift-Alfvén wave turbulence that do not necessarily exhibit a threshold [9].

The effective radial velocity of fluctuations computed as $v_r^{eff} =< \tilde{I}_s \tilde{E}_\theta > / < \tilde{I}_s > B$ is close to 20 m/s for small transport events (i.e. small deviations

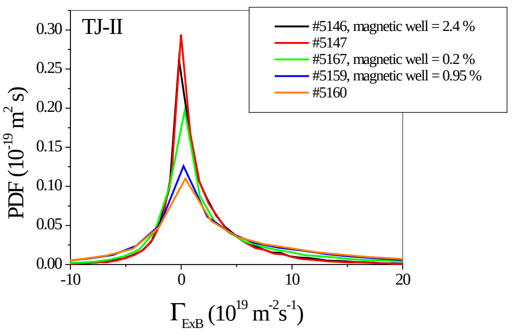


Fig. 2: PDFs of edge turbulent transport in plasma configurations having different magnetic well in the TJ-II stellarator

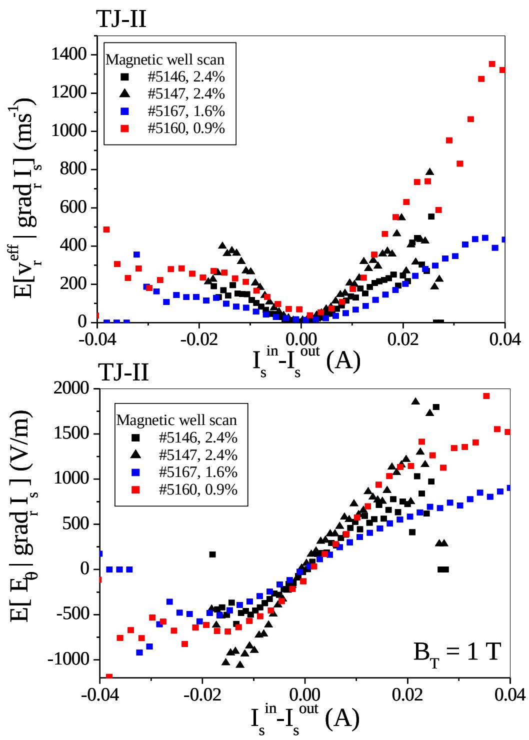


Fig. 3: Effect of the well on: (a) the expected value of the radial effective velocity for a given radial density gradient. For large displacements respect to the average gradient the pulses exhibits effective velocities around 1000m/s. The effective velocity increases with the degree of instability introduced on the plasma through the magnetic well variation; (b) the expected poloidal electric field for a given radial density gradient.

from the most probable gradient). On the contrary, the effective radial velocity increases up to 1000 m/s for large transport events (i.e. large deviations from the most probable gradient) (fig. 3a). This radial velocity is consistent with the ExB drift velocity (Fig. 3b). Similar results have been recently found in the plasma boundary of the JET tokamak [10].

## IV. Conclusions

The investigation of the dynamical interplay between fluctuations in density gradients and turbulent transport has shown that these parameters are strongly coupled from the dynamical point of view. The bursty behavior of turbulent transport is linked with a departure from the most probable radial gradient suggesting the existence of different transport mechanisms for small and large transport events. It would be very interesting to clarify whether this dynamical interplay of edge turbulent fluxes with density gradients is also 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 ExB turbulent transport. These results indicate that statistical properties of turbulent transport might be also computed in the plasma core from measurement of density fluctuations with microwave reflectrometry or beam emission spectroscopy [10].

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