Characterization of the Perpendicular Rotation Velocity of the Turbulence by Reflectometry in the Stellarator TJ-II

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Abstract. The formation of the edge perpendicular velocity shear layer in the stellarator TJ-II has been investigated using microwave reflectometry. Experimental results show that the origin of the velocity shear layer is the region of maximum density gradient. The velocity shear layer starts its formation at this position and expands radially, until it is fully established in the proximity of the Last Closed Magneitc Surface (LCMS), where it shows the universal properties of the edge sheared flows observed in the boundaries of fusion plasmas. The process of appearance and disappearance of the sheared flow propagates radially at a velocity of about 1.8 m/s and no evidence of hysteresis effects has been found. This velocity is small compared to the radial propagation velocity of biasing-induced perpendicular rotation velocity modification; the later being 10-15 m/s at nominal bias voltages of 250-300V.

1. Introduction

In the TJ-II stellarator plasmas, the perpendicular rotation velocity of the turbulence changes from positive to negative (from ion to electron diamagnetic direction) inside the LCMS, forming the so called edge velocity shear layer, when the line-averaged plasma density exceeds some threshold value [1,2]. Heavy Ion Beam Probe (HIBP) and Langmuir probe measurements indicate that the inversion in the perpendicular rotation velocity of the turbulence is dominated by the inversion in the radial electric field [3]. A parametric dependence of the critical line-averaged density has been obtained studying plasmas confined in different magnetic configurations (different rotational transform and different plasma volume) and heated with different Electron Cyclotron Heating (ECH) power levels. The studied data set shows a positive exponential dependence on heating power and a negative one on plasma radius, while the dependence on rotational transform has low statistical meaning [4]. In this work we study the radial origin and the process of formation of the edge velocity shear layer using microwave reflectometry [5]. Dedicated experiments have been performed to trigger the perpendicular rotation velocity inversion by modulating the plasma density. Besides, to study the influence of the magnetic topology, these experiments have been carried out in three magnetic configurations with different rotational transform. Finally, the process of formation of the edge velocity shear layer is compared with the biasing-induced edge rotation velocity modification.

2. Experimental Results

The experiments have been carried out in ECH plasmas in the TJ-II stellarator (R =1.5 m, $\langle a \rangle \approx 0.22$ m, $B_T = 1$ T, $P_{ECH} \leq 600$ kW). In the experiments, the heating power is held constant at 420 kW; therefore, the line-averaged density can be used as an external control knob to trigger the appearance and disappearance of the velocity shear layer. The inversion in the perpendicular rotation velocity and its radial propagation are characterized by using a two-channel fast frequency hopping reflectometer [6]. This reflectometer is able to monitor the sign of the perpendicular velocity of turbulence due to a finite angle between the microwave beam and the normal to the cut-off layer [2]. Hence, using two different frequencies, it is possible to monitor the sign of the perpendicular velocity simultaneously at two different radial positions in the plasma. In each discharge, both, the appearance and disappearance of the perpendicular velocity shear layer are triggered by modulation of the line density. The frequencies of the two reflectometer channels are held fixed during each discharge, but changed on a shot-to-shot basis. In all cases, channel 1 measures at more external positions than channel 2. As an example, figure 1.a shows the time trace of the line-averaged density of a representative discharge. The threshold density is indicated by the shaded area. The line density crosses the threshold density twice: at t ≈ 1115 ms, the formation of the velocity shear layer takes place, while at t ≈ 1157 ms, the velocity shear layer disappears. Figure 1.b shows the center of gravity <f> of the power spectra of the two reflectometer channels. Negative and positive <f> correspond to ion- and electron-diamagnetic velocity, respectively. The slope of the reconstructed phase of the reflectometer measurement is positive when <f> is positive and vice versa (see figure 2). When the velocity shear layer is formed, the perpendicular velocity reverses its sign first at ρ = 0.62 (channel 1), then at ρ = 0.57 (channel 2), marked by vertical lines. The order of magnitude of the delay is of a few milliseconds. When the velocity shear layer disappears, the reversal of the plasma velocity is first noted at ρ = 0.56 (channel 2) and then at ρ = 0.63 (channel 1). Their exact radial positions are obtained using the density profiles measured by AM reflectometry [7].

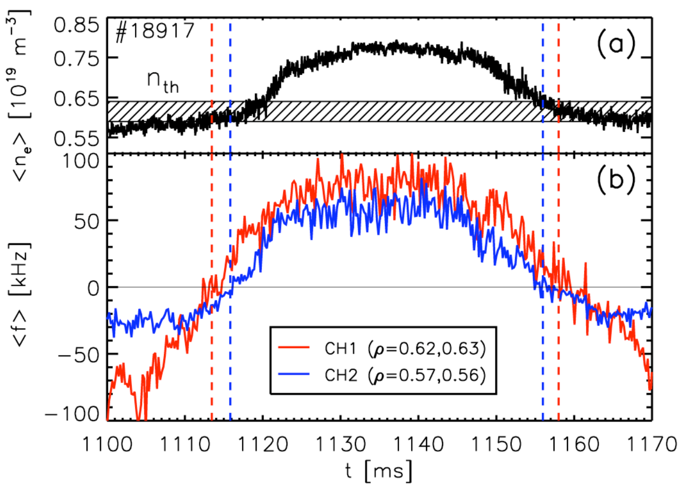

FIG. 1: Time evolution of the line-averaged density (a) and center of gravity of power spectra measured by the two-channel reflectometer (b). The shaded area and the vertical lines indicate, respectively, the threshold density and the time instants at which the perpendicular velocity inversion is detected by each channel.

For a precise evaluation of the time at which the perpendicular velocity inversion is detected by each channel, t_{CH1} and t_{CH2}, the reconstructed phases of the reflectometer are used. The values for t_{CH1} and t_{CH2} are obtained by fitting a second degree polynomial to the reconstructed phase and calculating the minimum (emergence of the shear, see figure 2) or the maximum (disappearance of the shear) analytically using the first derivative. The standard deviation of the results is obtained by varying the length of the temporal window for the fit from 8 to 14 ms.

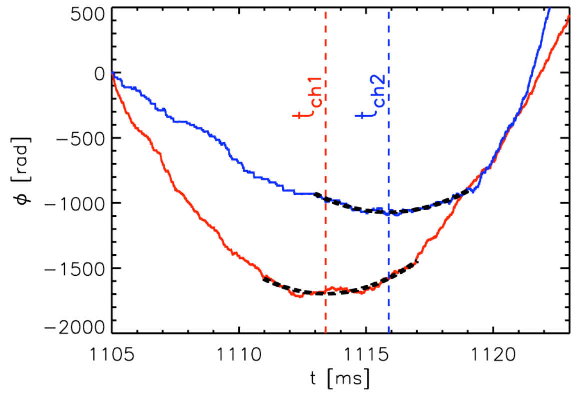

FIG. 2: Time evolution of the reconstructed phases during the emergence of the velocity shear. The second degree polynomial used to calculate the minima are shown.

By changing the probing frequencies of the reflectometer in a series of reproducible discharges, the time delay $\Delta t = t_{CH1} - t_{CH2}$ is measured at different radial positions. Figure 3.a shows the time delays dependent on the radial position when the line-density exceeds the threshold value, marked by stars connected by a continuous line, and when it falls below the threshold density, represented by diamonds connected by a dashed line. Each radial position corresponds to the mean of the two reflectometer measurement positions, obtained using the profiles from AM-reflectometry shown in figure 3.c. The radial measurement error is shown for one point and is representative for the error in all measurements. When the density rises (emergence of the velocity shear layer), for radii $\rho > 0.68$, the perpendicular velocity reverses sign first at the more internal, and then at the more external positions, because $\Delta t > 0$. However, for $\rho < 0.68$, the contrary takes place: the change in perpendicular velocity is first noted by the exterior channel and then by the interior channel ($\Delta t < 0$). When the line-density falls below the threshold density (disappearance of the velocity shear layer), the internal measurements show that the interior channel notes the change first, while the external measurements show that the exterior channel first measures the change in perpendicular velocity. This phenomenon can be explained as follows: when the line-density goes above the threshold density, the velocity shear layer starts to form at $\rho \approx 0.68$. Since $\Delta t \approx 0$, this radius is the origin of the formation of the velocity shear layer. For simplicity $\rho_0 = 0.68$ is defined. The formation of the shear layer continues, propagating outward for $\rho > \rho_0$ and inward for $\rho < \rho_0$. Figure 4 shows a scheme of the perpendicular rotation velocity evolution and the corresponding plasma potential profiles (assuming that the perpendicular rotation velocity of the turbulence is dominated by the ExB velocity, i.e., that the phase velocity of the turbulence moving in the plasma frame is negligible). Before the formation of the shear layer the perpendicular rotation velocity is positive, as is the radial electric field. As the shear layer develops, the radial electric field is negative around ρ_0; at this moment, only channel 1 of the interior measurement and channel 2 of the exterior measurement detect the inversion of $v_\perp$. When the velocity shear layer is completely developed, both channels measure negative velocities independently of their positions in the plasma. The process of disappearance of the velocity shear layer is the direct opposite: As the line-density falls below the threshold density, the shear layer starts to contract, the process ending at ρ_0. Hence the formation of the velocity shear layer as well as its disappearance occur at the same radial position. The lower part of figure 3 shows the density profiles (3.c) used for analysis and the respective density gradients (3.b). Continuous lines correspond to the density profiles when the velocity shear layer emerges while dashed lines show the profiles at the moment when the line-density falls below the threshold density (disappearance of the velocity shear layer). It should be noted that the profiles are very similar when the line-density crosses the threshold density. The region of maximum density gradient ($\rho = 0.66 \ldots 0.72$) is marked in figure 3.b by the horizontal bar. The agreement between the origin (and terminal point) of the velocity shear layer ($\rho_0 = 0.68$) with the region of maximum density gradient suggests that the plasma gradients can provide a seeding mechanism for edge shear flows.

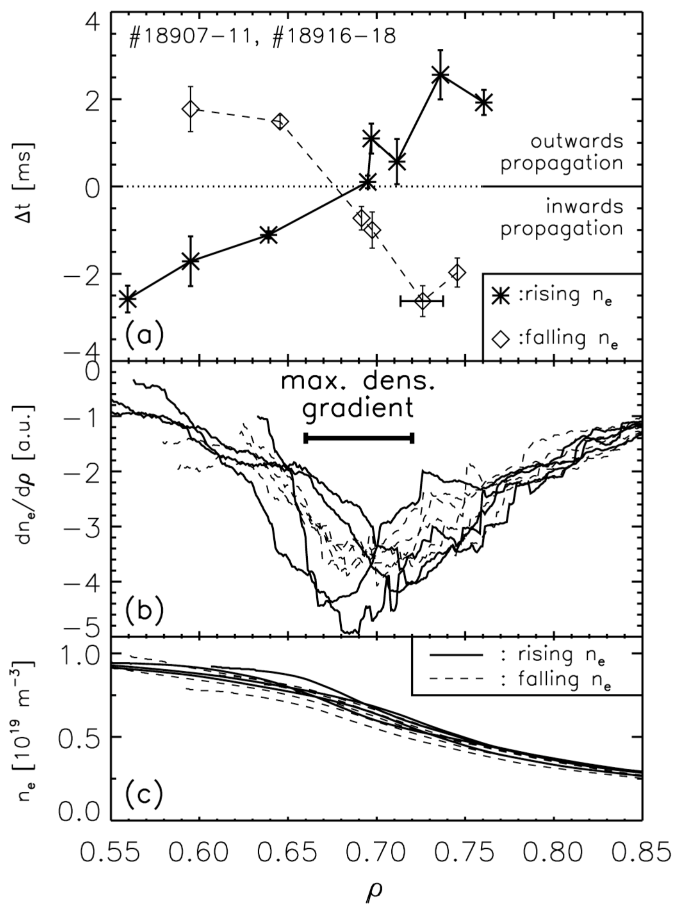

FIG. 3: (a) Time delays of the velocity shear layer appearance (stars, solid line) and disappearance (diamonds, broken lines). (b) Density gradients and (c) density profiles measured by AM reflectometry.

Due to the proximity of the 8/5 rational surface to the radial location where the velocity shear layer develops, the described experiment has been conducted in two other magnetic configurations changing the radial location of the rational in a range $\Delta\rho = 0.3$. The obtained values of ρ_0 are very close to 0.7, independently of the radial location of the rational surface. The radial propagation velocity of the velocity shear layer when it is formed (stars) and when it vanishes (diamonds) is shown in figure 5. Positive and negative velocities correspond to outward and inward propagation, respectively. The velocity is calculated by obtaining the absolute distance between the two measurement positions of the reflectometer and dividing by the time delay Δt (figure 3.a). The radial measurement error is the same as in figure 3.a. Since both the radial distance of the measurements and the delays Δt are subject to errors, the error in the radial propagation velocity is calculated using the method of linear propagation of uncertainties. The shear layer starts to form at ρ_0 and expands from this point to exterior and interior regions of the plasma. The disappearance shows the inverse behaviour of radial propagation velocity: the velocity shear layer starts to contract radially in the direction of ρ_0. The resulting radial propagation velocity of the flow reversal $v = \Delta R/\Delta t$, with ΔR the separation of the reflectometer channels, is $v = 1.8 \pm 1$ m/s. This value is obtained by taking both the mean of the velocities and the errors. These radial velocities are in good agreement with the radial velocities obtained using the delay between the perpendicular rotation velocity inversion detected by reflectometry and that detected by Langmuir probes (located at $\rho \approx 0.85$).

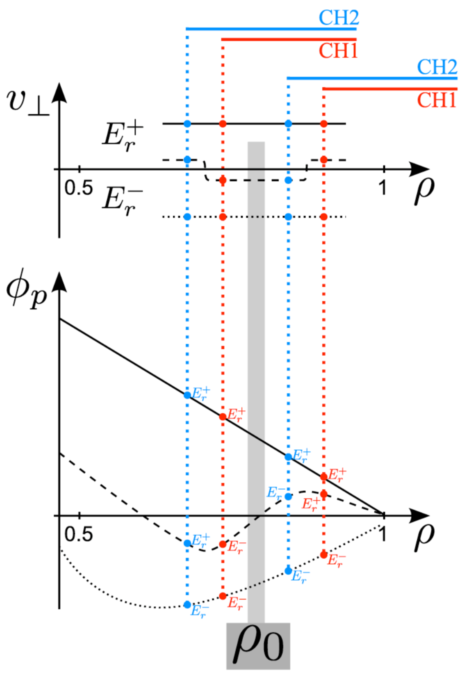

FIG. 4: Scheme of the perpendicular rotation velocity evolution and the corresponding plasma potential profiles for $n < n_{th}$ (solid lines), $n \approx n_{th}$ (dashed lines) and for $n > n_{th}$ (dotted lines). Reflectometry measurements located at $\rho < \rho_0$ and $\rho > \rho_0$ are indicated by vertical dotted lines.

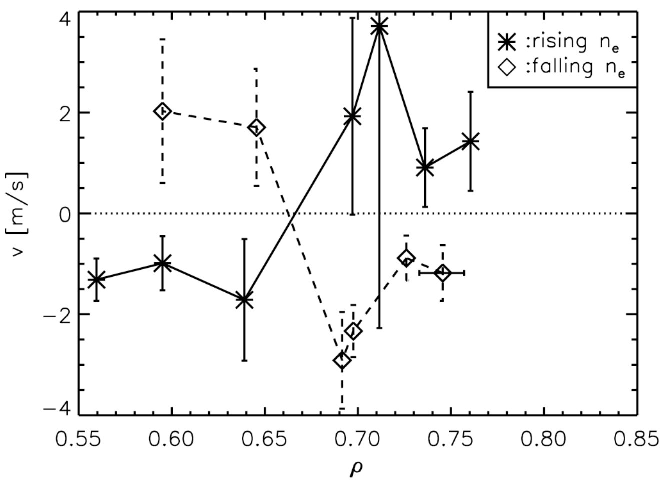

FIG. 5: Radial propagation velocity of the formation (stars) and disappearance (diamonds) of the velocity shear layer. Positive velocities point radially outward and negative ones point radially inward.

In order to compare the process of formation of the edge velocity shear layer with the biasing-induced edge rotation velocity modifications, similar reflectometry measurements keeping fixed the frequencies of both channels have been carried out during edge plasma biasing experiments. Changes in the radial electric field induced by means of electrode biasing at the plasma edge [8], induce changes in the perpendicular rotation velocity that are more pronounced as the bias voltage increases [9]. Reflectometry measurements allow measuring both, the radial extension of the plasma affected by the biasing and the radial propagation velocity of the perpendicular rotation velocity modification. Three examples are shown in figure 6. In these examples the plasma density is above the threshold density and consequently the edge velocity shear layer is already present before the bias voltage is applied. Positive bias voltage, applied at $\rho \approx 0.9$, produces an inversion in the edge perpendicular rotation velocity from electron to ion diamagnetic direction. While the frequency of the external channel is kept fixed during the experiment, the frequency of the second channel is changed on a shot-to-shot basis to vary the distance between the cut-off layers.

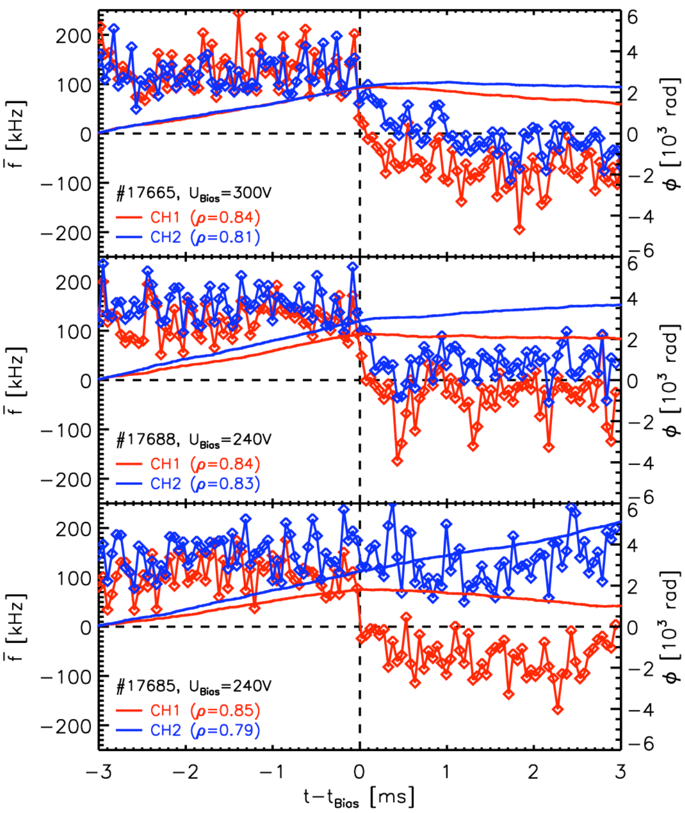

FIG. 6: Center of gravity of power spectra (lines-points) and reconstructed phases (lines) measured by the two-channel reflectometer during edge plasma biasing experiments. The frequency of channel 1 is fixed while the frequency of channel 2 changes to vary the distance between the cut-off layers.

In all three cases, the external channel (channel 1 measuring at $\rho \approx 0.85$) detects the inversion in the perpendicular rotation velocity immediately after the application of the bias voltage. The second channel detects the inversion afterwards provided that its radial location is kept close to the first channel (first and second examples in figure 6); further inside (ρ <

0.8) channel 2 does not detect changes in the perpendicular rotation velocity (third example in figure 6). The radial propagation velocity of the change in the perpendicular rotation velocity is: 15 m/s in the first case and 10 m/s in the second one, being the applied bias voltage 300 and 240 V, respectively. These velocities are considerably higher than radial propagation velocities measured during the spontaneous shear layer formation and disappearance.

3. Summary and Conclusions

Reflectometry measurements in TJ-II have allowed the detailed study of the edge perpendicular velocity shear layer formation. The radial origin of the perpendicular rotation velocity inversion and its radial propagation have been characterized using a two-channel fast frequency hopping reflectometer. This system monitors the sign of the perpendicular rotation velocity simultaneously at two different radial positions in the plasma.

Experimental results show that the radial origin of the velocity shear layer coincides with the region of maximum density gradient ($\rho \approx 0.7$). The velocity shear layer starts its formation at this position and expands radially, until it is fully established in the proximity of the LCMS. These results suggest a two step process in the edge shear formation: 1) a seeding mechanism linked to plasma gradients and 2) an amplification process in which edge shearing rates and fluctuations are self-organized near marginal stability.

The influence of the magnetic topology on the velocity shear layer formation has been studied conducting the experiment in three magnetic configurations. The velocity shear layer develops at $\rho \approx 0.7$ irrespective of the radial location of the 8/5 rational surface.

The process of appearance and disappearance of the sheared flow propagates radially at a velocity of about 1.8 m/s and no evidence of hysteresis effects has been found. This velocity is small compared to the radial propagation velocity of biasing-induced perpendicular rotation velocity modifications.

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