Accurate poloidal rotation measurement in TCV: an indirect method based on the inboard-outboard difference of toroidal rotation

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In tokamaks, one of the obstacles preventing further progress in the understanding of poloidal rotation physics is certainly the limited accuracy of available measurements. Plasma flows are generally measured with spectroscopic methods where the plasma velocity in the direction of observation is deduced from the Doppler shift of a chosen spectral line. Charge eXchange (CX) reactions between neutrals and impurity ions (even main ions in a few studies) provide suitable spectral lines. In practice, the accuracy of the measurement is limited to a few km/s, at best about 0.5km/s, and is particularly delicate for lines of view perpendicular to the magnetic field [4]. Poloidal rotation is measured and predicted to be of a few km/s, therefore comparable to the accuracy of the measurement, as a result severely hinders detailed comparisons between experiments and theory. In spite of the difficulty, sophisticated experimental setups including a careful control of all the possible sources of systematic errors have been developped and comparisons between measured flows and neoclassical theory conducted. The measurements sometimes agree and sometimes disagree with the neoclassical predictions (see for instance [4] and the references therein for a concise overview of the existing literature). No clear picture is however emerging on the question of when and why poloidal rotation is not neoclassical, probably because the comparisons have so far been limited to specific confinement configurations. A more accurate, and to some extent simpler, measurement of poloidal rotation would certainly help to address this issue. The present contribution explores the possibility of exploiting the link between the toroidal flow variation on a flux surface and the poloidal flow to provide an alternative measurement of poloidal rotation. More precisely, the toroidal and poloidal components of the first order plasma flow can be expressed as (see for instance [2]):

$$U_t = R\omega_t + \hat{u}B_t \qquad \text{and} \qquad U_p = \hat{u}B_p \tag{1}$$

where the 't' and 'p' subscripts stand for 'toroidal' and 'poloidal', respectively, R is the major radius, B the magnetic field, ω_t a rotation frequency and $\hat{u}$ characterises the poloidal flow. The two quantities ω_t and $\hat{u}$ are in general flux functions and will be considered as such in the following (for exceptions, see [2, 3]). The 2D flow pattern is therefore completely determined by ω_t and $\hat{u}$ and these two quantities can be readily obtained from two measurements of toroidal rotation on the same flux surface and different radial locations R_1 and R_2:

$$\begin{aligned}\omega_t &= (R_1U_{t1}-R_2U_{t2})\,/\left(R_1^2-R_2^2\right)\\ \hat{u} &= (U_{t1}/R_1-U_{t2}/R_2)\,/\left(F/R_1^2-F/R_2^2\right)\end{aligned}$$

with $F = RB_t$ a flux function. The best choice for the two measurement positions is the low and high field sides of a flux surface since it maximises the numerators and denominators in the expressions above. In the following, we will use $R_1 = R_{HFS}$ and $R_2 = R_{LFS}$. The main advantage of the method lies in the amplification of the quantity of interest: instead of measuring the poloidal rotation U_p, one measures the difference of toroidal rotation frequency $U_{t1}/R_1 - U_{t2}/R_2$ which is much larger and roughly scales as $4qU_p/R$ with q the safety factor. Put differently, compared to the direct method the uncertainty from the flow measurement is divided by about $2\sqrt{2}q$. Another advantage is that the measurement of toroidal rotation involves lines of sight almost parallel to the magnetic field and the apparent velocity arising from gyro-motion and cross-section effects is minimized. Naturally, the indirect method also has drawbacks, the main ones being that the flux surfaces position needs to be known accurately and that a HFS measurement is required. The application of the method as described here is also limited to regions without large particle sources or radial fluxes.

The CX spectroscopy system available in the TCV tokamak [1] has been used to test the method described above on intrinsic carbon impurity (CVI $n = 8$ to 7 transition at 529.1nm). The poloidal rotation is measured directly in the outer half of the plasma using vertical lines of view and compared to the value inferred from HFS and LFS measurements of toroidal rotation with horizontal lines of view. The localisation of the measurement is provided by the intersection of the lines of view and the diagnostic neutral beam (DNBI) used to inject high energy neutrals. A typical toroidal rotation profile obtained in an Ohmic L-mode limited on the inner carbon wall of the torus is shown in Fig. 1. The line averaged electron density was $n_e = 1.8\times10^{19}\,\mathrm{m}^{-3}$, the magnetic field $B = 1.44\,\mathrm{T}$, the plasma current $I_p = 160\,\mathrm{kA}$ and the edge safety factor $q_{95} = 5.3$. Data shown covers a 400ms interval (> 10 energy confinement times) during a stationary phase in which the DNBI was modulated (16ms ON, 32ms OFF) to subtract the passive component of the CX spectra. The scatter of the points is a combination of the statistical uncertainties and of the plasma

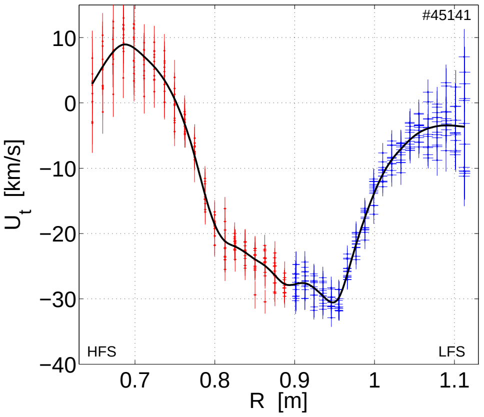

Figure 1: Example of C^{6+} toroidal rotation profile across the plasma diameter from the HFS and LFS systems. The magnetic axis is at $R = 0.88\,\mathrm{m}$

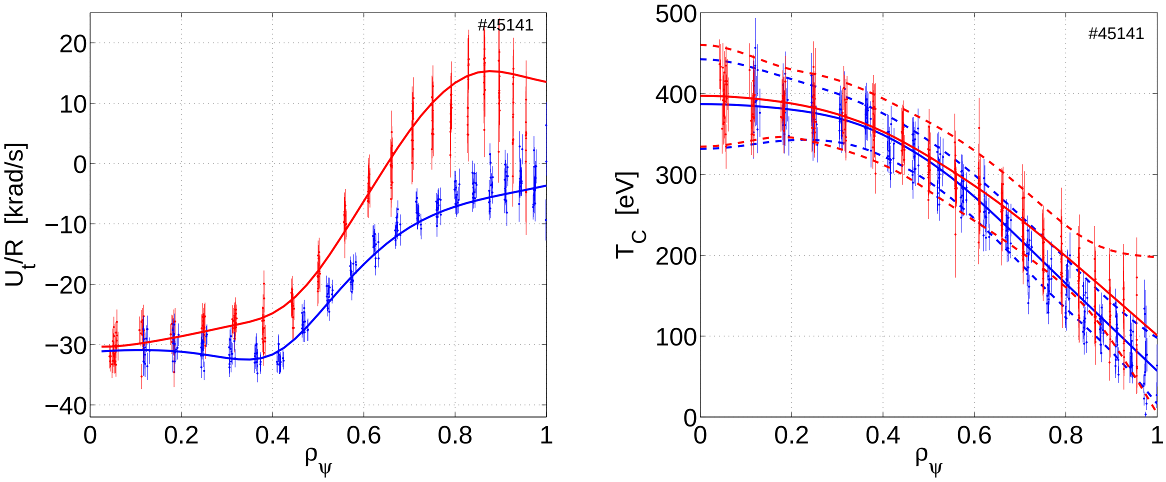

Figure 2: Left: toroidal rotation frequency of C^{6+} corresponding to fig 1 and mapped on the flux surface label ρ_ψ (normalised square root of the poloidal magnetic flux). HFS and LFS data are in red and blue, respectively. Right: corresponding temperature profiles to test the accuracy of flux surface mapping.

intrinsic variability. The plasma toroidal rotation is inboard-outboard asymmetric with the core rotating in the counter-current direction, as usually observed in Ohmic TCV low density plasmas, and the edge being slightly co-current at the HFS edge. Half of the profile is acquired with the HFS spectrometer and the other half with the LFS spectrometer. The match of the two profiles at the magnetic axis therefore brings confidence on the quality of the absolute calibration. The same data is then mapped on a flux surface label, ρ_ψ, to infer $\hat{u}$ and the corresponding poloidal rotation. On the same flux surface, the HFS toroidal rotation frequency is higher than the LFS frequency, see Fig. 2, implying a finite poloidal rotation. As anticipated, the flux surface mapping is a critical point of the indirect method. To check the accuracy of the flux surface reconstruction (and of the diagnostic alignement) the carbon temperature profile obtained with the HFS and LFS profiles are shown in the right plot of Fig. 2. The two measurements coincide within the experimental uncertainties. Assuming that the carbon temperature is constant on a flux surface, the equilibrium reconstruction is therefore consistent with the measurements.

Finally, the poloidal rotation profile obtained with the indirect method is compared to the direct measurement and to the neoclassical prediction in Fig. 3. The uncertainty on the profiles (and radial derivatives) is assessed by a classical Monte-Carlo method: the experimental points are randomly shifted following a gaussian distribution of standard deviation corresponding to the uncertainty on the measurements and a large number (typically a thousand) of experimental profiles are generated. Each profile is then fitted by a cubic spline. The final profile is the average of all the fits and the shaded area represents plus or minus one standard deviation. The confidence intervals of the two measurements overlap and as expected the confidence interval

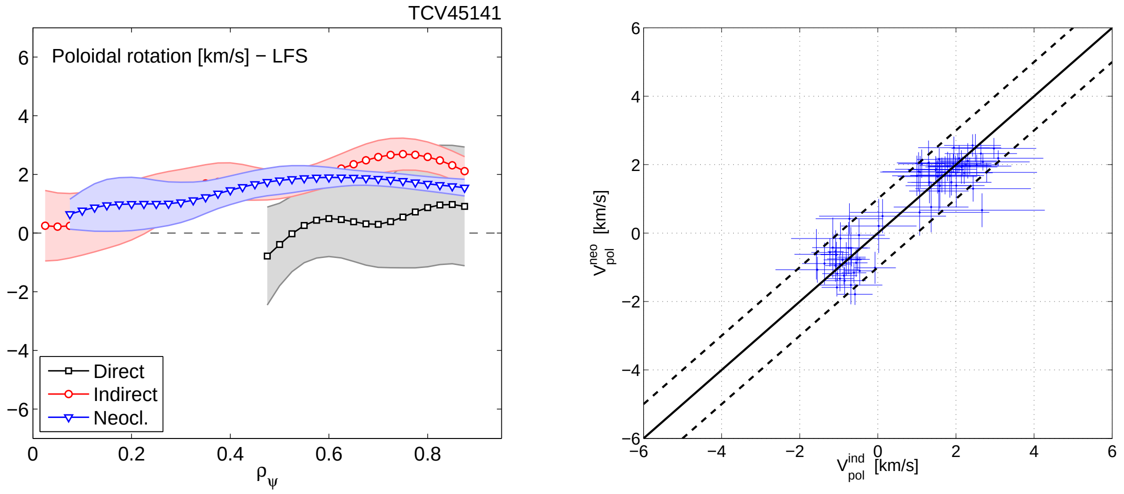

Figure 3: Left: comparison of the poloidal rotation profile from the direct and indirect measurements and from the neoclassical theory. Right: comparison of neoclassical and measured poloidal rotation (indirect method) for Ohmic an ECH L-mode plasmas. Each point corresponds to an average over a radial interval $\delta\rho_\psi = 0.1$with $0.35 < \rho_\psi < 0.75$. Positive values means upward at the LFS midplane.

for the indirect measurement is about 4 times smaller than for the direct measurement (keeping in mind however that the uncertainty on the equilibrium reconstruction was not included in the calculation). This reduced uncertainty allows to discriminate the sign of the poloidal rotation: the carbon impurity rotates poloidally in the electron diamagnetic drift direction. Neoclassical poloidal rotation computed with the NEOART code [5] (a variant of NCLASS) coincides with the indirect measurement. The comparison has then been extended to a set of Ohmic and EC heated plasmas for which the HFS system was available. The selection covers plasmas with co- and counter-current (intrinsic) toroidal rotation and with positive and negative magnetic field and plasma current. The collisionality range in the radial region investigated ($0.35 < \rho_\psi < 0.75$) is $0.15 < \nu_{ii}^* < 1.5$ (banana and lower plateau regime). In all cases, the poloidal rotation measured with the indirect method is found in the electron diamagnetic drift direction and agrees with the neoclassical prediction to within 1km/s, as shown in the right plot of Fig. 3.

Hopefully, these preliminary results are enough to highlight the potential of the indirect poloidal rotation measurement. A detailled presentation of this work will soon be available in a regular paper (A. Bortolon *et al.* submitted to Nuclear Fusion).

References

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