First Measurements of Core Toroidal Rotation
by Deuterium Neutral Fluxes Analysis

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1. Introduction

Rotation plays an important role in many regimes of tokamak plasma. For example, poloidal rotation in the edge plasma region has been closely associated with the L-H transition, and toroidal momentum confinement is well correlated with energy confinement. Core plasma toroidal rotation is usually investigated by measuring the rotation of impurities. The behaviour of main ions is then calculated using theoretical models. We present preliminary measurements of core toroidal rotation velocity V_t of deuterium ions deduced from the observation of charge exchange neutral fluxes on Tore-Supra. The necessity to take into account toroidal plasma rotation to interpret measured "parallel" ion temperature for discharges with NBI heating has been reported in ref. [1]. The possibilities to extract poloidal and toroidal rotations of main ion by measuring neutral fluxes are shown in ref. [2,3]. In [3], the plasma attenuation of neutrals is neglected, and a good accuracy is obtained only for very low density. In order to increase the density range for this measurement, we present a method based on simultaneous measurement of near "perpendicular" and "parallel" spectra of fast neutrals. Thus V_t is obtained for line electron density up to $4 \; 10^{19}$ m^{-2}, which corresponds on Tore Supra to $<n_e> \, < 2.5 \; 10^{19}$ m^{-3}.

2. Method

For a moving plasma, the familiar expression for the neutral flux emitted into a Neutral Particle Analyser (NPA) must be modified [2, 3]. For modest plasma velocity V ($V << \sqrt{2E/M}$), the expression writes:

$$I_n \cong A \int_S n_i n_o \langle \sigma_{cx} v \rangle \frac{\Delta E \sqrt{E}}{T_i^{3/2}} \left(1 - 2V\sqrt{\frac{M}{2E}}\right) \exp\left(-\frac{E}{T_i} + \frac{V\sqrt{2EM}}{T_i} - \beta(E)\right) dl \qquad (1)$$

Here, A is a numerical constant; ΔE is the width of the energy channels; V is the component of the plasma velocity in the direction of the analyser; $\exp(-\beta(E))$ is the attenuation of neutrals (CX and ionisation). With E and T in keV, we have $\sqrt{2E/M} = 309\sqrt{E}$ [km/s] and $\sqrt{2EM} = 0.0065\sqrt{E}$ [keV/km/s]. The integral runs along the NPA line of sight S. However, for $E >> T_i$ and not too high density, most of the flux is emitted by a restricted volume. Therefore we may write:

$$\frac{d(\ln f)}{dE} \approx -\frac{1}{T_i} + \sqrt{\frac{M}{2E}}\left(\frac{1}{E} + \frac{1}{T_i}\right)V - \frac{d\beta}{dE} \qquad (2)$$

where $f = I_n /(\langle \sigma_{cx} v \rangle \sqrt{E})$ and T_i is the ion temperature in this volume. For a set-up with two analysers (a and b), symmetrically implanted in the equatorial plane (see fig.1), making angles α_a and $\alpha_b = (180° - \alpha_a)$ with respect to the toroidal direction, the terms $\frac{d\beta}{dE}$ are

identical. If we note T_a and T_b the apparent temperature $-\left(\dfrac{d(\ln f)}{dE}\right)^{-1}$ given by the two analysers around energy E*, the toroidal velocity in the restricted volume is:

$$V_t = \frac{1}{2\cos\alpha_a}\sqrt{\frac{2E^*}{M}}\frac{1/T_b - 1/T_a}{1/E^* + 1/T_i} \tag{3}$$

Too small angles ("very parallel" line of sight) would imply a high value for β(E) and would not permit to "see" the plasma bulk. It would also enlarge the volume of emission and decrease the accuracy (α is changing along the line of sight).

On Tore-Supra, the experimental set-up is not in this ideal symmetrical situation. The two analysers in the equatorial plane, number 1 and 6, make different angles with the toroidal direction, respectively $\alpha_1 = 100°$ and $\alpha_6 = 38°$ at R = 2.5 m (see fig.1. With our sign convention, a positive velocity means motion towards analyser 6). From geometrical considerations on the absorption length of neutrals along the line of sight, we expect: $\beta_1 \cos(90 - \alpha_1) \approx \beta_6 \cos(90 - \alpha_6)$. So we can eliminate the third term in eq.(2), and eq.(3) becomes:

$$V_t \approx \frac{1}{\Delta}\sqrt{\frac{2E^*}{M}}\left(\left(\frac{1}{T_i}-\frac{1}{T_6}\right)\sin\alpha_6 - \left(\frac{1}{T_i}-\frac{1}{T_1}\right)\sin\alpha_1\right)\left(\frac{1}{E^*}+\frac{1}{T_i(0)}\right)^{-1} \tag{4}$$

where $\Delta = \sin\alpha_6\cos\alpha_6 - \sin\alpha_1\cos\alpha_1$ and $E^* = (E_{max} + E_{min})/2$ (maximum and minimum of the energy range taken into account for the determination of the apparent temperature, see fig.2).

It has to be mentioned here that the analysers 1 and 6 are not at the same port. Due to the lack of toroidal symmetry in particle recycling, the neutral density and consequently the radius of the origin of fast neutral could be different for the two analysers. For this reason we apply this method only for plasmas leaning on the toroidaly symmetric inner wall and we check that the neutral fluxes are of the same order of magnitude on the two analysers.

The accuracy of measured V_t is given by the uncertainties of T_i, T_1 and T_6 (count statistics), and by the variation of the angle α along the integration path. Due to the non-ideal configuration, the error bar is quite large in our experiments.

3. Absolute measurement of core V_t in ohmic deuterium plasmas

During a current-inversion experiment, we have studied a set of deuterium discharges, for which all plasma parameters are kept constant except the sign of the current (lIpl = 1.0MA, see fig.3). The spectra are cumulated over the 5 s long stationary phase of the discharges. The ion temperature is deduced from X ray crystal spectroscopy [5] and from simulation of the measured perpendicular deuterium spectra (analysers 1 to 5) [6]. Both methods give close results. In fig. 2, one can see the clear difference in the slope of deuterium spectra for the "parallel" analyser (number 6) between positive and negative plasma current. We find deuterium rotation in the direction opposite to plasma current, with a typical value for V_t of 40±20 km/s, as shown in fig.4.

We can also consider the parallel analyser only and determine the relative rotation between identical shots with opposite current. By analogy with eq.3, we have:

$V_t = \dfrac{1}{2\cos\alpha_6}\sqrt{\dfrac{2E^*}{M}}\dfrac{1/T_{6-} - 1/T_{6+}}{1/E^* + 1/T_i}$, and we find 37±15 km/s in the direction opposite to the current.

4. Core rotation in plasmas with LHCD

We have also examined discharges with scenario of additional heating or current drive, in particular those discharges where both the ohmic and LHCD phases last for several seconds. As an example, we report here on a low-density, low-Ip (+0.75MA) shot with LHCD at 3.6MW. For the ohmic phase ($<n_e>$=1.3 10^{19} m^{-3}) we get $V_t = -43 \pm 25$km/s; for the LHCD phase ($<n_e>$=1.45 10^{19} m^{-3}) we get V_t = +25±20 km/s. Despite of the large uncertainty (±20 km/s) it is well established that the plasma is always accelerated in the positive direction when LH power is switched on. This confirms earlier measurements based on the Doppler shift of X-ray lines [7].

5. Conclusion

We have presented the first measurements of near-axis toroidal rotation of the main ions. The measurements are based on the analysis of the energy spectra of the CX neutrals as observed in near parallel and near perpendicular directions (with respect to Ip). Taking advantage of a current-inversion experiment, we have studied ohmic plasmas. The toroidal velocity of the main ions is always opposite to the plasma current ($V_t = -40 \pm 20$ km/s in the presented experiment). The magnitude of counter rotation is an issue. The core radial electric field is estimated at 10 kV/m (negative field) for a central electron temperature around 2 keV. The possible source of the strong negative electric field could be related to ripple trapped ions losses. The results for the ohmic plasmas, as well as the results from the X-ray diagnostic will be revisited in the frame of neo-classical theory in a forthcoming paper [8].

When LH-power is applied, the plasma is accelerated in the co-current direction (ΔV_t=+65±30 km/s in a particular example), in agreement with earlier measurements of the Doppler shift of X-ray lines from heavy impurities.

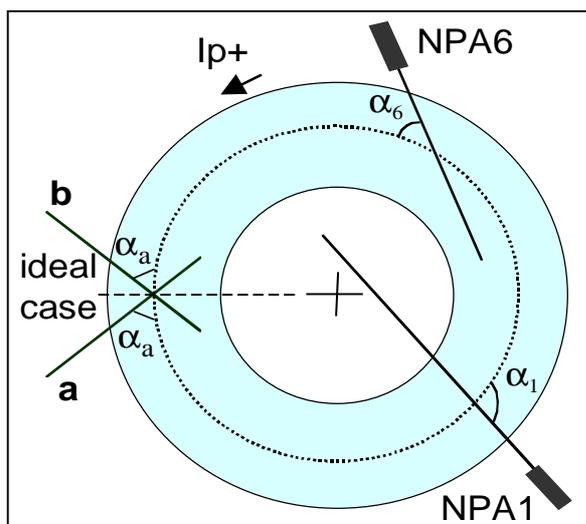**Fig.1**: Ideal and Tore Supra experimental set-up for Neutral Particles Analysers.

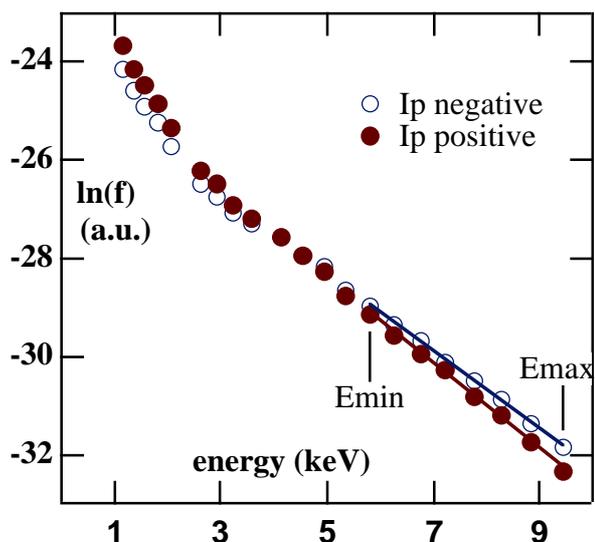**Fig.2**: D spectra (NPA6) for positive and negative plasma current.

Fig.3: Central electron temperature and line integrated density for two plasmas of the current inversion experiment (#25733 and 25738).
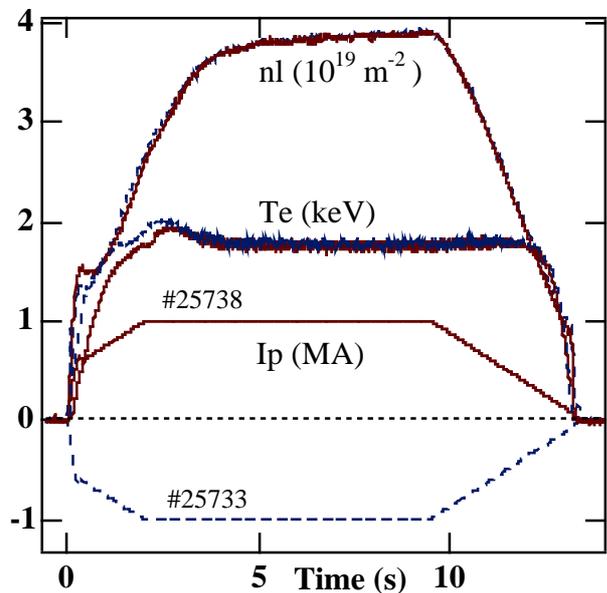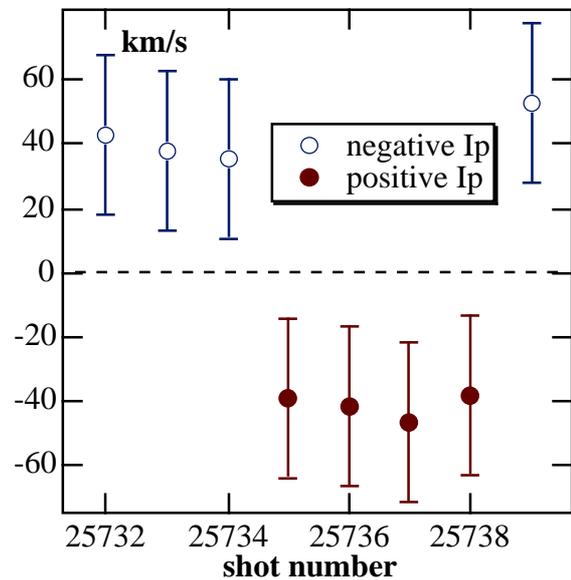
Fig.4: Toroidal velocity of the main ion in a 1 MA current-inversion experiment.

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