IAEA nuclear fusion

PAPER

Investigation of rotation at the plasma edge in TCABR

To cite this article: J.H.F. Severo *et al* 2015 *Nucl. Fusion* **55** 093001

IOP Publishing | International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion 55 (2015) 093001 (7pp) doi:10.1088/0029-5515/55/9/093001

Investigation of rotation at the plasma edge in TCABR

J.H.F. Severo[1], G. Ronchi[1], R.M.O. Galvao[1], I.C. Nascimento[1], Z.O. Guimaraes-Filho[1], Yu.K. Kuznetsov[1], M.F.F. Nave[2], A.M. Oliveira[1], F. do Nascimento[1] and M. Tendler[3]

[1] Plasma Physics Laboratory, Institute of Physics, University of São Paulo, Brazil
[2] Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, 1049-001 Lisbon, Portugal
[3] Royal Institute Technol. Alfven Lab., Stockholm, Sweden

E-mail: jhsevero@if.usp.br

Received 19 December 2014, revised 14 May 2015
Accepted for publication 15 May 2015
Published 30 July 2015

Abstract

This paper summarizes experimental results from recent studies on intrinsic rotation at the plasma edge of the TCABR tokamak. These results were obtained after upgrading the number of channels of the rotation diagnostic to three. The measurements were carried out in the collisional (Pfirsch–Schluter) regime and the rotation profiles of the ions were obtained from the Doppler shifts of the impurity carbon lines, CIII (464.74 nm), and CVI (529.06 nm). Results on the correlation between toroidal rotation at the plasma edge and direction of gas injection are also presented. They indicate that the direction of gas injection has a small effect on rotation; the velocity of the background neutral hydrogen is affected by direct momentum transfer from the injected gas (also hydrogen), while the carbon ions' velocity is affected by inward radial friction force between the injected gas atoms and ions, increasing their velocity in the opposite sense of the plasma current.

Keywords: plasma rotation, diagnostic, spectroscopy

(Some figures may appear in colour only in the online journal)

1. Introduction

Poloidal and toroidal rotation play an important role in the energy and particle transport and can suppress magneto-hydrodynamic (MHD) instabilities in toroidal magnetic configuration systems [1, 2]. In general, turbulence suppression and consequently improvement of heat and particle transport appear when there exists a $\mathbf{E} \times \mathbf{B}$ shear of poloidal rotation. On the other hand, toroidal rotation can contribute to MHD stabilization, in particular resistive-wall and neoclassical tearing modes if some level of rotation is achieved. In spite of extensive investigation of plasma rotation in the last two decades, toroidal rotation still attracts considerable attention due to its relevance in present and future large tokamaks. Indeed, for the stabilization of resistive-wall modes, it is well know that there exists a threshold on the toroidal rotation velocity. However, in reactor-size devices its value is expected to be below the threshold due to ineffectiveness of external angular momentum input by neutral-beam injection (NBI). Therefore, it is very important to understand the physical mechanisms responsible for plasma rotation, in order to predict the plasma behavior, in reactor machines. Considerable effort has been expended to identify the sources and sinks of the intrinsic toroidal rotation [3]. Recently, non-ambipolar flux and parallel viscosity have been recognized as having an important role in the determination of the rotation level. Mechanism such as turbulence, ion temperature gradient modes [4], ion orbit loss [5], and friction with neutrals [6] were also investigated. The DIII-D results for rotation at zero neutral beam (NB) torque show the existence of anomalous torque with magnitude equivalent to that obtained with NBI [7]. Also in the TEXTOR tokamak, two tangential neutral beam injectors providing different initial plasma rotation velocities, both co- and counter-rotating, were used to investigate the relation between plasma rotation and mode excitation [8].

According to the standard understanding, intrinsic or spontaneous rotation of the plasma is that observed without external momentum input. In tokamaks, intrinsic counter-current rotation is frequently observed in ohmic discharges. However, in some machines [9–12], co-current rotation is also observed at the plasma edge. In addition to the models that assume that momentum might be generated by the turbulence, during gas injection the radial friction force between neutral particles and ions/electrons, taking into account the poloidal magnetic field, may also drive toroidal rotation. If the neutral particle velocity is much larger than the diffusion velocity of ions/electrons, the friction force is in the radial direction (outward), leading to co-current rotation.

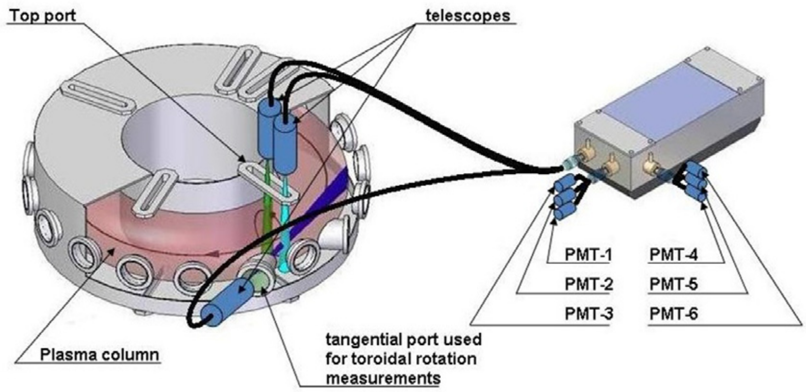

Figure 1. Experimental setup used for temporal evolution measurements of the poloidal and toroidal impurity rotation velocity in the TCABR tokamak.

In this work, the dependence of rotation on gas injection direction is investigated in experiments carried out in the TCABR tokamak. The diagnostic is described in section 2. The motivation for this investigation is outlined in section 3. The experimental results are presented in section 4. Discussions and conclusions are given in sections 5 and 6, respectively.

2. Diagnostic

The plasma rotation measurements were performed in the TCABR tokamak, which is a small machine with the following parameters: minor radius $a = 0.18$ m, major radius $R = 0.61$ m, toroidal magnetic field 1.1 T, discharge current 100 kA, line integrated density (1–4.5) $\times$ 10^{19} m^{-3}, $T_e(0) \simeq 600$ eV, $T_i(0) \simeq 200$ eV. The duration of the stationary phase of the discharge is about 60 ms. The rotation velocity was measured using quite an original spectroscopic method [10], which allows the measurement of poloidal and toroidal velocity components with up to 10 mm of spatial resolution and temporal resolution of 600 Hz. This diagnostic was upgraded and the same technique based on the ratio of two different parts of the same spectral line, used in [10], is now applied in with a new monochromator. The scheme is based on determining the ratio between two different parts of the same impurity emission line. These parts are directed to two different detectors installed at the exit slits of the monochromator, as indicated in figure 1.

The light from the plasma is collected and transmitted to the entrance slit of the monochromator through an optical fiber. Inside the monochromator, using a semi-transparent mirror, the light is divided into two parts and directed to the photomultipliers located at the exit slits. The lateral exit slit selects the left part (area A_L in figure 2) of the spectral line profile and the axial slit the right part A_A. In the presence of plasma rotation, the center of the spectral line moves to the right or left, changing the ratio $R = A_L/A_A = R(\Delta\lambda)$, which is proportional to the plasma rotation. Here $\Delta\lambda$ is the Doppler shift of spectral line.

In the current measurements, we have upgraded the diagnostic used in [10] by increasing the number of channels to three, making it possible to measure simultaneously the temporal evolution of poloidal and toroidal rotation velocities.

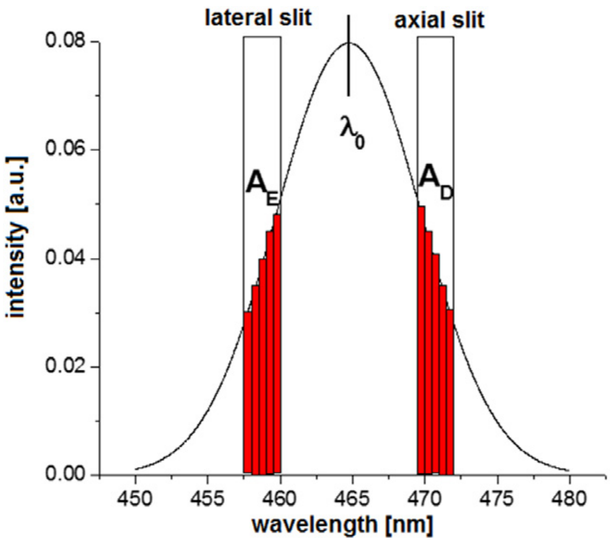

Figure 2. Schematic representation of the spectral profile of the spectral line.

As can be seen from figure 1, the central telescope collects light from the central part of plasma column where the poloidal component of velocity is approximately zero. This channel can be used to check possible changes in the signal ratio not related to plasma rotation, for example changes caused by room temperature variations. However, even considering that the poloidal component of velocity may be not equal to zero at the center of the plasma column, this effect does not introduce an error within the current diagnostic resolution. Recently, in ASDEX Upgrade a strong antisymmetry was observed in the parallel flows between the low-field and high-field sides, suggesting that the poloidal component is not zero at the plasma center, once the flow velocities on a flux surface must have a specific structure in order to provide zero divergence [13]. However, even considering that the poloidal velocity may not vanish at the center of the plasma column, this effect does not introduce systematic error within the current diagnostic resolution.

In the current series of measurements, the rotation velocity in the TCABR tokamak was obtained using a new f/4.7 Czerny-Turner optical monochromator (MacPherson 207),

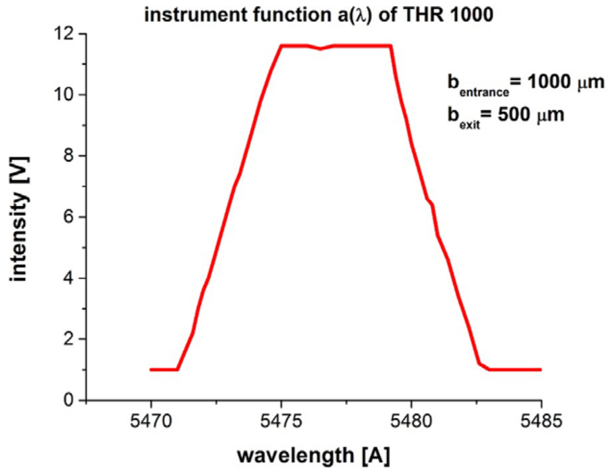

Figure 3. Instrument function $a(\lambda)$ of monochromator THR 1000 used for plasma rotation measurements in [10], for the entrance and exit slit widths equal to 1000 and 500 μm, respectively.

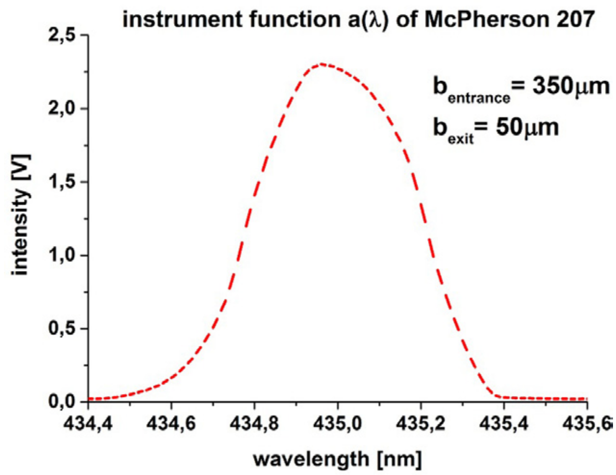

Figure 4. Instrument function $a(\lambda)$ of monochromator McPherson 207 used for plasma rotation measurements in the TCABR tokamak for the entrance and exit slit widths equal to 350 and 50 μm, respectively.

which employs a commercial grating with a 1200 g mm^{-1} and six R6060-2 (Hamamatsu) photomultipliers installed at the exit slits. The monochromator has 700 mm focal length and inverse dispersion of 1.24 nm mm^{-1}. The instrument function of the THR 1000 used previously [10] is trapezoidal, different from the one used in the current measurements, which is Gaussian. This is indicated in figures 3 and 4.

Data acquisition was carried out using NI PXI5105 digitizers from National Instruments with an acquisition rate up to 60 MSamples/s and 12 bits resolution. For more details of the data acquisition system see [14].

3. Investigation on intrinsic rotation

According to the theory presented in [15, 16], for partially ionized plasmas, friction between ions and neutral particles R_{iN} causes drift of ions in the $\mathbf{R}_{\mathrm{iN}} \times \mathbf{B}$ direction. In the TCABR tokamak case, the velocity of neutral particles is of order 10^3 m s^{-1} while the ions/electrons have diffusion velocities of about 10 m s^{-1}, which produces an outward radial friction force that can drive co-current rotation. The electron temperature in the SOL is of order 10 eV, so that the neutral gas atoms can penetrate into the plasma column for a short time before being ionized, therefore producing co-current rotation. Actually, a rough estimate for ionization time in the TCABR, where electron temperature is of the order 10 eV and density 10^{18} m^{-3}, is 10^{-4} s. For this ionization time, neutral particles can travel a distance of about 10 cm. To investigate this possible mechanism of generation of co-current rotation, we carried out an experimental program for measuring the toroidal rotation at the plasma edge for outboard poloidal gas injection. In this position the gas was injected in three different directions, i.e. radial, co and counter current (see figure 5). We expect that if the friction between ions and neutral particles cannot produce an ion drift then the ratio $V_{\mathrm{co-rotation}}/V_{\mathrm{radial}} \geqslant 1$, because there is a probability of momentum transfer from the neutral gas to CIII ions, and $V_{\mathrm{counter\text{-}rotation}}/V_{\mathrm{radial}} \leqslant 1$ due the loses of CIII momentum during collisions.

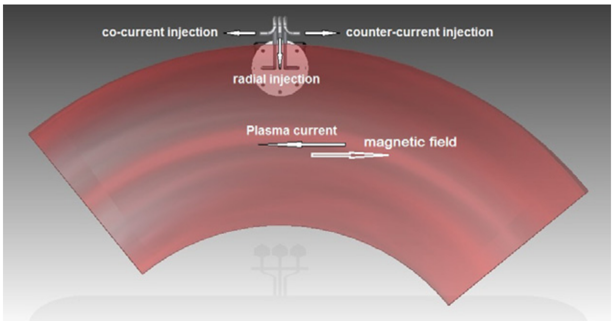

Figure 5. Schematic representation of the gas injection in the TCABR plasma column.

We also investigated the influence of direction of gas injection on hydrogen using the Halpha emission. In this case, a drift cannot be observed because there is no charge and $\mathbf{R}_{N,N} \times \mathbf{B} = \mathbf{0}$. Therefore, we expect $V_{\mathrm{co-rotation}}/V_{\mathrm{radial}} \geqslant 1$ and $V_{\mathrm{counter-rotation}}/V_{\mathrm{radial}} \leqslant 1$ by the same reasons that were pointed out above.

4. Results

Here we present some results of toroidal and poloidal rotation velocities obtained in this research. The measurements were carried out in the collisional regime (Pfirsch–Schluter) using the Doppler shift of the Halpha (656.28 nm) and carbon lines, CIII (464.74 nm) and CVI (529.06 nm). The temporal evolution of the main parameters of the reference discharge used in this campaign is shown in figure 6.

Figures 7 and 8 show the brightness and emissivity of CIII and CVI carbon spectral lines. To reconstruct the rotation profile, an inverse technique was employed assuming that the impurity emissivity has a Gaussian shape and determining its parameters by a least-squares fit of the experimental data. The adjusted emissivity profile is then used to calculate the brightness (blue dashed line in figures 7 and 8) and to check the quality of the fit.

Figures 9 and 10 show the line integrated and radial rotation profiles for CIII and CVI. The inversion technique

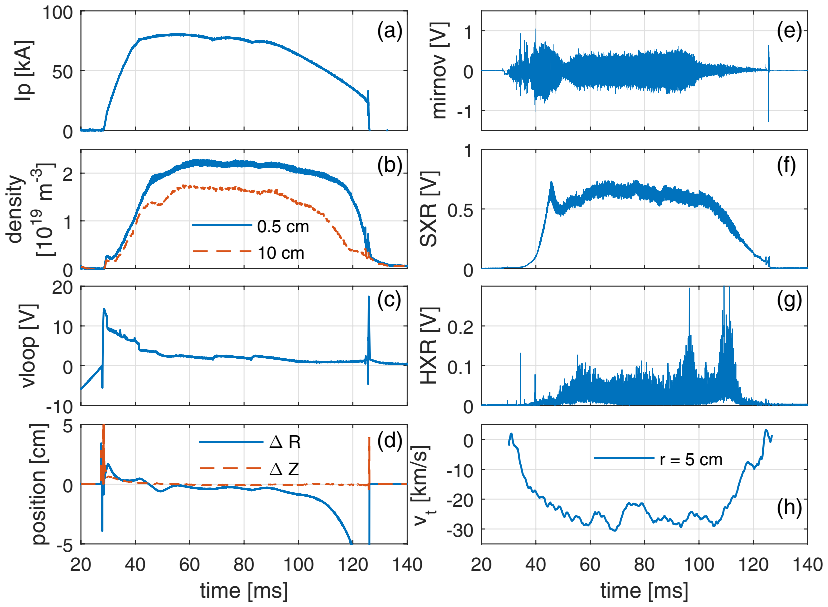

Figure 6. Temporal evolution of the main parameters of the reference discharge 30 464 of TCABR; (*a*) plasma current I_p; (*b*) line density at two viewing chords of the interferometer ($r = 0.5$ cm and $r = 10$ cm); (*c*) loop voltage; (*d*) radial (Δr) and vertical (Δz) displacements of the magnetic axis; (*e*) MHD signal; (*f*) central soft x-ray emission; (*g*) hard soft x-ray emission; (*h*) CVI toroidal rotation velocity measured at $r = 5$ cm.

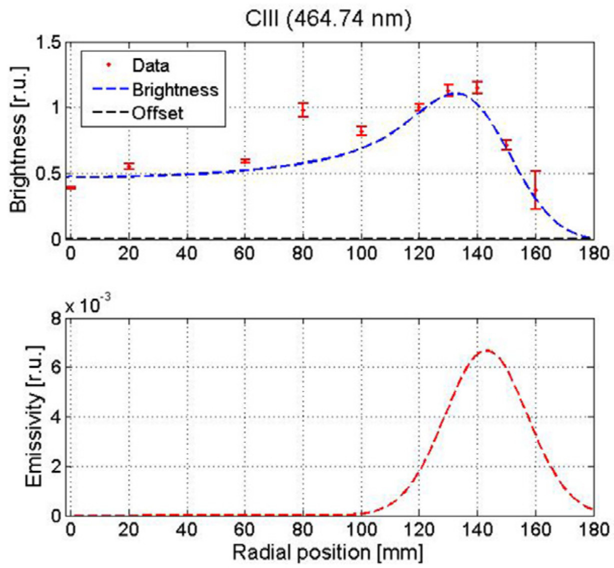

Figure 7. Top: brightness of CIII spectral line (blue line) adjusted to experimental data (red points with error bar). Bottom: emissivity of CIII spectral line (red line).

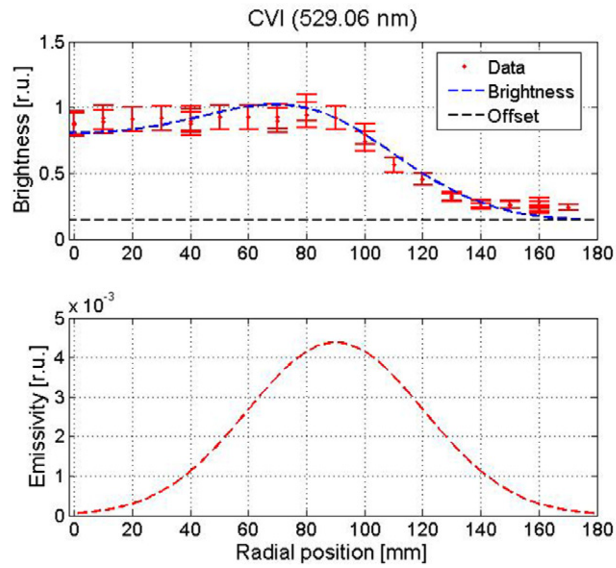

Figure 8. Top: brightness of CVI spectral line (blue line) adjusted to experimental data (red points with error bar). Bottom: emissivity of CVI spectral line (red line).

used in this paper was the same as in [10] e.g. it was assumed that the plasma velocity has the following profile $V(r) = C_0+C_1r+C_2r^2+C_3r^3$, where C_0, C_1, C_2 and C_3 are parameters determined by least-square fit of the experimental data.

In these graphics, positive poloidal velocity represents rotation in the diamagnetic electron drift direction while positive toroidal velocity represents the same direction of the plasma current, that is, co-current direction. As it can be observed from these figures, the rotation velocity of the CIII seems to exhibit, in TCABR, a small shear in the poloidal and toroidal components at plasma edge. We also note that in this region the CIII and CVI impurity ions rotate in opposite directions. Of course, the uncertainties in the measurements are too large to confirm the presence of shear, so that the rotation velocity at plasma edge must be investigated in greater detail. In these figures we also show the confidence interval in the inverse process.

Figure 11 shows the temporal evolution of line integrated measurements of poloidal and toroidal velocities of the background neutral gas, measured using H_α (656.28 nm) spectral line. According to the theory, if viscosity is not too strong to stop neutral particles, they must rotate together with the plasma at the edge [15, 16]. These results show that the

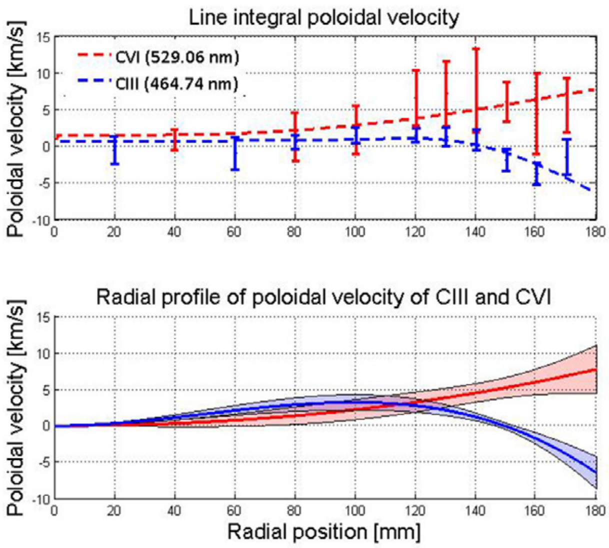

Figure 9. Top: line integrated radial profile of poloidal rotation velocities of CIII (blue) and CVI (red). Bottom: radial profile of poloidal rotation of CIII (blue) and CVI (red).

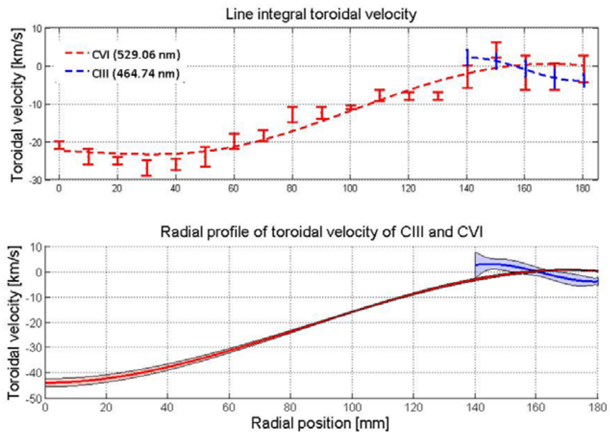

Figure 10. Top: line integrated radial profile of toroidal rotation velocities of CIII (blue) and CVI (red). Bottom: radial profile of toroidal rotation of CIII (blue) and CVI (red).

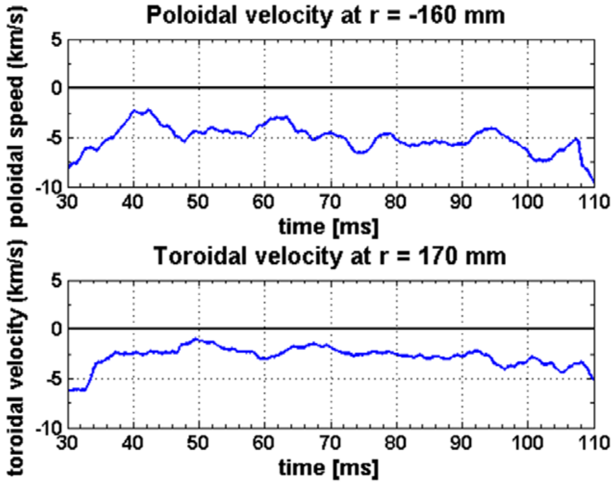

Figure 11. Temporal evolution of the poloidal and toroidal component of the background neutral gas velocity for radial gas injection. The measurements were carried out using the H_α spectral line.

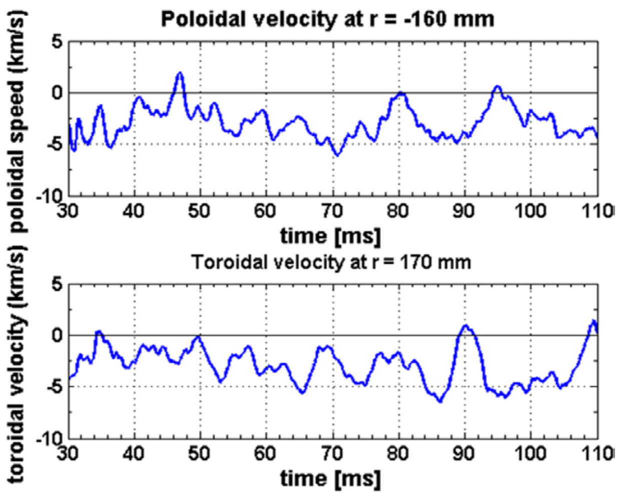

Figure 12. Temporal evolution of the poloidal and toroidal component of CIII velocity for radial gas injection. The measurements were carried out using the CIII (464.74 nm) spectral line.

neutral gas exhibits a rotation velocity of the same order of the CIII ions, which is shown in figure 12. These velocities are in the direction opposite to the diamagnetic electron drift for the poloidal component and in the counter-current direction for the toroidal component. Figure 12 shows also the temporal evolution of line integrated measurements of poloidal and toroidal velocities of the CIII (464.74 nm) spectral line. As can be observed from this figure, the level of oscillation in time is higher than that of Halpha, which is probably related to location the peak concentration of CIII ions excited hydrogen atoms i.e. the Halpha emission is located in SOL while the CIII ions is located inside of plasma column (see figure 7).

Figure 13 shows the ratio of the value of the background gas toroidal velocity, when gas is injected opposite to CIII ions velocity (counter-rotation) to that obtained for radial gas injection. Figure 14 show the same ratio for co-rotation to radial gas injection. The results suggest that the value of neutral gas rotation decreases when the gas is injected in the opposite to CIII ions rotation and increases when the gas is injected in the opposite direction with respect to the value for radial gas injection.

Figure 15 shows the ratio of the value of the CIII ions toroidal velocity for counter-rotation to that obtained for radial gas injection. Figure 16 shows the same ratio for co-rotation to radial gas injection. The results shown in the figure 16 suggest that the rotation of the CIII ions is substantially smaller when gas is injected in the same direction of rotation than that when gas is injected in the radial direction. This result is completely different that observed for neutral gas. On the other hand, figure 15 shows that for co-rotation injection no correlation with the direction of gas injection is observed; indeed in this case 50% of the data shows $V_{\mathrm{co-rotation}}/V_{\mathrm{radial}} \geqslant 1$.

5. Discussions

The results obtained for the dependencies of the toroidal rotation of excited hydrogen atoms and CIII impurity, close

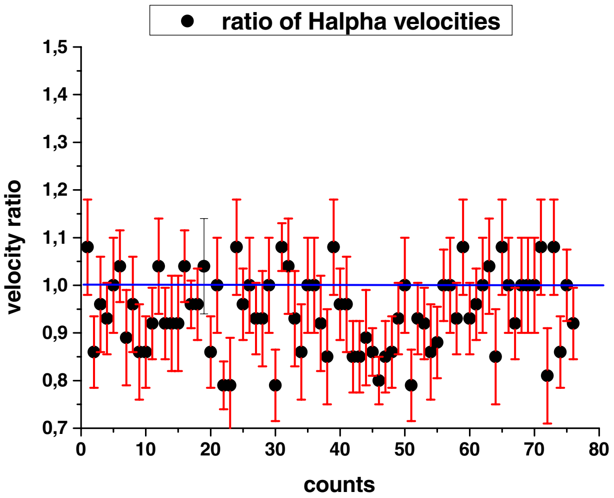

Figure 13. Ratio of the values of the background neutral gas toroidal velocity obtained for counter-rotation and radial gas injection.

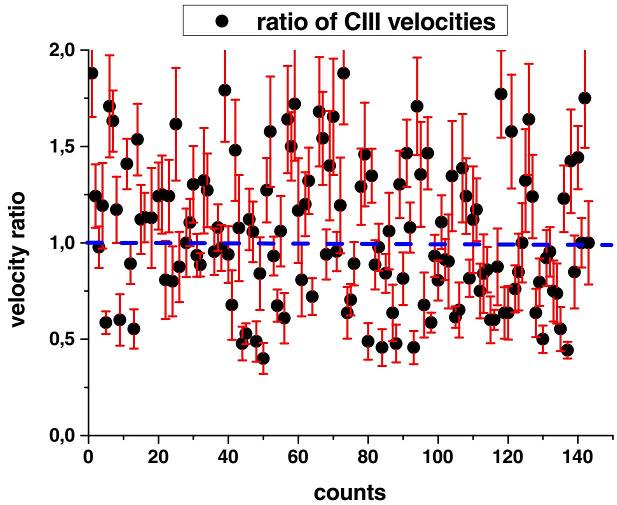

Figure 15. Ratio of the values of the CIII toroidal velocity obtained for counter-rotation to that for radial gas injection.

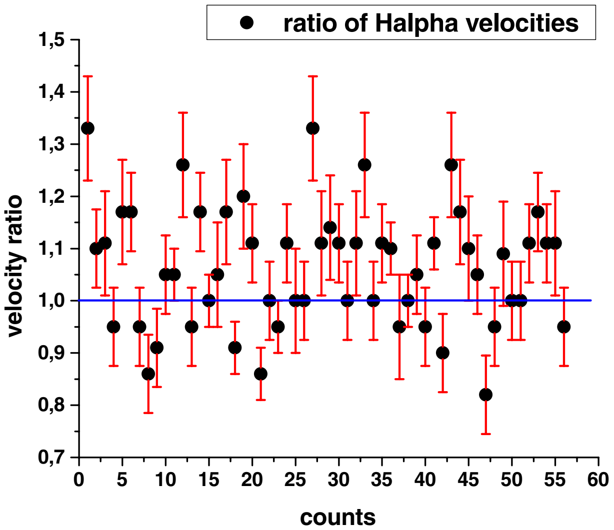

Figure 14. Ratio of the values of the background neutral gas toroidal velocity obtained for co-rotation and radial gas injection.

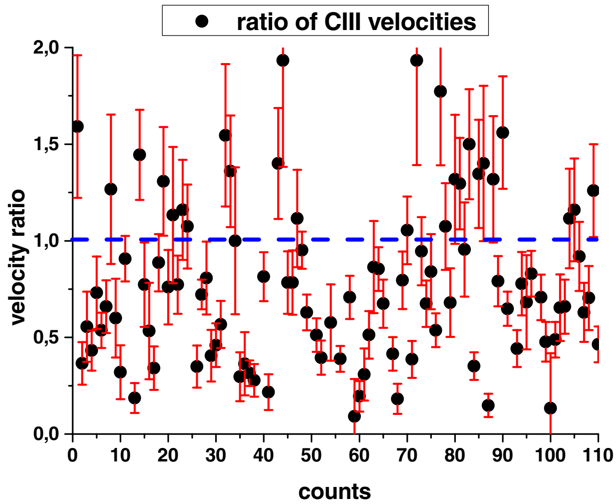

Figure 16. Ratio of the values of the CIII toroidal velocity obtained for co-rotation to that for radial gas injection.

to the plasma edge, on the direction of flow of the injected gas can be qualitatively understood in terms of the model discussed by Rozhansky [15, 16], assuming that the gas in the scape-off-layer is not fully ionized and that the neutral gas density is not large enough to be considered constant. In this case, if viscosity is not large enough to stop the neutral atoms, they tend to be dragged by the ions. Indeed, as shown in figures 11 and 12, the toroidal velocities of the H* excited atoms and CIII ions are about the same, both with values close to 3 km s^{-1}, in spite of the somewhat larger temporal fluctuations observed in the velocity of the ions, which are concentrated more inside the plasma. In this case, the effect of direction of flow of the injected gas on the background neutral atoms is just simple momentum transfer. The H_2 molecules are injected at the velocity close to the thermal speed, around 2 km s^{-1}, and, since the injection tube has a large length to diameter ratio, the gas beam profile is much narrower than the standard cosinusoidal effusive beam profile. Then, if the injected gas flow is in the direction of rotation of the plasma ions (here we assume, without proof, that the CIII ions rotate in the same direction of the main plasma ions), the average velocity of the background neutral atoms increases; otherwise decreases. The situation with respect to the CIII ions is quite different. Again, according to the model of Rozhansky, the main physical mechanism is the friction between the injected neutrals and the ions, which cause a $\mathbf{R}_{iN} \times \mathbf{B}$ drift on the latter, where $\mathbf{R}_{iN}$ is the ion-neutral collisional force. TCABR operates with the plasma current opposite to the toroidal magnetic field. Due to collisions, the injected neutrals atoms cause a radial inward force on the outward diffusing ions. The cross product of this force with the poloidal magnetic field causes a drift in the direction of the toroidal field, which is precisely a drift in the direction of flow of the CIII ions close to the plasma edge. Therefore, we expect the toroidal velocity of the CIII ions to increase for radial gas injection and to be not much affected for injection in the toroidal direction. This is indeed statistically verified from the ratio of values of the toroidal velocity obtained for co-rotation and radial gas injection, as shown in figure 16. The same result is not clearly seen for the same ratio of the values obtained for counter-rotation and radial gas injection, as shown in figure 15. The reason for this discrepancy is not yet clear to us.

6. Conclusions

We presented in this work some results of impurity rotation at the plasma edge of the TCABR tokamak. The main results of this work are the investigation of the dependence of the toroidal rotation of neutral hydrogen and CIII at the plasma edge on the direction of hydrogen gas injection. They show that the neutral hydrogen and CIII have different behaviors, depending on the direction of gas injection. The hydrogen velocity is increased when gas is injected in the same direction of rotation which is consistent with direct momentum transfer from the gas atoms to the excited hydrogen atoms that rotate with the plasma ions. On the other hand, the CIII velocity is decreased for co-rotation injection which is consistent with the existence of an inward radial friction force that increases the rotation in the direction of the plasma ions.

In conclusion, in this work we investigated the relationship between impurity rotation and direction of gas injection. Of course, we realize that, for tokamak reactor-size machines, the most relevant question is not this, but principally to identify the sources and sinks of toroidal rotation of the main ionic components, and there are reasons to believe that the measured CIII velocity might differ from that of the plasma ions [17]. Nevertheless, we believe that, at least close to the plasma boundary, our results provide relevant information for pinning down one of the possible mechanisms related to the sources and sinks of spontaneous toroidal rotation.

Acknowledgments

This work was supported by the Research Support Foundation of the State of São Paulo FAPESP (procs: 10/50496-4, 14/13296-8 and 11/50773-0).

References

[1] Doyle E.J. *et al* 2007 Progress in the ITER physics basis chapter 2: plasma confinement and transport *Nucl. Fusion* **47** S18
[2] Hender T.C. *et al* 2007 Progress in the ITER physics basis chapter 3: MHD stability, operational limits and disruptions *Nucl. Fusion* **47** S128–202
[3] de Grassie J.S. 2009 *Plasma Phys. Control. Fusion* **51** 124047
[4] Peeters A.G. *et al* 2006 *Plasma Phys. Control. Fusion* **48** B413
[5] Yoshida M. *et al* 2007 *Nucl. Fusion* **47** 856
[6] Honda M., Takizuka T., Fukuyama A., Yoshida M. and Ozeki T. 2009 *Nucl. Fusion* **49** 035009
[7] Solomon W.M. *et al* 2009 *Nucl. Fusion* **49** 085005
[8] De Bock M.F.M. *et al* 2008 *Nucl. Fusion* **48** 015007
[9] Severo J.H.F. *et al* 2003 *Nucl. Fusion* **43** 1047
[10] Severo J.H.F. *et al* 2009 *Nucl. Fusion* **49** 115026
[11] Onchi T. *et al* 2013 *Plasma Phys. Control. Fusion* **55** 035003
[12] Kaveeva E. *et al* 2008 *Nucl. Fusion* **48** 075003
[13] Putterich T., Viezzer E., Dux R., McDermott R.M. and The ASDEX Upgrade Team 2012 *Nucl. Fusion* **52** 083013
[14] Ronchi G., Severo J.H.F., Sá W.P. and Galvao R.M.O. 2015 *J. Phys.: Conf. Ser.* **591** 012007
[15] Rozhansky V. 2013 *Phys. Plasma* **20** 101614
[16] Rozhansky V.A. 2008 *Reviews of Plasma Physics* vol 24 ed V.D. Shafranov (Berlin: Springer)
[17] Stacey W.M. and Grierson B.A. 2014 *Nucl. Fusion* **54** 073021