Parametric dependence of the perpendicular velocity shear layer formation in TJ-II plasmas

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In TJ-II plasmas, the perpendicular rotation velocity of the turbulence changes from positive to negative (from ion to electron diamagnetic direction) inside the LCMS when the line-averaged plasma density exceeds some critical value, this change being dominated by the inversion in the radial electric field. In this work we study the parameters that control the inversion in the perpendicular rotation. A parametric dependence of the critical density has been obtained studying plasmas confined in different magnetic configurations (different rotational transform and/or plasma volume) and heated with different ECH power levels. The studied data set shows positive exponential dependence on heating power and negative one on plasma radius, while the dependence on rotational transform has low statistical meaning. Besides, analysis of local plasma parameters points to plasma collisionality as the parameter that controls the inversion of the perpendicular rotation velocity of the turbulence.

Keywords: Stellarator, Reflectometry, Perpendicular Rotation, Collisionality

1. Introduction

In TJ-II ECH plasmas, a perpendicular velocity shear layer develops spontaneously at the plasma edge, above a certain line-averaged density [1]. The transition for the shear layer formation has been characterized using Langmuir probes [2], Ultra Fast Speed cameras [3] and microwave reflectometry [4]. Langmuir probe measurements indicate that below the critical density the perpendicular velocity of the turbulence is positive (in the ion diamagnetic direction) at both sides of the LCMS, while above this critical density, the perpendicular velocity remains positive outside the LCMS and it turns out to be negative inside. Besides, probe measurements show that there is a coupling between the development of the shear layer and an increase in the turbulence level at the plasma edge; the experimental results being consistent with the expectations of second-order transition models of turbulence-driven sheared flows [5]. In addition, HIBP measurements indicate that the radial electric field at the plasma edge reverses from positive to negative as the plasma density exceeds the critical value, while it remains positive in the plasma core [6]. These HIBP measurements indicate that the inversion in the perpendicular rotation velocity of the turbulence is dominated by the radial electric field.

In order to investigate the parameters that control the radial electric field, we have studied the dependence of the critical line-density on the ECH heating power and on the magnetic configuration: rotational transform and plasma volume. Besides, to further investigate the physics behind it, we have studied the behaviour of local plasma parameters: density, temperature and pressure and their radial gradients.

2. Experimental Results

The discharges used in this work correspond to ECH heated plasmas at 53 GHz, second harmonic and X-mode polarization. These discharges belong to six magnetic configurations, heated with three power levels: 200, 300 and 400 kW and with line-averaged densities from 0.3 to 1.2 10^{19} m^{-3}. The six magnetic configurations cover three rotational transform values (1.4, 1.8 and 2.2) and, for each rotational transform, two plasma volumes (0.65 and 1.0 m^3). The rotational transform profiles are shown in figure 1, while figure 2 shows the plasma volume as a function of the rotational transform at $\rho = 2/3$ for these configurations. Each magnetic configuration is labelled with three numbers that refer to the currents in the circular, helical and vertical coils of TJ-II; by changing these currents, the ι-profile and/or the plasma volume can be scanned. These magnetic configurations were

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selected in order to have very low correlation between both configuration parameters: rotational transform and plasma radius. The electron and ion contributions to the plasma energy are calculated using the electron density and temperature profiles measured by the Thomson Scattering diagnostic and the ion temperature measured by the charge-exchange spectrometer. This data set (155 plasma discharges) reproduces the parametric dependence of the energy confinement time reported in [7]: the confinement improves with plasma density, plasma radius and rotational transform and degrades with heating power.

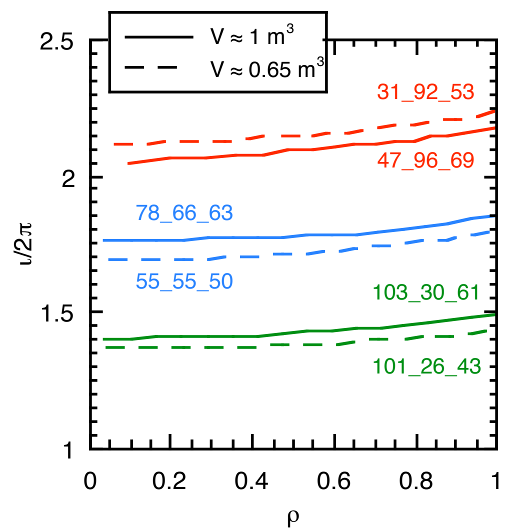

Figure 1: Rotational transform profiles for the six selected magnetic configurations.

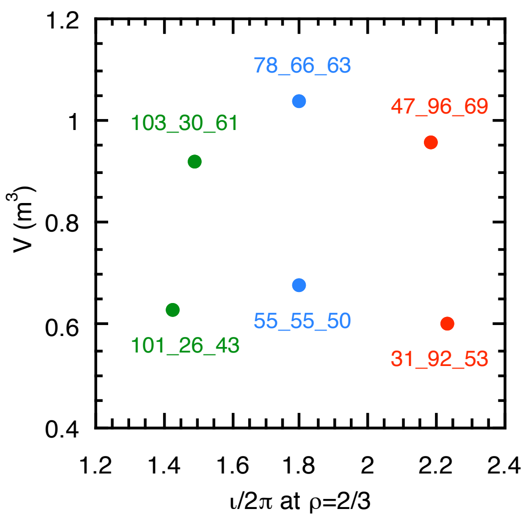

Figure 2: Plasma volume as a function of the rotational transform at ρ = 2/3 for the magnetic configurations shown in figure 1.

To monitor the inversion in the perpendicular rotation velocity we have used microwave reflectometry. The sign of the perpendicular rotation velocity of the turbulence can be resolved by the asymmetry of the turbulence spectra measured using the reflectometer [4, 8]. We have classified the discharges in three groups attending to the perpendicular rotation velocity in the plasma edge region (ρ ≥ 0.6). The first and second set of discharges includes plasmas with positive and negative perpendicular rotation velocity, respectively. The third set of discharges includes plasmas in which the inversion in the perpendicular rotation velocity is detected during the discharge; the corresponding critical line-density is obtained as the line-averaged density measured by the microwave interferometer at the inversion time. The obtained critical line-density values vary within a rather broad range, from 0.5 to 1 10^{19} m^{-3}, depending on magnetic configuration and ECH heating power. From this last set of discharges (44 discharges) we have extracted the parameter dependence of the critical line-density on ECH power, plasma radius and rotational transform, assuming a factorial dependence:

$$<n_{cr}> \propto P^{\alpha_P} a^{\alpha_a} \left(\iota/2\pi\right)^{\alpha_\iota}$$

The best fit that results from the regression analysis is shown in figure 3 and is given by:

$$<n_{cr}> \propto P^{+0.34\pm0.03} a^{-1\pm0.1} \left(\iota/2\pi\right)^{+0.09\pm0.05}$$

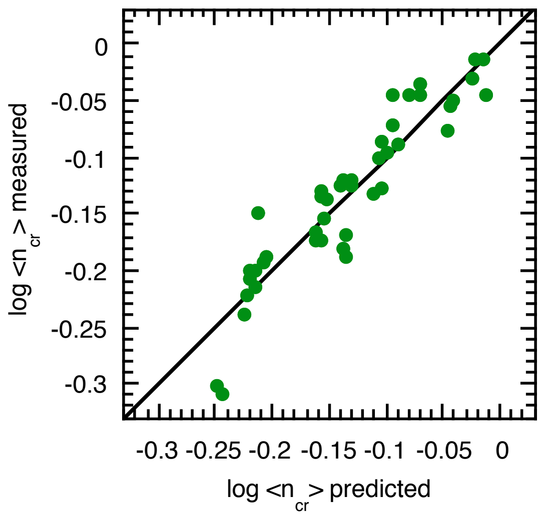

Figure 3: Critical line-density values obtained experimentally versus the best fit found in the regression analysis, represented in a log-log scale.

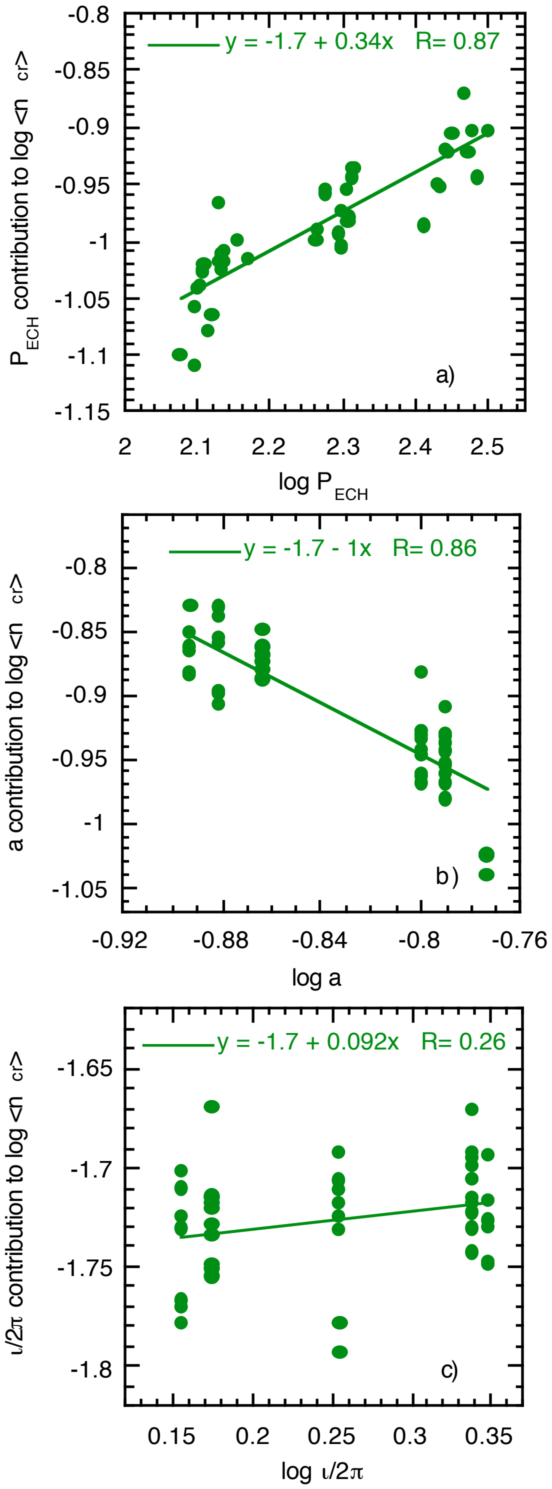

Figure 4: ECH power (a), plasma radius (b) and rotational transform (c) contribution to the critical line-density, represented in a log-log scale. The linear fits reproduce the regression coefficients.

The critical line-density shows opposite exponential dependences as compared with the energy confinement time: positive exponential dependence on the heating power and negative one on the plasma radius, while the dependence on the rotational transform has low statistical meaning. These dependences are shown in figures 4.a to 4.c. The contribution from each parameter to the critical line-density is obtained subtracting the contribution from the other parameters. These results partially confirm some preliminary results reported in [9]. The opposite exponential dependences as compared with the energy confinement time may reflect the influence of the radial electric field profile on the confinement. Moreover, particle transport analysis of TJ-II plasmas indicates that above the threshold density the particle confinement time improves considerably [10].

So far we have considered the line-density as the external knob to control the perpendicular rotation velocity; however, the large variation of the critical line-density with the ECH power and with the plasma volume indicates that line-density may not be the relevant parameter. To investigate the physics behind the radial electric field inversion we have studied the behaviour of local plasma parameters: electron density, temperature and pressure. These local values are obtained from the radial profiles measured using the Thomson scattering diagnostic in the three sets of discharges. Experimentally it is observed that, in a given magnetic configuration and at fixed ECH power, the inversion in the radial electric field (from positive to negative) takes place by increasing the plasma density; however, local values of plasma density or plasma pressure do not show any clear trend when data measured in plasmas with different ECH power and in different magnetic configurations are merged. The same result is found for the local values of density or pressure gradients. On the other hand, ECH power modulation experiments indicate that the inversion in the radial electric field (from positive to negative) occurs as the electron temperature decreases. These observations point to plasma collisionality as a likely candidate to control the sign of the radial electric field. In fact, experiments performed in LHD show that the sign of the radial electric field is controlled by the plasma collisionality [11]. This conclusion is supported by the plasma discharges analysed in this work. Local values of plasma collisionality measured in plasmas with different ECH power and in the six magnetic configurations are shown in figure 5. Plasma collisionality is calculated as the average of the local values measured within the radial range 0.5<ρ<0.7. Plasmas with negative radial electric field are found to have higher collisionality than those having positive radial electric field. The plasma collisionality measured at the inversion time is comparable to that measured for $E_r < 0$. This result explains the dependence of the critical line-density on the ECH power (shown in figure 4.a): as the ECH power is increased the electron temperature rises (the collisionality decreases) and a higher plasma density is required to increase the collisionality to the critical value that triggers the radial electric field inversion.

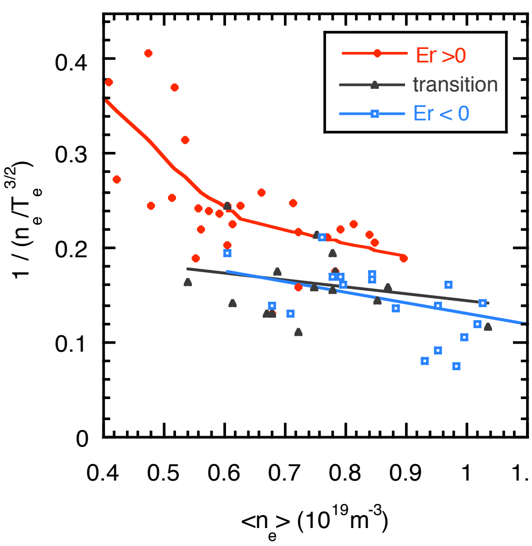

Figure 5: Plasma collisionality as a function of the line-density for plasmas heated with different ECH power and in the six different magnetic configurations. Plasmas with positive and negative radial electric field are represented in red and blue, respectively, while those in which the radial electric field transition is detected are shown in black.

The dependence of the critical density on the ECH heating power allows the study of the plasma response time during ECH power modulation experiments [12]. In these ECH power modulation experiments the temperature profile follows the power modulation frequency (360 Hz) while the density profile remains constant. The perpendicular velocity reverses following the ECH modulation in a time scale faster than 200 μs and in a wide plasma region, from the plasma edge up to ρ ≈ 0.6.

3. Conclusion

The behaviour of the perpendicular rotation velocity in the edge region of TJ-II plasmas has been studied in six different magnetic configurations, scanning both ECH power level and plasma density. The inversion in the perpendicular rotation velocity occurs when the line-averaged density reaches a certain critical value that depends on plasma conditions. The parametric dependence of the critical line-density on ECH power level and magnetic configuration characteristics shows a positive exponential dependence on EC heating power and a negative one on plasma radius; the dependence on rotational transform is weak and has low statistical meaning. Besides, analysis of local plasma parameters points to plasma collisionality as the parameter that controls the inversion of the perpendicular rotation velocity of the turbulence. This result explains the positive exponential dependence of the critical line-density on the ECH power. Further studies are needed to understand the dependence on the plasma radius.

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