Parametric Dependence of the Perpendicular Velocity Shear Layer Formation in TJ-II Plasmas

Luis GUIMARAIS, Teresa ESTRADA[1)], Enrique ASCASIBAR[1)], María E. MANSO, Luis CUPIDO,
Tim HAPPEL[1)], Emilio BLANCO[1)], Francisco CASTEJON, Rubén Jimenez-GOMEZ[1)],
María A. PEDROSA[1)], Carlos HIDALGO[1)], Ignacio PASTOR[1)] and Antonio Lopez-FRAGUAS[1)]
As. Euratom-IST, CFN, Instituto Superior Técnico, Lisbon, Portugal
[1)]*Laboratorio Nacional de Fusión. As. Euratom-CIEMAT, Madrid, Spain*

(Received 16 November 2007 / Accepted 29 February 2008)

In TJ-II plasmas, the perpendicular rotation velocity of the turbulence changes from positive to negative (from ion to electron diamagnetic direction) inside the Last Closed Magnetic Surface (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 a positive exponential dependence on heating power and a 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: radial electric field, perpendicular rotation, turbulence, reflectometry, stellarator

DOI: 10.1585/pfr.3.S1057

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 Last Closed Magnetic Surface (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, Heavy Ion Beam Probe (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]. As it is discuss in next section, 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, using microwave reflectometry. 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 $1.2 \times 10^{19}\,\mathrm{m}^{-3}$. 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 $1.0\,\mathrm{m}^3$). The rotational transform profiles are shown in Fig. 1, where lines of the same colour indicate similar $\iota/2\pi$-profiles, but different volumes. 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 $\iota/2\pi$-profile and/or the plasma volume can be scanned. These magnetic configurations

---

author's e-mail: teresa.estrada@ciemat.es

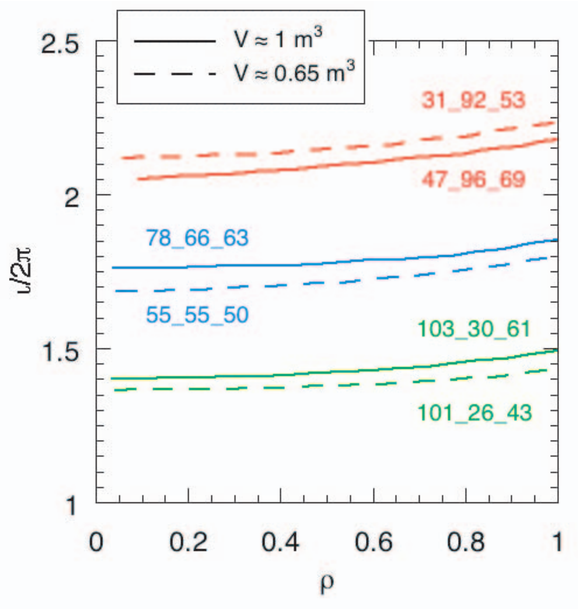

Fig. 1 Rotational transform profiles for the six selected magnetic configurations.

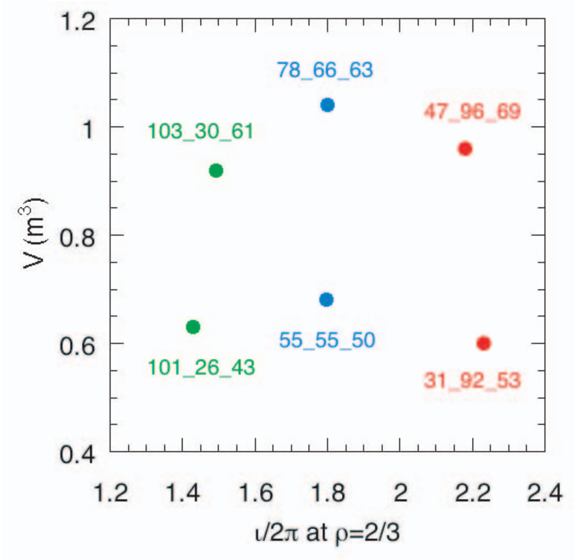

Fig. 2 Plasma volume as a function of the rotational transform at $\rho = 2/3$ for the magnetic configurations shown in Fig. 1.

were 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 [7] and the ion temperature measured by the charge-exchange spectrometer [8]. This data set (155 plasma discharges) reproduces the parametric dependence of the energy confinement time reported in [9]: the confinement improves with plasma density, plasma radius and rotational transform and degrades with heating power.

To monitor the inversion in the perpendicular rotation velocity we have used the broadband fast frequency hopping reflectometer designed for measuring plasma turbulence [10]. The main feature of the reflectometer is its possibility to be tuned to any selected frequency within a fraction of a millisecond. This property enables to probe several plasma layers within a short time interval during the discharge, permitting the characterization of the radial distribution of plasma fluctuations. The reflectometer works in the frequency band 33 - 50 GHz, in X-mode, covering the density range from about 0.3 to $1.5 \times 10^{19}\,\mathrm{m}^{-3}$, almost the whole density range of the TJ-II plasmas heated by ECH. However, due to the flat (or even hollow) ECH plasma density profiles, and due to the low radial gradient of the magnetic field, the radial range covered by the reflectometer is limited in most cases to normalized effective radius $\rho \geq 0.5$. During the magnetic configuration scan experiments, the reflectometer probing frequency was changed from 33 to 50 GHz every 50 ms in a staircase mode: 10 steps of 5 ms each.

The sign of the perpendicular rotation velocity of the turbulence can be resolved by the asymmetry of the turbulence spectra measured using the reflectometer. The reflectometer arrangement is such that when the perpendicular velocity of the turbulence is positive (in the ion diamagnetic direction) the mean frequency of the reflectometer signal spectrum is positive and vice-versa [4]. The perpendicular velocity of the turbulence is the sum of two components, the plasma $E \times B$-velocity and the phase velocity of the turbulence moving in the plasma frame. The separation of the two contributions is not simple. A possible way has been reported in Ref. [11], and requires the combination of theory, numerical simulations and experimental measurements. More frequently, and supported by the comparison between the experimental results obtained using reflectometry and those obtained by other methods, like for example spectroscopy [12], the phase velocity is assumed to be very small as compared with the $E \times B$-velocity and the radial electric field is obtained directly from the experiments. Similarly, HIBP measurements carried out in TJ-II experiments, support that the inversion in the perpendicular rotation of the turbulence is dominated by the change in the radial electric field sign [6]. Unfortunately HIBP measurements are not available in all the magnetic configurations explored in the present work; consequently, possible dependences (if any) of the phase velocity on the studied plasma parameters could give rise to different dependences of the critical density required for the radial electric field inversion as compared with the ones reported here.

Using the reflectometer measurements, we have classified the discharges in three groups attending to the perpendicular rotation velocity of the turbulence in the plasma edge region. 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;

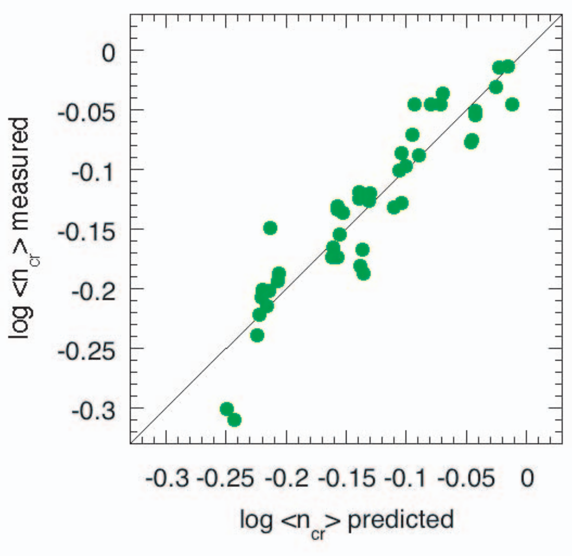

Fig. 3 Critical line-density values obtained experimentally versus the best fit found in the regression analysis, represented in a log-log scale.

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 $1 \times 10^{19}\,\mathrm{m}^{-3}$, 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, $<n_{cr}>$, on ECH power, P, plasma radius, a, and rotational transform, ι, assuming a factorial dependence:

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

where α_P, α_a and α_ι are the associated exponents that give the strength of the dependence of $<n_{cr}>$ on each variable, P, a and ι, respectively. The best fit that results from the regression analysis is shown in Fig. 3 and is given by:

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

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 Figs. 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 preliminary results obtained using Langmuir probes and reported in [13, 14]. 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

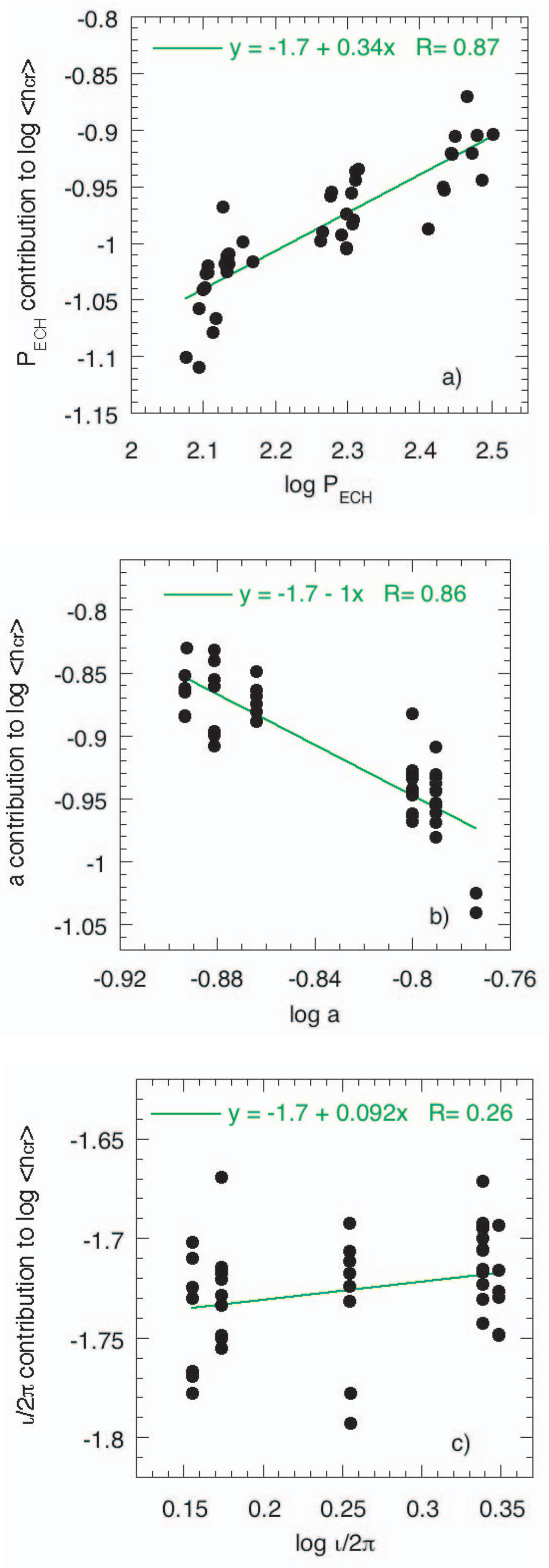

Fig. 4 ECH power (a), plasma radius (b) and rotational transform (c) contribution to the critical line-density, represented in a log-log scale. The linear fits reproduce the regression coefficients.

plasmas indicates that above the threshold density the particle confinement time improves considerably [15].

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 proves that line-density is not 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 [16]. 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 Fig. 5. Plasma collisionality is calculated as the average of the local values measured within the radial range $0.5 \leq \rho \leq 0.7$. 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 Fig. 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. The dependence of the critical density on the ECH heating power has allowed the study of the plasma response time during ECH power modulation experiments [17]. 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 $\rho \approx 0.6$.

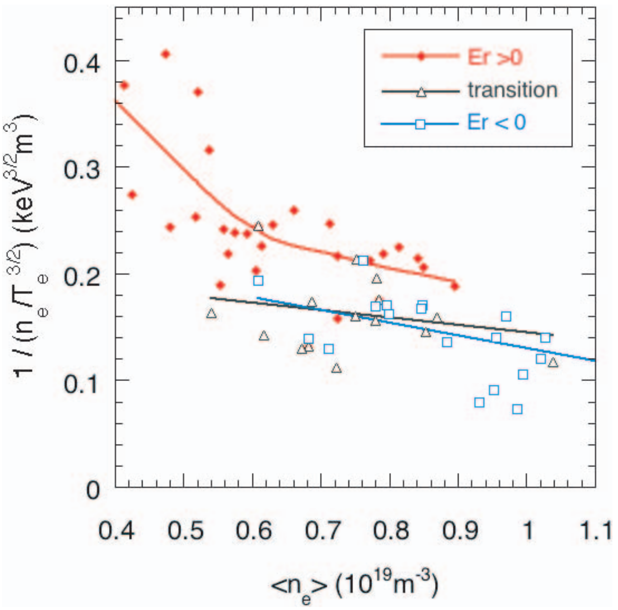

Fig. 5 Collision time as a function of the line-density for plasmas heated with different ECH power and in the six different magnetic configurations. Plasmas with positive and negative radial electric field are represented in red and blue, respectively, while those in which the radial electric field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

The inversion in the radial electric field as the plasma collisionality changes could be explained in terms of the different ion and electron collisional transport balance. Neoclassical calculations, reported in Ref. [18], show a remarkable dependence of the electron and ion diffusion coefficients on the plasma collisionality normalized to the bounce frequency, and show a critical collisionality value at which the ion flux surpasses the electron one, thus changing the radial electric field sign from positive in the electron root to negative in the ion root. The precise value of the critical collisionality depends on the specific plasma profiles and magnetic configuration considered in the calculations. Unfortunately, a direct comparison of the estimated critical collisionality with the dependences found experimentally is not straightforward, because neoclassical calculations are presently unavailable for the specific plasma conditions reported in this paper. Nevertheless, despite the interest of such comparison, one should take into account that the conditions for the validity of the standard neoclassical approach in TJ-II are hardly fulfilled in the outer plasma region ($\rho > 0.5$), since the typical radial excursions of the particles are large in comparison with the plasma gradient lengths and their kinetic energy is not conserved in presence of the electric field [19, 20].

Finally, the dependence of the critical line-density on the plasma radius (shown in Fig. 4 (b)) may be explained in terms of the different ion and electron transport balance as the magnetic ripple changes. In order to confirm this hypothesis, simulations using the code ISDEP (Integrator of Stochastic Differential Equations for Plasmas [20]) are planned for studying the ion collisional transport in magnetic configurations with different plasma radii.

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 ECH 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.

Acknowledgments

The authors would like to acknowledge the entire TJ-II team for their support during the experiments.

[1] C. Hidalgo, M.A. Pedrosa, L. García and A. Ware, Phys. Rev. E **70**, 067402 (2004).
[2] M.A. Pedrosa, C. Hidalgo, E. Calderón, T. Estrada, A. Fernández, J. Herranz, I. Pastor and the TJ-II team, Plasma Phys. Control. Fusion **47**, 777 (2005).
[3] J.A. Alonso, S.J. Zweben, P. Carvalho *et al.*, Plasma Phys. Control. Fusion **48**, B465 (2006).
[4] T. Estrada, E. Blanco, L. Cupido, M.E. Manso and J. Sánchez, Nucl. Fusion **46**, S792 (2006).
[5] B.A. Carreras, L. García, M.A. Pedrosa and C. Hidalgo, Phys. Plasmas **13**, 122509 (2006).
[6] A.V. Melnikov, J.A. Alonso, E. Ascasíbar *et al.*, Fusion Sci. Tech. **51**, 31 (2007).
[7] J. Herranz, I. Pastor, F. Castejón *et al.*, Phys. Rev. Lett. **85**, 4715 (2000).
[8] J.M. Fontdecaba *et al.*, Fusion Sci. Tech. **46**, 271 (2004).
[9] E. Ascasíbar, T. Estrada, F. Castejón, A. López-Fraguas, I. Pastor, J. Sánchez, U. Stroth, J. Qin and TJ-II team, Nucl. Fusion **45**, 276 (2005).
[10] L. Cupido, J. Sánchez and T. Estrada, Rev. Sci. Instrum. **75**, 3865 (2004).
[11] G.D. Conway, C. Angioni, R. Dux *et al.*, Nuclear Fusion **46**, S799 (2006).
[12] M. Hirsch, E. Holzhauer, J. Baldzuhn, B. Kurzan and B. Scott, Plasma Phys. Control. Fusion **43**, 1641 (2001).
[13] M.A. Pedrosa, C. Hidalgo, E. Calderón, J.A. Alonso, R.O. Orozco, J.L. de Pablos and TJ-II team, Czech. J. Phys. **55**, 1579 (2005).
[14] M.A. Pedrosa, C. Alejaldre, J.A. Alonso *et al.*, EX/P 6-21 IAEA (2004).
[15] V.I. Vargas, D. López-Bruna, J.M. Reynolds, T. Estrada and J. Guasp, *34th EPS Conference on Plasma Physics*, Warsaw, Poland (2007).
[16] K. Ida, M. Yoshinuma and M. Yokoyama *et al.*, Nucl. Fusion **45**, 391 (2005).
[17] T. Happel, T. Estrada, L. Cupido, E. Blanco, M.A. Pedrosa and R. Jiménez-Gómez, *8th International Reflectometry Workshop*, St. Petersburg, Russia (2007).
[18] V. Tribaldos, Phys. Plasmas **8**, 1229 (2001).
[19] V. Tribaldos and J. Guasp, Plasma Phys. Control. Fusion **47**, 545 (2005).
[20] F. Castejón, L.A. Fernández, J. Guasp, V. Martín-Mayor, A. Tarancón and J.L. Velasco, Plasma Phys. Control. Fusion **49**, 753 (2007).