*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.173 (2004)*

Toroidal rotation of protons and impurities in the TJ-II stellarator: ECRH heating versus unbalanced NBI

D. Rapisarda, B. Zurro, A. Baciero, K. J. McCarthy, C. Fuentes, M. Liniers, J. Guasp and V. Tribaldos

Laboratorio Nacional de Fusión por Confinamiento Magnético, Asociación EURATOM / Ciemat para Fusión, Madrid, Spain.

Introduction. The measurement of toroidal rotation has become an important goal in fusion plasmas for several reasons. First, it enters into the basic equation for deriving the radial electric field when using spectroscopic techniques. Second, there exists evidence that rotation, stability and confinement are not independent. Third, moment confinement is an interesting topic, in particular when external sources of momentum, such as neutral beam injection are involved.

Whereas both poloidal and toroidal velocities have been measured simultaneously in tokamak devices, mainly using charge-exchange recombination spectroscopy, few toroidal rotation measurements have been reported for stellarator devices [1, 2]. The main reasons for this are: 1) it is assumed often to be negligible due to the higher toroidal ripple of these devices, and 2) it can be difficult to set up a geometry of observation to perform absolute measurements due to their more cumbersome geometry.

Although the measurement of main ion rotation is widely recognized as being important, the approaches employed in few attempts that have been made to do so [3-5] are often device dependent and cannot be easily implemented in other machines. In this work we extend the method previously used for proton poloidal rotation [6], while adding a method for calibration of absolute velocities, to the problem of measuring toroidal rotation in TJ-II and we present measurements for protons and impurity ions, made in ECRH and unbalanced NBI heated plasmas, obtained by this passive spectroscopic method.

Experimental. The impurity toroidal rotation has been measured in the TJ-II heliac by determining the line-shift of selected impurity lines (C V 2271 Å, He II 4668 Å, C III 2296 Å) while proton rotation was deduced from the analysis of H_α emission; note that in all cases the plasma line emission was monitored through a central plasma chord tangential to the magnetic axis. For this, we used a 1 m spectrometer equipped with an intensified photodiode array to record the spectral line shapes with a moderate time resolution (~15–30 ms), this being mainly limited by the photon flux available in these clean boronized discharges. Also, the plasma emission was relayed by means of 1 mm diameter fibres to the spectrometer which was fitted with a 1200 l/mm grating to provide a reciprocal dispersion of ~7.9 Å/mm.

The toroidal position used for these measurements was well away from the neutral beam injector while being close to the spectrometer. A 2 m quartz fibre with two branches was used, one branch collecting the plasma emission and the other relaying the emission from a hollow cathode lamp used to perform absolute wavelength calibrations and to determine instrumental widths in real time. The reference lines for these calibrations included Ne I, Cd I and Cd II lines.

Results and discussion. We present here the first results obtained in plasmas heated by ECR alone and with different magnetic configurations and electron densities. The examples selected here represent typical behaviour from a larger number of discharges investigated. First, it is found that the protons have a wide range of toroidal velocities that depend on the effective radius. The analysis method used was based on a three components gaussian fitting of the H_α spectral line at 6562.8 Å.

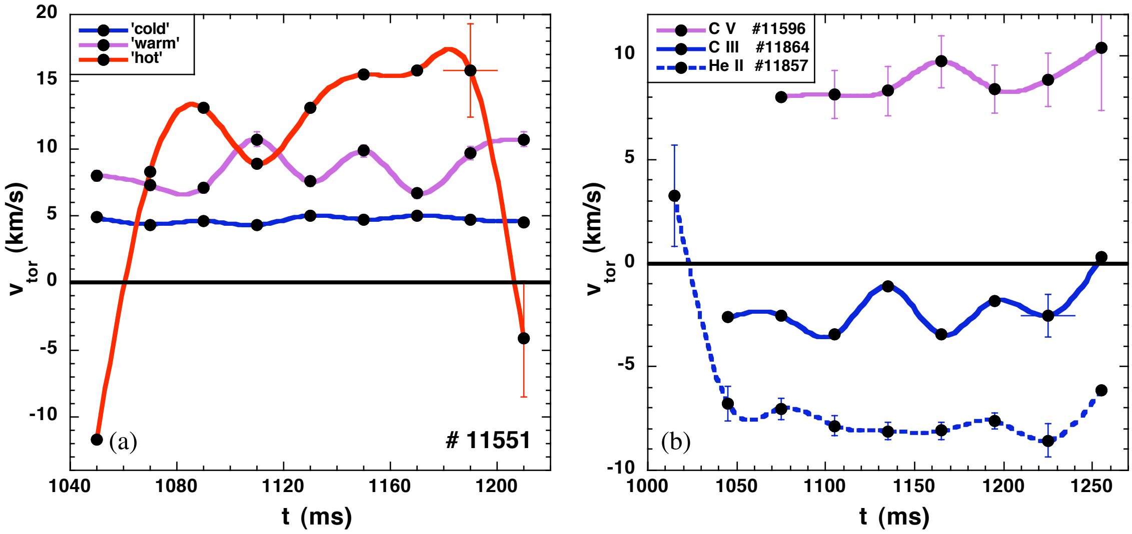

***Figure 1.** a) Toroidal rotation velocities from H_α emission, with an exposure time of 20 ms. Discharge #11551. b) Toroidal rotation velocities for three impurities, C V (ρ≈0.5), C III and He II (most external impurities), with exposure times of 30 ms. Positive values indicate co-magnetic field direction, negative values indicate counter-magnetic field direction.*

In Fig. 1 (a), we present the results obtained from a ECRH discharge made in the TJ-II standard configuration (100-44-64) with n_e ~$0.4 \cdot 10^{19}$ m^{-3} . By interpreting the Doppler shift of the line centre as a pure rotation, the 'cold' component, corresponding to hydrogen atoms from the plasma boundary, exhibit a rotation of 4.7 km/s in the magnetic field direction. The 'warm' component shows a rotation which is a factor 2 greater than the former, whereas the 'hot' component, representing the bulk plasma centre, reaches toroidal rotation values of about 14 km/s. See Fig. 1 (b) where the results are plotted for three different impurity ions from several similar discharges, with exposure times of 30 ms. The toroidal rotation velocity from C V 2270.89 Å line, belonging to a plasma zone about ρ = 0.5, is similar to the H_α 'warm' component (8 km/s). For the boundary, analysis of C III 2296.871 Å and He II 4685.7 Å lines show that these impurities rotate in the counter-magnetic field direction with velocities from about -3 to -8 km/s, respectively.

In the following examples, the plasma is heated initially by electron cyclotron heating and later sustained by tangential unbalanced neutral beam injection. Fig. 2 (a) shows the typical toroidal rotation behaviour of the main plasma ions during neutral beam injection, which takes place between the dashed vertical lines. The inner 'hot' H_α component shows a more dramatic reduction in toroidal velocity than the 'warm' component, this probably being due to the increase in electron density and a peaking of its profile. In contrast, the plasma boundary doesn't show any effect.

Also, the plasma centre (red line) even changes its rotation direction, i.e. to the counter-magnetic field direction.

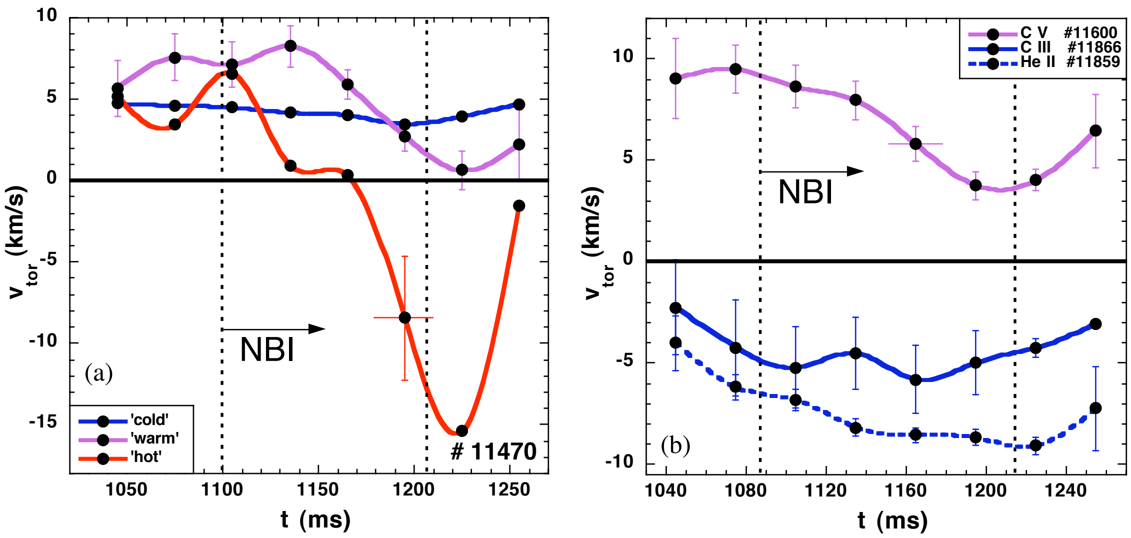

Figure 2. *a) Toroidal rotation velocities from H_α emission, with an exposure time of 30 ms. Discharge #11470. b) Toroidal rotation velocities from three impurities, C V (ρ≈0.5), C III and He II (most external impurities), with 30 ms time resolution.*

For bulk impurities the qualitative dependence is the same. Indeed C V shows rotation values that are in good agreement with the 'warm' proton component. Most external impurities, such as He II and C III show typical ECRH behaviour.

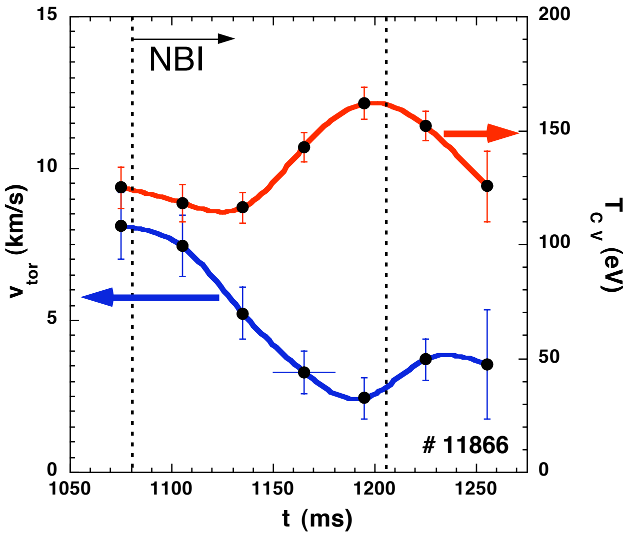

Figure 3. *Temperature (eV) and toroidal rotation velocity behaviour from C V emission, with neutral beam injection heating (discharge #11866). The exposure time was 30 ms.*

The simultaneous effect of neutral beam injection on C V ion rotation (blue line) and ion temperature (red line) is shown in Fig. 3 (red line). Note that the density increases from ~$6\cdot10^{18}$ m^{-3} before injection to ~$2.5\cdot10^{19}$ m^{-3} after the NBI pulse, whilst the rotation (blue line) decreases to ~2.5 km/s. In contrast, the ion temperature, as deduced from the C V line width, increases from 120 to 160 eV with neutral heating. After NBI, the temperature decreases and rotation experiences a small recovery due to the density fall when the discharge finishes.

In conclusion, we have measured proton and impurity toroidal rotation in ECRH and NBI plasma discharges using a spectroscopic method with absolute calibration in real time. Central ions: C V, hot and warm protons tend to rotate in the toroidal magnetic field direction, except for the hottest proton component at the highest densities achieved by NBI where can invert its direction, whereas peripheral ions rotate in opposite direction with both heating methods. Preliminary estimates suggest that bootstrap current could account at least qualitatively for the toroidal rotation behaviour and their directions [8].

Acknowledgments. This work was partially funded by the Spanish Ministry of Science and Education under project FTN2003-00905. DR was supported by a Scholarship from CIEMAT.

References.

[1] K. Ida, Plasma Phys. Control. Fus. **40** (1998) 1429.

[2] J.V. Hofmann *et al.*, Proc. 21th EPS Conference, Vol. **18B** (1994) 393.

[3] K. Ida *et al.*, Phys. Plasmas **4** (1997) 310.

[4] J. Kim et al., Phys. Rev. Lett. **72** (1994) 2199.

[5] H. F. Tammen et al., Phys. Rev. Lett. **72** (1994) 356.

[6] A. Romannikov et al., Nuclear Fusion **40** (2000) 319.

[7] B. Zurro et al., Rev. Sci. Instrum. **74** (2003) 2056.

[8] V. Tribaldos et al., Proc. 30th EPS Conf. **27A** (2003) P1.28.