Coupling between long-range toroidal correlations and radial transport in the TJ-II boundary plasma

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1. Introduction

Several experimental observations demonstrating the existence of zonal flows (both the near zero low frequency zonal flow and the oscillatory flows termed geodesic acoustic mode) have been obtained in the last decade presenting characteristics consistent with the theoretical predictions [1-2]. The underlying physics of zonal flows involves a disparate interaction between different scales (large scale coherent flows and local turbulence). Experimental evidence of energy transfer between ZFs and turbulence has been found in different devices ([2] and references therein). Evidence for the effect of zonal flows on plasma confinement is however much more limited. The direct experimental verification of the key role of ZFs in the regulation of transport in fusion plasmas still remains as an open issue. Recent experiments in the TJ-II stellarator have identified the presence of long-distance correlations in plasma potential fluctuations [3] with a zonal-flow like structure.

2. Experimental set-up

Experiments were carried out in the TJ-II stellarator in Electron Cyclotron Resonance Heated (ECRH) plasmas ($P_{ECRH} \leq 400$ kW, $B_T = 1$ T, $\langle R \rangle = 1.5$ m, $\langle a \rangle \leq 0.22$ m, $\iota(a)/2\pi \approx 1.5 - 1.9$) and in pure Neutral Beam Injection (NBI) heated plasmas (P_{NBI} port through $\approx$ 450 kW). Different plasma parameters were simultaneously measured at two different toroidal locations using two multi-Langmuir probes. The results reported here were made possible by the use of a rake probe (figure 1) installed on a fast reciprocating drive at the top of the plasma. The rake probe consists of twelve Langmuir probes (R1 to R12) radially separated 3 mm together with three poloidally separated tips at the rake probe front that allow the determination of the cross-field fluctuations induced particle flux, $\Gamma_{E\times B} = \langle \tilde{n}\tilde{E}_\theta \rangle / B$, being $\tilde{n}$ and $\tilde{E}_\theta$ the density and poloidal electric field fluctuations, respectively. A second probe (Probe 2), with three poloidally separated tips, is located at a different position of the torus, separated about $\Delta\phi \approx$ 160º toroidally and $\Delta\theta \approx$ 155º poloidally from the rake probe. This experimental set-up permits the simultaneous investigation of the radial structure of fluctuations and long-range fluctuation scales in the plasma boundary region of the TJ-II stellarator ($\rho = r/a > 0.8$).

3. Experimental results

A series of NBI heated discharges has been performed with the Probe 2 fixed at $\rho = r/a \approx 0.87$ and the rake probe moved on a shot-to-shot basis from the scrape-off layer (SOL) to the edge plasma. Figure 2 shows the radial profile of floating potential using rake probe signals from the discharges indicated together with the radial profiles of the maximum cross-correlation between floating potential signals separated radially and toroidally. The radial correlation has been computed using pairs of V_f signals radially separated by 6 mm for the different shots of the series. Rake probe measurements allow identifying a decrease in the radial correlation of fluctuations in the region where the radial gradient in floating potential reverses sign (shear layer).

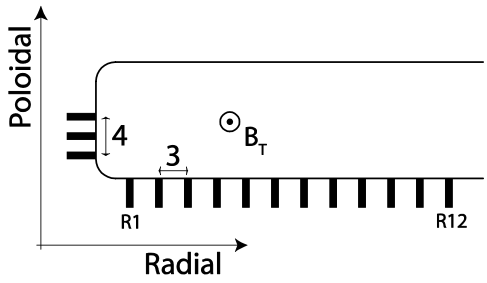

Figure 1: Schematic view of the rake probe.

The long-range correlation was estimated between a V_f signal from Probe 2 and the signals measured simultaneously at different radial positions by the rake probe. For $\rho < 0.93$, a high long-range cross-correlation (up to 0.7) is found between floating potential signals measured by the two probe systems that are toroidally and poloidally separated. As no significant phase shift was observed, results suggest that the potential has a symmetric structure (m = n = 0) compatible with zonal flows. The long-range cross-correlation is highest when the two probes are approximately at the same radial location showing a radial scale in the order of 1 cm.

The long-range correlation was also estimated between two V_f signals measured approximately at the same radial location by both probe systems toroidally separated (full symbols). In this case, the long-range correlation provides direct information on the amplitude of the ZF-like fluctuations radial profile. Similar profiles are observed in both cases (full and open symbols), being however, a narrower

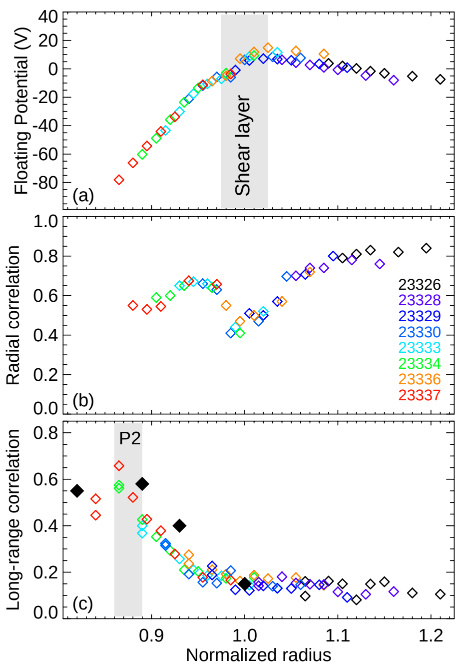

Figure 2: Radial profiles of floating potential (a) and maximum radial (b) and long-range (c) correlation. Open symbols correspond to discharges with the Probe 2 fixed at $\rho \approx 0.87$ and the rake probe moved on a shot-to-shot basis. Full symbols correspond to the long-range correlation estimated between signals measured at the same radial location by both probe systems.

profile obtained when using pins at different radial locations (open symbols) since, in this latter case, measurements also reflect the radial correlation of the fluctuations.

The radial coherence spectrum between floating potential signals measured by the rake probe at different distances (Δr = 3, 6 and 9 mm) in the edge plasma (ρ ≈ 0.89) and in the SOL (ρ ≈ 1.05) have been compared and results are illustrated in figure 3. The radial correlation length (*e*-folding length) at different frequencies can be roughly estimated from the data presented in figure 3. In the SOL, the radial coherence is dominated by low frequencies (f < 40 kHz) that have a long radial correlation length (> 1 cm), while the high frequencies have a much shorter correlation length (< 6 mm). In the edge plasma, both the magnitude of the radial coherence and the radial correlation length show a weaker frequency dependence. When moving from the SOL to the edge plasma, the radial coherence is observed to decrease at low frequencies (< 20 kHz), particularly for Δr = 6 and 9 mm, increasing slightly above that frequency. From the data presented in figure 3 we conclude that the correlation length of the large scale fluctuations is similar to that of the ambient turbulence.

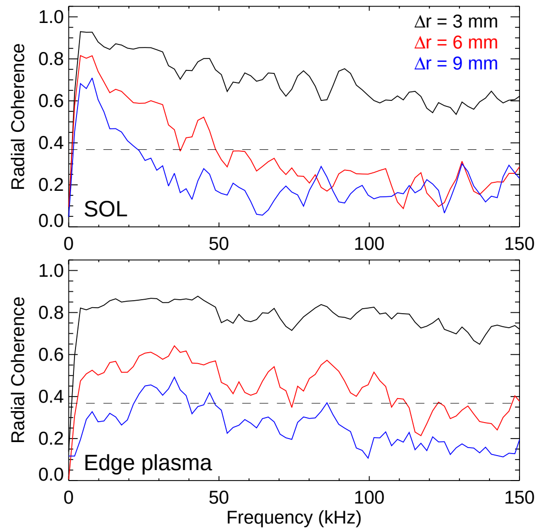

Figure 3: Radial coherence spectrum between potential signals separated by 3, 6 and 9 mm in the edge plasma (ρ ≈ 0.89) and in the SOL (ρ ≈ 1.05).

On TJ-II the cross-field turbulent particle transport has been estimated using the rake probe data. To better understand the effect of ZFs on transport, the frequency resolved coherence, cross-phase between I_{sat} and V_f fluctuations and turbulent particle flux measured at two radial location, edge plasma (ρ ≈ 0.89) and SOL (ρ ≈ 1.05), have been compared (see figure 4). Note that $\Gamma_{E\times B}(w) \propto k_\theta(w) \times \gamma_{n,V}(w) \times \sin[\alpha_{n,V}(w)]$, where k_θ is the poloidal wavenumber, $\gamma_{n,V}$ the coherence between density and potential fluctuations and $\alpha_{n,V}$ the phase between them. As shown in figure 4 the coherence between I_{sat} and V_f fluctuations at ρ ≈ 0.89 is smaller than that in the SOL for low frequencies (< 30 kHz). Furthermore, in the edge plasma both the phase between I_{sat} and V_f fluctuations and the poloidal wavenumber are close to zero for frequencies below 30 kHz, implying that the cross-field turbulent transport is modest in the frequencies range where ZFs dominate. On the contrary, transport in the SOL is dominated by frequencies below 50 kHz as the coherence between I_{sat} and V_f fluctuations is higher and their phase difference around $\pi/2$ in this frequency range. This high transport at low frequencies is consistent with the large correlation length of the fluctuations observed in the SOL for f < 40 kHz (figure 3). Results suggest therefore that ZFs may influence the local turbulent particle transport. Furthermore, the turbulent transport at low frequencies is cancelled as large scale potential fluctuations have symmetric characteristics.

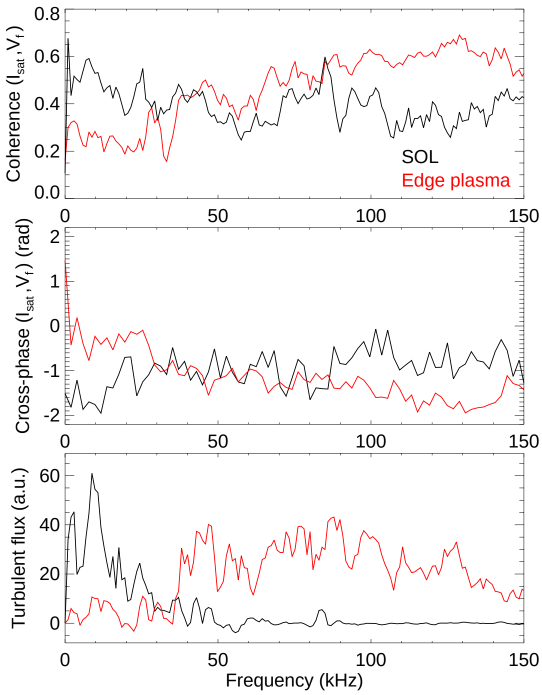

Figure 4: Frequency spectra of the coherence, phase between I_{sat} and V_f fluctuations and turbulent particle flux in the edge plasma and in the SOL.

The fact that, in the plasma edge, low frequency fluctuations do not contribute to the turbulent particle transport has been observed previously in different devices (e.g. TEXT [4], ATF [5] and JET [6]). These results are remarkably similar to the ones described in present paper and suggest a possible universal behaviour, in which turbulent transport is strongly reduced at low frequencies showing long-range toroidal correlation.

4. Summary

The fluctuations in the TJ-II boundary plasma have been investigated using two probe systems that allow the simultaneous measurement of the long-distance correlation in the toroidal direction as well as the radial structure of the fluctuations with high temporal resolution. ZF-like fluctuations have been identified in the TJ-II edge plasma and their properties investigated. Experimental evidence is presented that both the radial correlation and the turbulent particle transport are reduced in the region dominated by zonal flows. Furthermore, it was shown that the measured ZF-like fluctuations have a short radial correlation length comparable to that of the ambient turbulence.

References

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