Transport and fluctuations during electrode biasing experiments on the TJ-II stellarator

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Abstract. The effect of electrode biasing on plasma confinement, turbulence and plasma flows has been investigated in the TJ-II stellarator. Experimental results show that it is possible to modify global confinement and edge plasma parameters with biasing. In addition evidence of electric field induced improved confinement has been found. The plasma response is different at densities below and above the threshold value to trigger the spontaneous development of ExB sheared flows in TJ-II. Two different time scales have been observed in the modification of the edge plasma potential both during spontaneously driven and in biasing induced radial electric fields experiments. The measured fast decay times are in the range of few turbulence correlation times. These results can help to test critically neoclassical and anomalous damping mechanisms in fusion plasmas.

Non-exponential decays of plasma parameters in the scrape-off layer (SOL) have been observed in TJ-II. By means of externally applied radial electric fields the level of fluctuations and the radial velocity of turbulent events are reduced and non-exponential tails observed in the SOL disappear.

1. Introduction

The role of neoclassical mechanisms to explain poloidal flows is an open issue in the fusion community. Plasma flows play crucial roles in magnetically confined fusion plasmas, in particular in the suppression of turbulence via ExB shear, and consequently on transport [1, 2, 3] and in the formation of transport barriers. Both neoclassical (e.g. ion orbit losses [4]) and anomalous mechanisms (i.e. anomalous stringer spin-up [5], Reynolds stress [6, 7]) have been considered as candidates to explain the generation of sheared flows. Atomic physics via charge-exchange momentum losses [8, 9], parallel viscosity (magnetic pumping) [10] and turbulent viscosity are considered as candidates to explain perpendicular flow damping physics. Poloidal rotation measurements, an order of magnitude higher than the neoclassical predictions, for thermal particles across internal transport barriers have been reported in the JET tokamak [11]. In addition, poloidal rotation measurements have been recently compared with neoclassical theory predictions in the D-III-D tokamak showing a significant discrepancy [12].

The influence of a biased limiter on plasma confinement, turbulence and plasma flows has been previously investigated in the TJ-II stellarator [13]. Experimental results showed that it is possible to modify global confinement and edge plasma parameters with both positive and negative biasing and the evidence of electric field induced improved confinement via multiple mechanisms.

In this contribution, we report the results of edge electrode biasing experiments carried out in TJ-II. The existence of a threshold density value for the development of the spontaneous shear layer in TJ-II has lead to the study of the effect of bias at different plasma densities, particularly in what concerns their effects on the edge plasma parameters and particle confinement [14, 15]. Electrode biasing experiments in TJ-II show that it is possible to modify the edge radial electric field and the particle confinement with both positive and negative biasing. The plasma response is different at densities below and above the threshold value for triggering the spontaneous development of ExB sheared flows [16].

Two different time scales have been observed in the modification of the edge plasma potential both during spontaneously driven and in biasing induced radial electric field experiments performed in TJ-II. A fast time scale decay in the range of tens of μs, and a slow time scale in the order of tens of ms. Biasing experiments have been performed in different TJ-II configurations having different volumes (and consequently distinct ripple). In biasing experiments carried out in the stellarator HSX [17], and in the CASTOR tokamak [18] decay time scales of the plasma potential in the same range as that obtained in TJ-II have been found. This similarity is rather striking considering that TJ-II, CASTOR and HSX magnetic topologies are extremely different. These results can help to understand and quantify the importance of anomalous versus neoclassical mechanisms on the damping physics of radial electric fields and flows in fusion plasmas [19].

Evidence of non-exponential decays of plasma parameters in the scrape-off layer (SOL) has been observed in tokamaks [20]. Comparative studies of the structure of turbulence in ECRH and NBI plasmas in the TJ-II stellarator have shown a drastic decrease in the level of turbulence in the transition from ECRH to NBI plasmas [21]. Externally applied radial electric fields, using electrode biasing, have a crucial impact in non-exponential SOL decays. Once edge biasing is turned on the level of fluctuation and the radial velocity of turbulent events are reduced and the observed non-exponential tails in the SOL disappear. These results show that there exists a direct link between the level of turbulence and the development of non-exponential tails in the SOL region.

2. Experimental arrangement

Experiments were carried out in Electron Cyclotron Resonance Heated plasmas (P_{ECRH}= 200 - 400 kW, B_T = 1 T, R = 1.5 m, <a> ≤ 0.22 m, $\iota(a)/2\pi \approx 1.7 - 1.8$) created in the TJ-II stellarator. The plasma density was modified in the range (0.35 – 1) x 10^{19} m^{-3}. Different edge plasma parameters were characterized using a multi-Langmuir probe system, installed on fast reciprocating probe drives [22].

A 2-D Carbon composite mushroom shaped electrode (12 mm high with a diameter of 25 mm) was developed and installed on another fast reciprocating probe drive. The electrode was inserted typically 2 cm inside the last-closed flux surface (LCFS) and biased positively (200-300 V) with respect to one of the two TJ-II limiters located in the scrape-off layer region (about 0.5 cm beyond the LCFS). Measured electrode currents were in the range of 30-50 A [16].

3. Biasing experimental results

The modifications in the plasma properties induced by electrode biasing depend on several parameters, such as the biasing voltage, the electrode location and the plasma density. The latter is very important in TJ-II as the edge parameters depend strongly on it [15]. Previous experiments in TJ-II showed that the development of the naturally occurring velocity shear layer requires a minimum plasma density [14]. In the region just inside the LCFS the radial electric field increases significantly when the plasma density reaches the threshold value and the perpendicular phase velocity of fluctuations reverses sign. The plasma response to bias is therefore different at densities below and above the threshold value needed to trigger the spontaneous development of ExB sheared flows.

3.1. Effect of biasing on plasma parameters

The edge plasma profiles are modified during biasing independently of the plasma density value (above or below the threshold for triggering the spontaneous development of ExB sheared flows). Figure 1 shows the modification of the floating potential radial profile when electrode bias is active in TJ-II for plasma density above the critical. The floating potential profile is strongly modified by the electrode bias in the region r/a < 0.9, leading to the formation of a strong positive radial electric field (up to 10 kV/m). These results are consistent with the time evolution of the perpendicular phase velocity, which changes sign during biasing. Ion saturation current profiles (i.e. edge electron density) become steeper during biasing in the region where the electric field is modified.

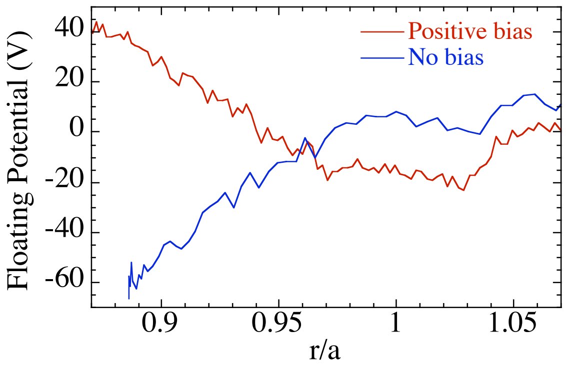

FIG 1. Radial profiles of the floating potential measured in TJ-II low field side ECRH plasmas with and without biasing.

The effect of positive electrode bias for values of plasma density below the threshold is shown in figure 2. The bias voltage was applied at t=135 ms for 70 ms, and the electrode was located approximately 2 cm inside the LCFS. Figure 2 shows temporal traces of bias current and voltage, line-average density, n, average H_α emission and ratio n/H_α. Also shown are edge parameters derived from the Langmuir probe measurements (located at r/a≈0.8). The floating potential increases by more than 100 V, confirming that both the plasma potential and the edge radial electric field can be strongly modified for positive applied voltages. As shown in figure 2, both the turbulent transport and the fluctuation level of the edge quantities are strongly reduced after bias is applied. Observations are therefore consistent with a local reduction of the anomalous particle flux, as a result of a reduced electrostatic turbulence. It has been observed that the emission intensity increase is generally proportional to the variation in the line-averaged density, so that the density rise can be unequivocally attributed to better particle confinement, as opposed to increased ionization by impurity penetration [16]. In summary, it is observed that for low density the edge plasma potential is fully controlled by external biasing.

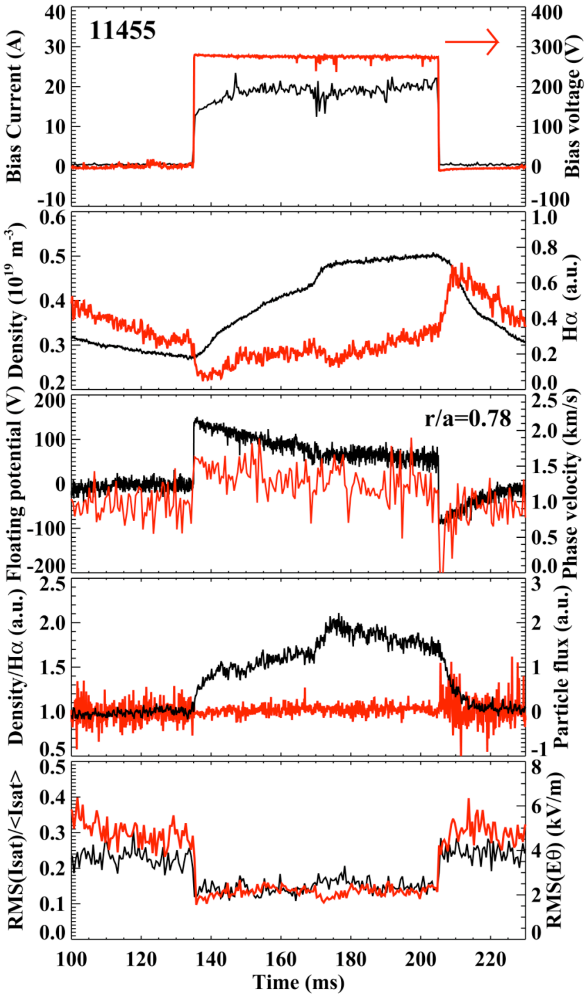

FIG. 2. Time evolution of some global and edge plasma parameters with applied positive biasing at low plasma density.

At higher densities (above the threshold value) edge plasma potential profiles are determined not only by external biasing but

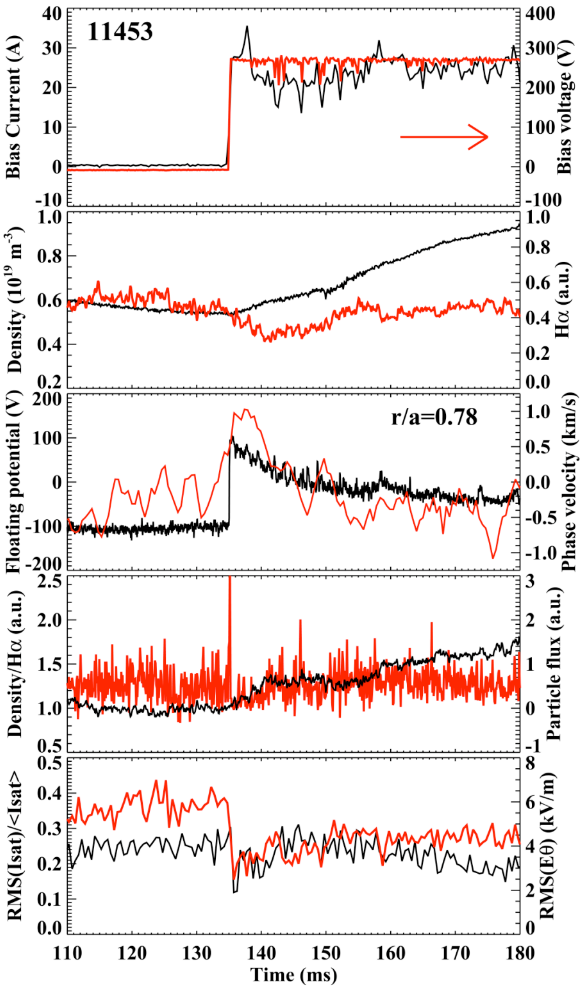

FIG. 3. Time evolution of some global and edge plasma parameters with applied positive biasing at high plasma density.

also by the electric field spontaneously developed. Positive bias will tend to increase the edge floating potential at the electrode location and therefore reverse the plasma rotation direction. As shown in figure 3, when bias is applied, the density increases and the H_α emission decreases, leading to a clear improvement in particle confinement. The floating potential is also strongly modified indicating that the edge electric field is modified in this case too. However, as the density increases above the critical value it will also influence the edge profiles. The H_α emission tends to follow the density time evolution; the floating potential decreases and the phase velocity can reverse again. In summary, at higher densities edge plasma potential profiles are determined not only by external biasing but also by the electric fields spontaneously developed.

3.2. Relaxation time scales measurements

The decay time of the plasma potential measured in the edge plasma region have been investigated when electrode biasing is turned off. Two different time scales have been observed in the modification of the edge plasma potential during biasing induced radial electric fields experiments. In figure 4a the two time scales can be clearly seen after biasing. The slow time scale (in the order of tenths of ms) is directly linked to the evolution of plasma density. Strong changes in the plasma potential (50 - 100 V) occur in the edge region after biasing in a fast time scale (10 - 50 μs).

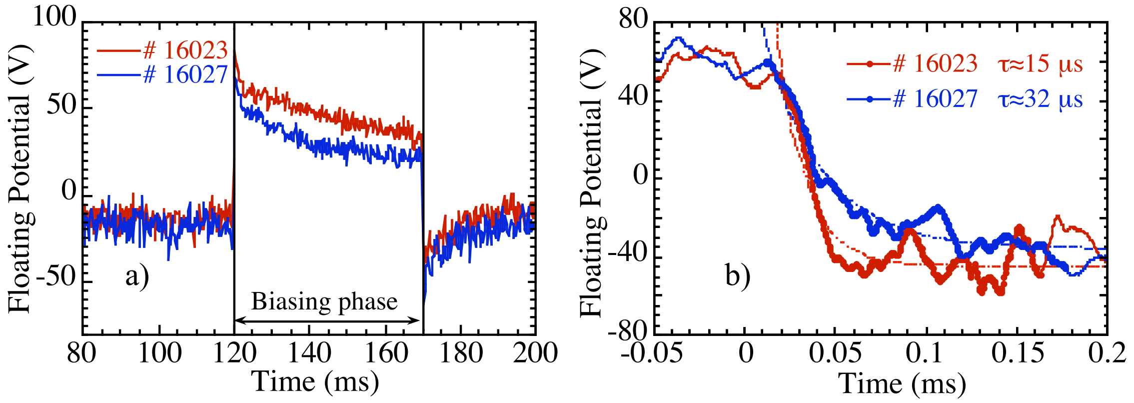

FIG. 4. a) Time evolution of floating potential when electrode bias is applied and b) fit of the floating potentials fast decay measured at the TJ-II plasma edge (r/a≈0.9).

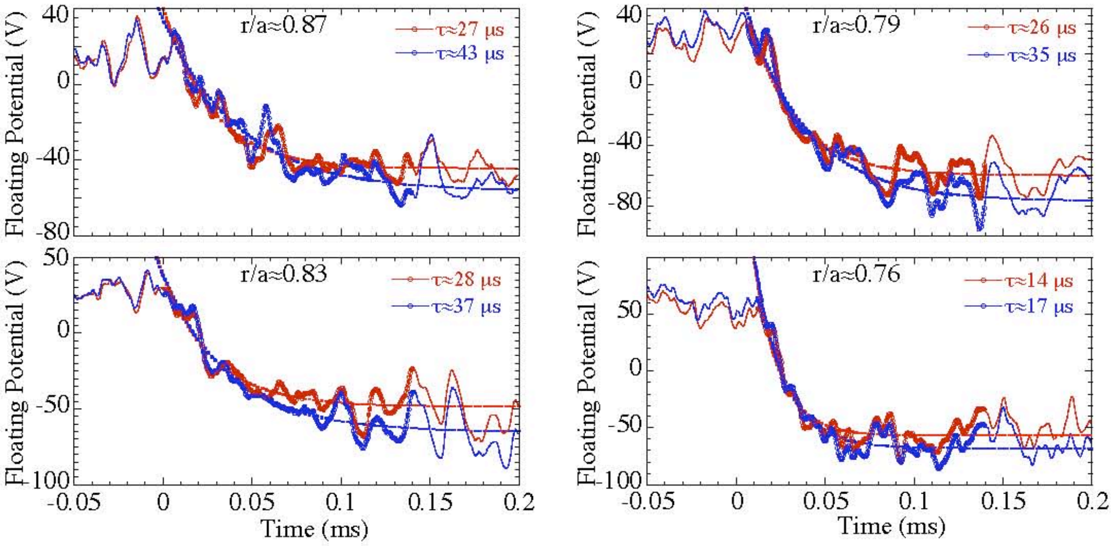

FIG. 5. Fit of the floating potentials decay measured at different radial probe positions in TJ-II. Two simultaneously measured signals poloidally apart were used in each position.

The time evolution of floating potential signals can be fitted to a function with the following shape,

$$V_{fl}(t) = V_{max} \exp(-t/\tau) + V_{min}$$

from which the exponential relaxation time τ is deduced. This fitting procedure has been done for floating potential signals measured at different densities and at different radial locations in TJ-II.

Experimental results show that floating potential signals can be well fitted by an exponential decay with characteristic time decay in the range of 10 - 40 μs. Figure 4 b shows the fitting of two floating potential signals measured under similar plasma conditions ($n_e \approx 0.7 \times 10^{19}$ m^{-3}) close to the LCFS ($r/a \approx 0.9$). So far, no significant differences have been found between the relaxation times measured in different toroidal positions (low and high field sides).

Figure 5 shows the decay time of floating potential measured at different plasma radius of the TJ-II plasma edge after switch off the biasing and with similar plasma conditions ($n_e \approx 0.7 \times 10^{19}$ m^{-3}). Results suggest a decrease of the decay time when moving radially inwards inside the plasma. It should be noted that the fast decay time in TJ-II might be in some cases as small as 15 μs.

The influence of plasma density (in the range 0.4 – 1 x 10^{19} m^{-3}) on relaxation times has also been investigated in TJ-II. Figure 6 shows the behaviour of the measured relaxation time in the TJ-II plasma edge ($0.75<r/a<0.85$) as a function of plasma density after switch off of the biasing and the corresponding signals and fitting for three different values of plasma density. No clear tendencies in the decay time with plasma density have been found so far, but results suggest an increase in decay times above the threshold density value (i.e. once edge perpendicular sheared flows are fully developed).

Recent results have shown similar values for the decay time scales measured in different devices (HSX stellarator and Castor tokamak) [19]. Neoclassical modelling for HSX has shown that the electric field damping time is of the order of 80 μs, a factor of 2 - 5 larger than the measured values [23]. Turbulence is also an important element in the physics of flows and electric fields. Turbulent damping mechanisms are likely to apply on short time scales, of the order of a few turbulence correlation times (typically $\tau_c \approx 10$ μs), in consistency

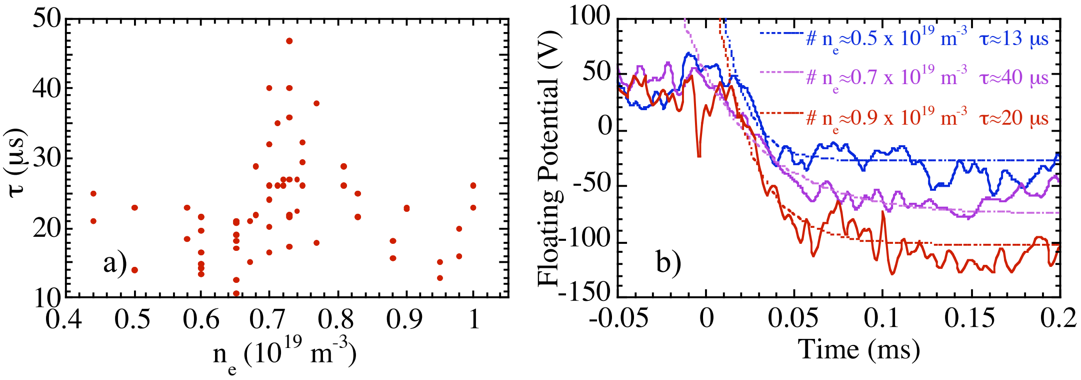

FIG. 6. a) Decay times of floating potential signals measured in the TJ-II plasma edge (r/a≈0.85-0.9) as a function of plasma density at the electrode switch-off time. b) Fitting of floating potential measured in plasmas with different line average density.

with the time decay found experimentally. Momentum loss via atomic physics mechanisms (charge exchange) might also play a role. However, using typical edge plasma parameters, the damping times due to charge exchange are expected to be in the range 100 - 1000 μs [19], being therefore significantly larger than the decay time measured experimentally. These results could help in understanding the impact of the level of turbulence on damping rates and have a direct impact in understanding the L-H transition physics in tokamak and stellarator plasmas. Parametric studies of the influence of different plasma regimes (e.g. collisionality, turbulence correlation times, magnetic configuration) on the damping time of poloidal flows and radial electric fields are in progress. This result would help to quantify the importance of anomalous versus neoclassical mechanisms on the damping physics of radial electric fields and poloidal flows in fusion plasmas.

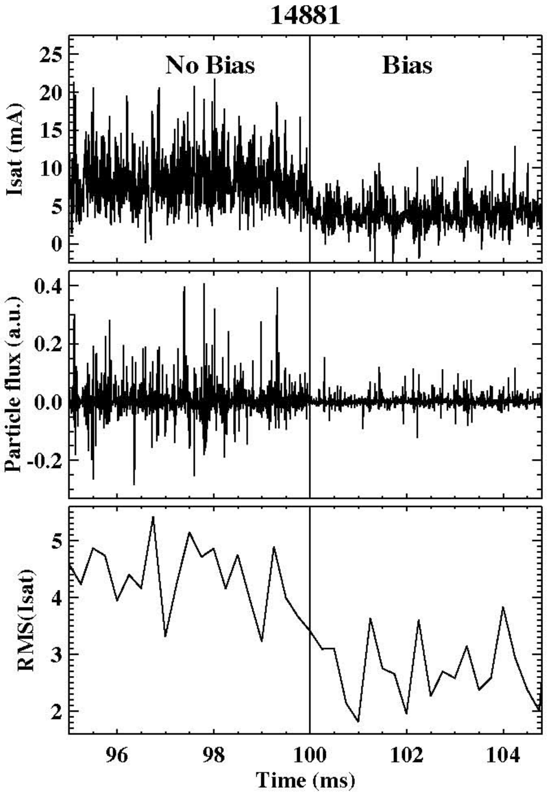

FIG. 7. Changes of SOL (r/a≈1.03) plasma parameters measured in electrode biasing experiments.

4. Decay behavior of plasma parameters in the scrape-off layer

Experimental evidence of intermittent events propagating radially with velocities in the range of 1000 m/s has been reported [24, 25]. This radial velocity suggests the importance of the competition between both parallel and radial transport in explaining particle losses onto the divertor plates in fusion devices. A direct link between the statistical properties of turbulent transport and non-exponential density profiles in the SOL region in the plasma boundary region of the TJ-II stellarator has been found [21].

The existence of non-exponential radial decays in some scrape-off layer (SOL) parameters has been previously reported [20]. Comparative studies of the structure of turbulence in combined ECRH and NBI plasmas in the TJ-II stellarator have shown a drastic decrease in the level of turbulence in the transition from ECRH (200 - 400 kW) to NBI (400 kW) plasmas. Once ECRH heating power is turned-off, a confinement regime characterized by a strong reduction in ExB turbulent transport and fluctuations and a significant increase in plasma density is achieved. As a consequence, the radial effective velocity of transport decreases by about a factor of ten and non-exponential tails usually observed in ECRH plasmas disappear in the NBI regime.

Externally applied radial electric fields have also a crucial impact in non-exponential SOL decays. Figure 7 shows the behaviour of ion saturation current turbulent transport and level of fluctuations in TJ-II plasmas with and without applied bias. Once edge biasing is switched on the level of fluctuations and the radial velocity of turbulent events are reduced and edge density profile becomes steeper. Simultaneously, there is a drastic reduction in the ExB turbulent driven transport due to a decrease in electric field and density fluctuations when biasing is turned on. These results show a direct link between the level of turbulence and the development of non-exponential tails in the SOL region.

5. Conclusions

- Experimental results have shown evidence of electric field induced improved confinement via multiple mechanisms by means of externally applied biasing.
- Two time scales have been found for edge plasma potential decay measured in the edge plasma region when electrode applied potential is turned off. In the fast time scale (10 -50 μs) the plasma potential changes in the edge region by about 50 - 100 V after biasing; in the slow time scale (comparable to the particle confinement time) plasma potential modifications are linked to the evolution of the plasma density.
- No clear tendencies of the fast decay time with plasma density have been found so far, but results suggest an increase in decay times above the threshold density value (i.e. once edge perpendicular sheared flows are fully developed).
- The measured fast decay times are in the range of few turbulence correlation times. As a consequence turbulence can be considered as an important element in the physics of flows and electric fields.
- The results presented could aid in understanding the impact of the level of turbulence on damping rates and can shed some light on quantifying the importance of neoclassical mechanisms on the damping physics of the radial electric fields and flows in fusion plasmas.
- A reduction in the level of turbulent driven transport in the SOL and the disappearance of non-exponential tails have been observed when biasing is applied. These results show a direct link between the level of turbulence and the development of non-exponential tails in the SOL region.

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