Edge Sheared Flows as a Source of Propagating Plasma Potential Events

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Abstract. The radial structure of plasma fluctuations has been investigated in the plasma boundary region of the TJ-II stellarator. Potential transport events are observed to be born in the proximity of the edge velocity shear layer in the TJ-II stellarator. They propagate radially predominantly outwards in the scrape-off layer (SOL) side of the shear layer, whereas in the edge region side the radial propagation is predominantly radially inwards with an effective radial propagation is the order of 1 - 10 km/s. These findings suggest the development of a momentum source linked to the edge velocity shear layer. The main focus of this paper is the discovery of the role of edge-sheared flows as a source of propagating inwards and outwards plasma potential. These findings suggest the development of a momentum source linked to the edge velocity shear layer. Experimental findings also show that radial transport and radial correlations are reduced in the region dominated by the presence of long-range toroidally correlated structures (zonal flows).

1. Introduction

Plasma flows play a crucial role in transport (e.g. transport barriers) and stability in magnetically confined plasmas [1]. Edge transport barriers are a key tool for enhancing the plasma confinement properties in magnetic fusion devices. Both tokamaks and stellarators develop edge bifurcations, the so-called Low to High (L-H) confinement transition, basically with similar properties showing the ubiquitous character of the L-H transition in fusion plasmas. At present there is substantial evidence for the decorrelation of the turbulence by E_r x B sheared flow (i.e. radial gradients in radial electric fields) during the development of the transport bifurcation. The force balance relation shows that the equilibrium radial electric field depends on the ion pressure gradient (∇P_i), flow velocity ($U_{i\phi}, U_{i\theta}$) and the magnetic field (B_ϕ, B_ϕ) in the toroidal and poloidal direction. Thus, the pressure gradient as well as the poloidal and toroidal flows play a crucial role in the development of radial electric fields and in the control of turbulence transport via sheared flows [1]. However, the underlying physics mechanisms driving the ExB sheared flow development still remain as a key open issue confronting the fusion community.

Experiments in the Alcator C-Mod tokamak have shown that the toroidal rotation propagates inwards radially from the plasma edge after the transition from low to high confinement regimes (L-H transition) [2] and the resulting core rotation was found to depend strongly on the edge magnetic configuration. Other experiments also show regimes with spontaneous or anomalous poloidal [3, 4] rotation of the plasma core [5]. Nevertheless, there are also experiments [6] that report poloidal rotation measurements in good agreement with neoclassical predictions. Various experiments [7, 8, 9, 10, 11, 12] have shown the detection of long-range correlations consistent with the theory of zonal flows, i.e., stable modes that are driven by turbulence and regulate turbulent transport [13, 14 and references therein].

The main focus of this paper is the discovery of the edge-sheared flows as a source of propagating inwards and outwards plasma potential events in the presence of sheared flows.

2. Experimental set-up and plasma conditions

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, <R> = 1.5 m, <a> ≤ 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 ≈ 450 kW). The results reported here were made possible by the use of two fast reciprocating drives with Langmuir probe arrays, named Probe 1 and Probe 2, located at two different toroidal positions (160° away approximately). Probe 1 is a rake probe made of twelve Langmuir probes radially separated 3 mm together with three poloidally separated tips at the rake probe front that allows the measurement of the floating potential and the ion saturation current, installed on a fast reciprocating drive (Fig. 1). This set-up permits the investigation of the radial structure of fluctuations in the plasma boundary region of the TJ-II stellarator and the local and long-range correlation measurements.

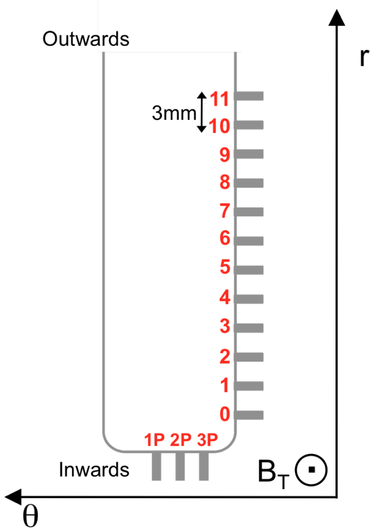

FIG. 1. Schematic view of the rake probe used in TJ-II.

The radial structure of fluctuations has been investigated at different plasma densities. Previous TJ-II experiments have shown that the emergence of the edge shear flow layer takes place [15, 16] at densities above a threshold value (typically in the order of $n_{th} \approx 0.6 \times 10^{19}$ m^{-3}) in ECRH plasmas. More recently, experiments with Li-coating and NBI heating have shown evidence for spontaneous bifurcations (L-H transition) occurring at a threshold value of the plasma density (in the order of 2×10^{19} m^{-3}), leading to an increase of the density gradient and the stored plasma energy with a concomitant reduction in the level of edge fluctuations [17]. Then, using the plasma density as a control knob, sheared flows can be easily driven and damped at the plasma edge of the TJ-II stellarator.

3. Radial plasma profiles and radial propagation of fluctuations in NBI plasmas

The floating potential shows negative radial gradients in the SOL region and positive radial gradients in the edge region, reflecting the reversal of the radial electric field (shear layer) in the proximity of the last closed flux surface (LCSF), in agreement with previous measurements. Rake probe measurements allow identifying a reversal in the effective radial velocity of fluctuations and a decrease in the radial coherence of fluctuations in the region where the radial gradient in floating potential reverses sign (shear layer).

Figure 2 shows edge floating potential and ion saturation current profiles measured below the density threshold ($n \approx 0.5 - 0.6 \times 10^{19}$ m^{-3}) in low-density ECRH plasmas and above that threshold in NBI heated plasmas ($n \approx 2 \times 10^{19}$ m^{-3}). In low density ($n < n_{th}$) ECRH plasma the floating potential is positive whereas in high density ($n > n_{th}$) NBI regime the edge potential becomes negative. At high densities ($n > n_{th}$) the floating potential shows negative radial gradients in the SOL region and positive radial gradients (in the order of 10 - 30 V/cm) in the edge region, reflecting the reversal of the radial electric field (shear layer) in the proximity of the last closed flux surface (LCFS), in agreement with previous measurements [15, 16]. Once the edge shear flow is fully developed, ion saturation current profiles become steeper in the proximity of the shear layer location.

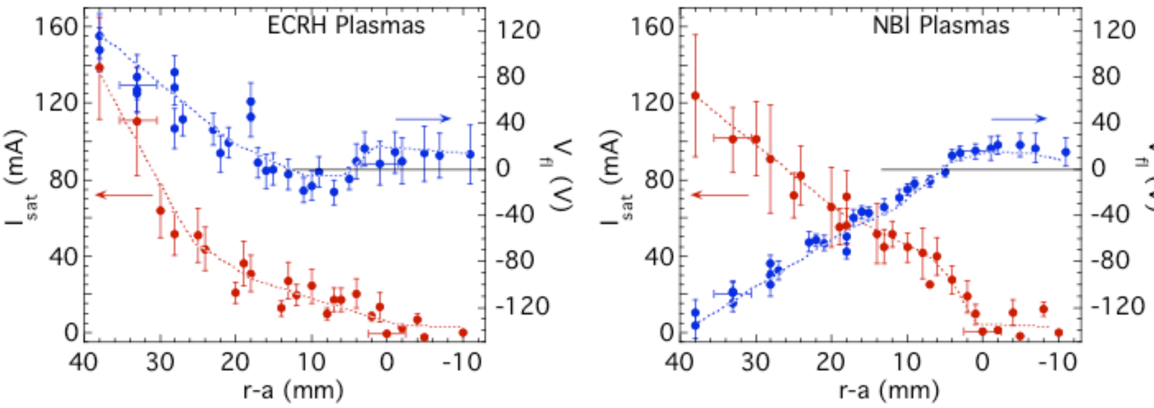

FIG. 2. Profiles of floating potential and ion saturation current in ECRH ($n \approx 0.5$ - 0.6×10^{19} m^{-3}) and NBI ($n \approx 2 \times 10^{19}$ m^{-3}) heated plasmas.

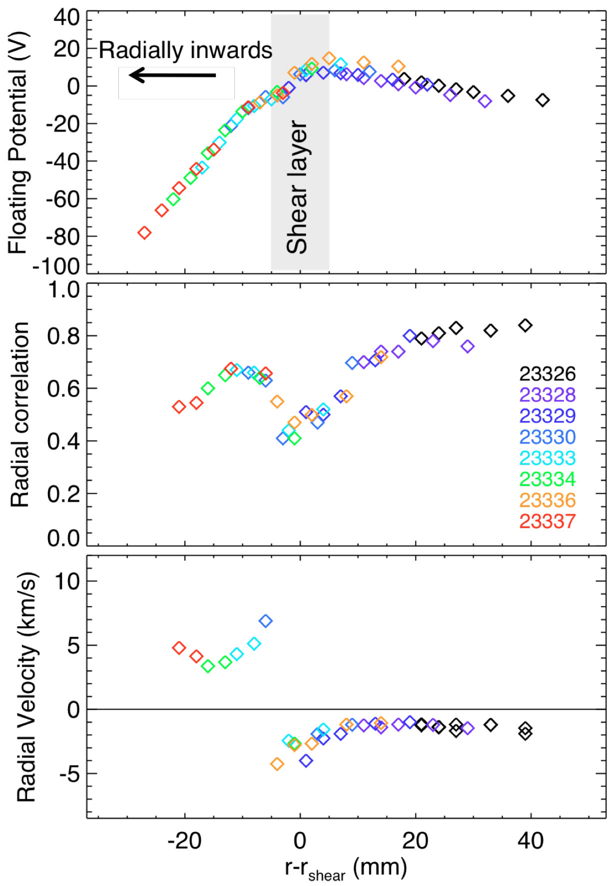

Fig. 3. Profiles of potential, radial coherence and radial effective velocity of fluctuations in NBI plasmas ($n \approx 2 \times 10^{19}$ m^{-3}).

The radial profile of floating potential, maximum radial cross-correlation between two floating potential signals radially separated by 6 mm and the effective radial velocity deduced from the time delay for the maximum cross-correlation in NBI heated plasmas are shown in figure 3. Rake probe measurements allow identifying a reversal in the effective radial velocity of fluctuations and a decrease in the radial coherence of fluctuations in the region where the radial gradient in floating potential reverses sign (shear layer). The radial correlation and velocity have also been calculated using signals radially separated by 12 mm. The radial correlation was found to be obviously smaller in this case being however the shape of the profile very similar in the two cases. Furthermore, the radial effective velocity was found to be very similar in the two cases.

Figure 4 shows the raw data of floating potential signals measured in NBI-heated plasma in which the rake probe is partially located in the edge and SOL regions. Evidence of potential events propagating radially inwards (with effective radial velocity in the order of 1 – 10 km/s) in the plasma edge region is clearly seen in the raw data, in agreement with cross-correlation analysis. The cross-correlation between the innermost pin and the remaining rake probe pins for density plasma values below and above the threshold value is shown in figure 5; it is clear the influence in the radial propagation of fluctuations of the presence of the edge shear flow.

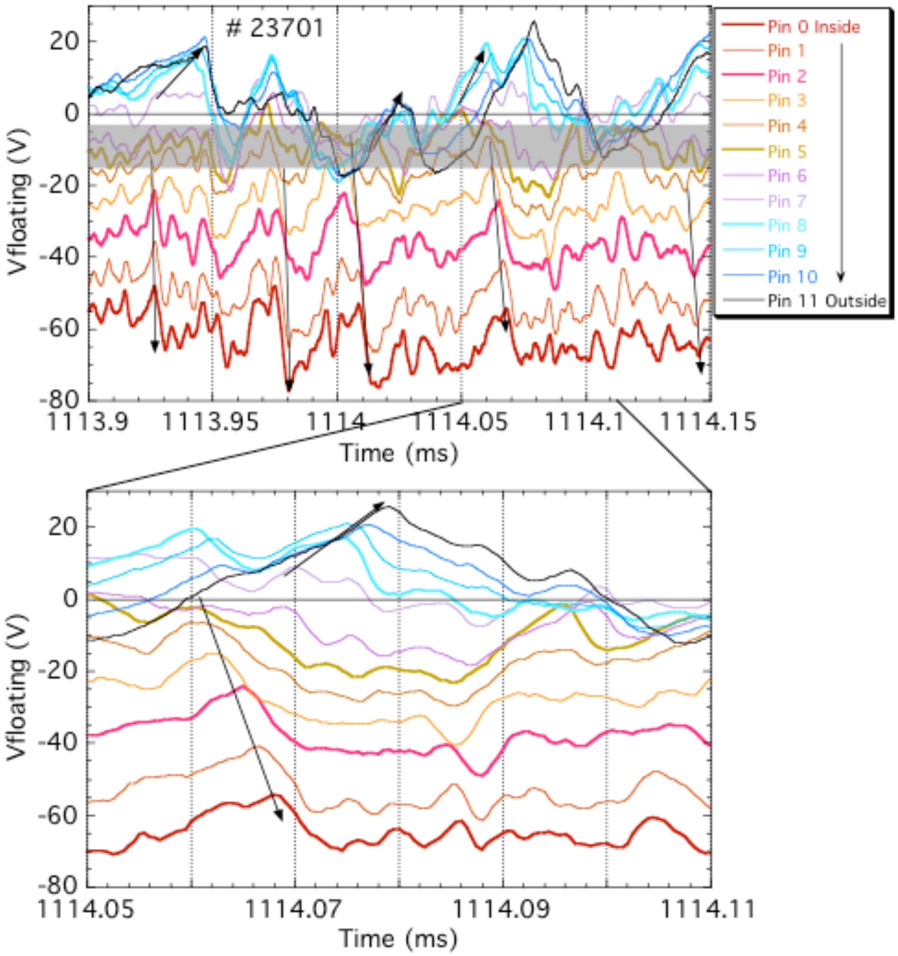

FIG. 4. Raw data of floating potential showing direct experimental evidence of both radial effective velocities propagating inwards/outwards from the shear location (shadowed area).

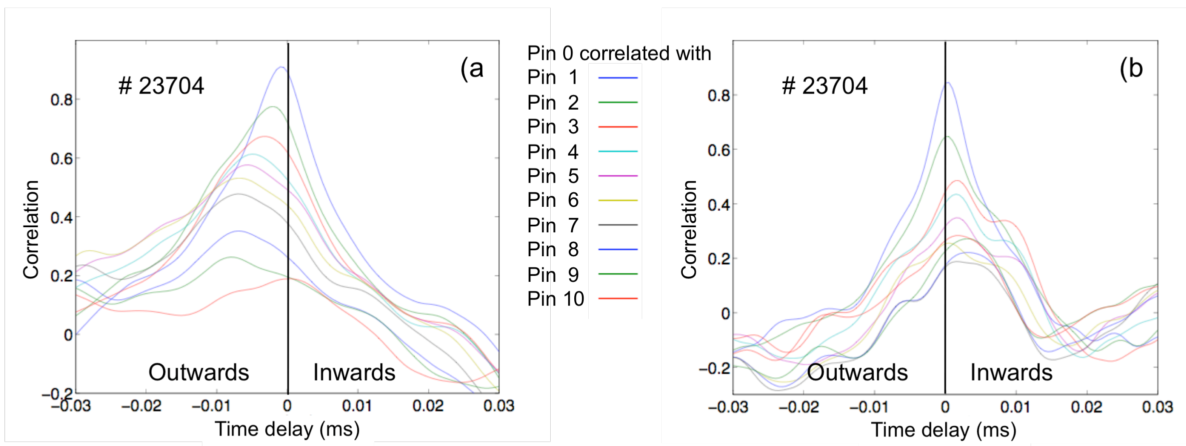

FIG. 5. Cross correlation between the innermost pin (0) and the remaining rake probe pins for densities below (a) and above (b) the threshold value.

4. Role of the edge shear layer on the radial propagation of fluctuations events

The effective radial propagation of potential events has been investigated with and without the emergence of the edge velocity shear layer (i.e. above and below the density threshold, n_{thr}). At low densities ($n < n_{thr}$) potential fluctuations are predominantly propagating radially outwards across the whole edge sampled region, whereas above the density threshold evidence of both outwards/inwards propagation has been observed depending on the position relative to the shear layer. It is important to note that for the discharge shown in Fig. 5, the innermost probe was located at $r-r_{shear} \approx -35$ mm and therefore the probe is only measuring the region inside the shear layer. This finding shows that the development of both radially inwards and outwards propagating potential events is related with the existence of the edge shear flows and not with the interface between open and closed field line topology in the proximity of the LCFS.

Different mechanisms could explain the development of radially inwards/outwards propagation potential events linked to the edge velocity shear layer.

The effective radial propagation of potential events might reflect both true radial propagation as well as the poloidal propagation of turbulent structures tilted by E_r x B sheared flows in the poloidal-radial plane. Actually, two dimensional plasma edge turbulence has been previously investigated by means of fast imaging in the visible range in the TJ-II stellarator; the observed turbulent structures are propagating poloidally with velocities in the order of 1 – 5 km/s which is comparable to the E_r x B drift. The impact of sheared flows on edge turbulent structures show results that are consistent with the picture of the shear layer stretching blobs as well as ordering them [18]. Experimentally the radial effective trajectories of potential events have been observed radially along the whole region sampled by the rake probe (≈ 4 cm) in the edge plasma region, which is larger than the radial correlation length of edge sheared flows (in the order of 1 cm). Furthermore, it has been observed that the time evolution of the radial velocity is substantially different from that of the poloidal velocity. Then, it is concluded that the observed inwards effective radial velocity is not dominated by the (local) eddy tilting effect of poloidaly propagating structures.

An alternative interpretation of TJ-II findings is based on the influence of plasma flows driven by turbulence. The interaction of large and small scales requires the simultaneous existence of several mechanisms including: i) a turbulent drive at small scales provided energy source associated with steep gradients, ii) a mechanism for transferring this (turbulent) energy to large scales (via Reynolds stress). These conditions can probably be fulfilled in a range of non-equilibrium systems, from fusion plasmas to planet atmospheres. Actually evidence of significant gradients in the electrostatic Reynolds stress, high enough to modify the plasma poloidal flow dynamics, has been reported in the plasma boundary region of tokamaks, stellarators and Reversed Filed Pinches [7]. Being the Reynolds stress driven flows (RS) a result of an internal force, the net momentum redistribution driven by RS should be zero. Then, this mechanism is expected to provide time dependent momentum re-distribution (e.g. E_r events) propagating in opposite directions, in agreement with the present experimental findings.

Avalanche-like events propagating inwards/outwards in the proximity of a region with steep plasma gradients provide an alternative explanation [19, 20]. Finally, an additional ingredient to explain the spontaneous (radially inwards) development of plasma (toroidal and poloidal) rotation in the edge is the preferential transport loss of particles having a particular sign of angular momentum. Due to force balance relation, relating plasma flows and radial electric fields, this mechanism would be consistent with the development of potential events propagating radially inwards from the edge plasma region.

Quantifying the importance of those mechanisms would require the investigation, both experimentally and using simulations, of the 2-D structure and dynamics of turbulence (to separate poloidal and radial propagation) in the proximity of sheared flows as well as the study of the coupling between mass flows/angular momentum losses in the plasma boundary region.

Present findings provide a possible explanation for the underlying physics of previous experimental results showing that plasma toroidal rotation propagates inwards radially from the plasma edge after the L-H transition in Alcator C-Mod as well as the core momentum spontaneous redistribution reported in TCV tokamak. Finally it should be noted that recently evidence of density perturbations (holes and blobs) have been observed to be born at the JET edge shear layer [20]. Then, comparative studies in the radial propagation of density and potential events are needed.

5. Radial transport and long-range toroidal correlations

Recent experiments performed in the TJ-II stellarator have shown that long-range correlations in potential fluctuations are present during the development of the edge sheared flows and that these correlations are amplified either by externally imposed radial electric fields [11] or when approaching the L-H confinement edge transition [12]. Simultaneous measurements with the two set of Langmuir probes located at different toroidal and radial (rake probe) locations in TJ-II have allowed studying and comparing the long-range (toroidal) and local (radial) correlations between potential signals in the edge plasma (large zonal flows amplitude) and scrape-off layer (no zonal flows observed) regions. Results shown in figure 6 indicate that outside the shear layer the radial coherence at low frequencies is higher than the toroidal one, whereas in the edge plasma the opposite behaviour is observed. Furthermore, turbulent transport driven by low frequencies (those showing long-range correlations) is strongly reduced, in the plasma edge side of the shear layer radial location. These results show that radial transport and radial correlations are reduced in the region dominated by the presence of long-range toroidally correlated structures (zonal flows).

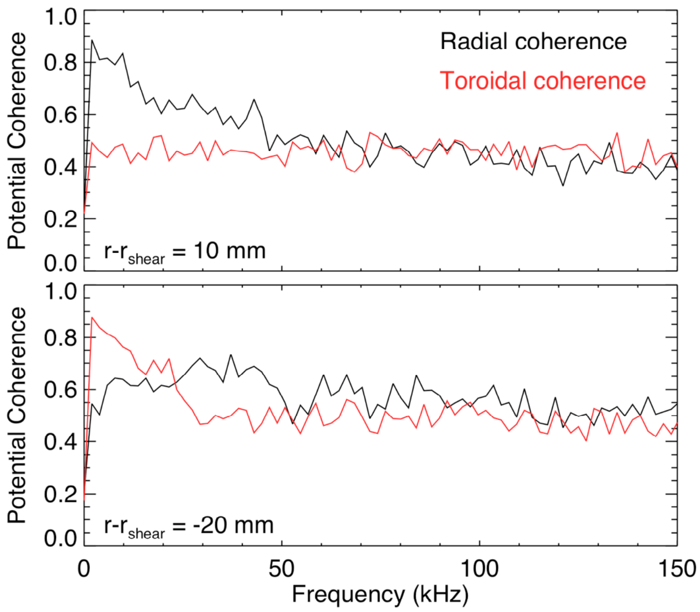

FIG. 6.- Coherence between floating potential signals radial (6 mm) and toroidaly apart, measured in the SOL side and in the edge side of the shear layer location.

7. Conclusion

In conclusion, we have presented a direct experimental evidence of the edge-sheared flows as a source of propagating plasma potential events. The effective radial inwards/outwards propagation of potential events might reflect the momentum re-distribution linked to the development of sheared flows in the plasma boundary region. Considering that potential events propagating radially outwards will be lost in the SOL region or/and interacting with the plasma-wall whereas those propagating radially inwards will remain confined, these findings suggest the development of a momentum source linked to the edge velocity shear layer.

Experimental findings also show that radial transport and radial correlations are reduced in the region dominated by the presence of long-range toroidally correlated structures (zonal flows), providing direct evidence that the long-range toroidal correlations play an important role in the control of the radial transport mechanisms.

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