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Toroidal Rotation Observation in Ohmic TCV Discharges

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Introduction

This paper presents measurements of the toroidal plasma rotation profile for an extended set of TCV Ohmic plasmas in a limited configuration with almost no applied torque (diagnostic neutral beam). The Charge eXchange Recombination Spectroscopy diagnostic was adapted to the experimental scenario, extending the usable plasma electron density to $1\div8\times10^{19}m^{-3}$. The influence of main plasma parameters (I_p, n_e) on the steady state rotation profile is presented. Observations of an inversion in the rotation regime occurring with increasing plasma density are reported.

Diagnostic Neutral Beam and CXRS

In TCV the spectral signal for CXRS (CVI 529.1nm) is provided by a 50 keV diagnostic neutral beam (extracted ion current ~ 2.5A) whose injected power (~80kW, modulated pulses of tens of ms) is relatively small compared with the TCV Ohmic power (0.25÷1MW) [1,2]. The beam is injected horizontally at a toroidal angle of 11.25° to the machine centre (Fig. 1): beam induced rotation is estimated < 1 km/s [3], negligible compared to the typical measured values. CX emission from the beam/plasma interaction is collected from 16 radial locations on the plasma low field side with 2.5 cm radial resolution, covering the range ρ=0÷0.9, for plasmas with Z_{axis}=0. In this work, the operational range (limited by the carbon content at low n_e and by beam attenuation at high n_e) has been extended by coupling the spectral fit of channels referring to the same ρ location.

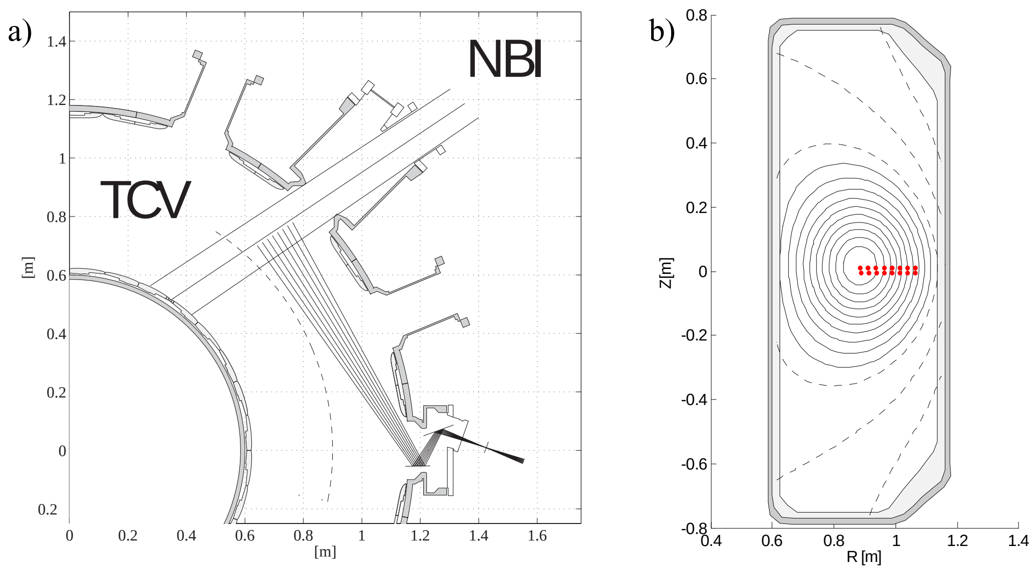

Figure 1. (a) CXRS experimental setup in horizontal cross-section of TCV. (b) Flux surfaces for a typical L-mode shot in limited configuration. CXRS measurement points are highlighted in red.

In order to measure the plasma rotation for these experiments, a 30 ms CCD detector integration was used. For $\bar{n}_e$~1÷8x10^{19} m^{-3} plasmas, S/N~10÷30 were routinely obtained for the background subtracted CX spectra of a central chord, resulting in a spectral fit uncertainty ~0.05 px on the CX line position ($\delta v_{\phi,fit} < 1$km/s).

Spectrometer wavelength calibration and signal extraction optimisation

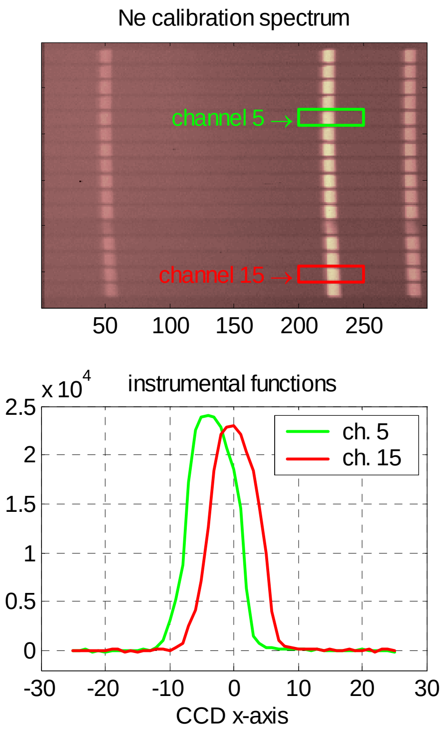

Figure 2. Typical full frame Neon calibration spectrum. Selected zones are used to define instrumental functions for the 2 channels.

To detect a velocity ~10 km/s with the present diagnostic a doppler shift Δλ~0.18Å (1.7 px on the CCD detector x-axis) must be resolved. The necessary dispersion, Δλ/λ~3x10^{-5}, was achieved with a 2400 g/mm grating equipped Czerny-Turner monochromator. Thermal expansion (up to 0.5 px hor. shift per day) is monitored by a wavelength calibration from a reference Neon lamp (NeI 528.0, 529.8, 530.5 nm) automatically acquired after each plasma shot.

The entrance slit width was set to 200μm for the 600μm fibres and the latter were re-arranged so that two fibres observed the same plasma position. The spectral line shapes are not symmetrical (Fig. 2), resulting in an uncertainty on the central position up to 0.5 px on ~10 px line width. A separate spectral deconvolution for each channel was developed using instrumental functions from the Ne calibration spectra, in such a way that: 1) wavelength alignment of deconvoluted spectra is recovered with each fibre pair treated together; 2) the deconvoluted wavelength scale is determined from the Neon spectra. Calibration line positions are determined with an uncertainty δx_0~0.02 px. In the linear fit $\lambda = mx + \lambda_0$ we regularly obtain $\delta\lambda_0$~3x10^{-4}Å and δm ~ 3x10^{-5} Å/px, which results in an

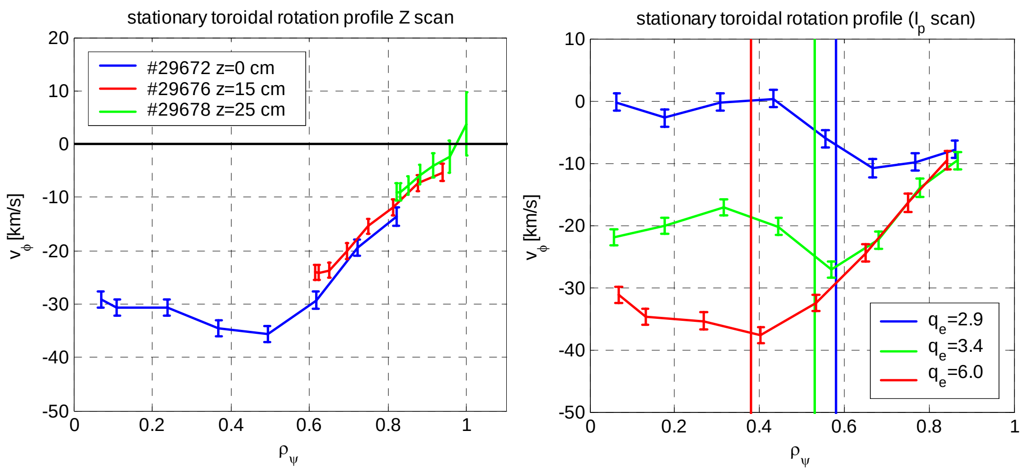

Figure 3. Z-scan reconstrunction of the full steady state rotation profile. Rotation profile for different qe: vertical lines indicates the inversion radius position from SXR measurements.

uncertainty $\delta v_{\phi,cal} < \pm 1$km/s.

Finally, for the analysed TCV discharges with $\bar{n}_e \sim 1 \div 8 \times 10^{19}$ m^{-3}, an experimental uncertainty of 2 km/s was regularly achieved near the plasma centre (beam attenuation becomes important) and up to 5 km/s at the plasma edge (limited by low signal level) and better values between.

Toroidal rotation in Ohmic limited L-mode

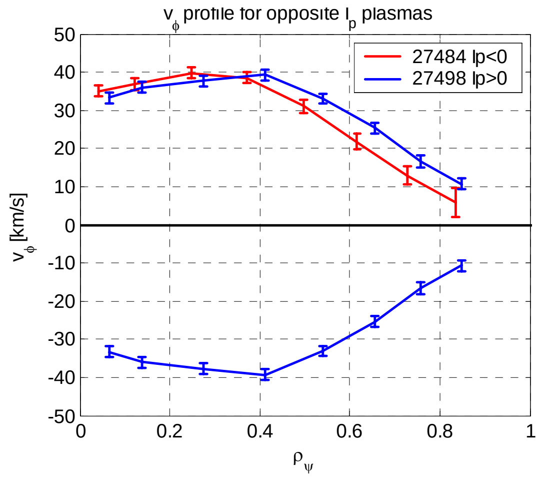

Figure 4. Toroidal rotation profiles at t=1.0 s for two discharges with inverse plasma current.

Toroidal rotation in limiter configuration L-mode has been characterised as function of the main plasma parameters I_p and n_e. In steady state discharges, with I_p=100÷350kA and $\bar{n}_e = 1 \div 7 \times 10^{19}$ m^{-3}, the carbon rotation velocity is in the counter current direction, with central values increasing up to 40 km/s (~50 krad/s). The plasma rotation at ρ>0.9 (measured from a configuration with the plasma axis displaced vertically) is found close to 0 km/s, as might be expected from the strong influence of the machine wall in a limiter configuration [4]. Profiles are typically hollow or flat in the presence of sawtooth activity, and peaked with q(0)>1. In comparing discharges with different I_p (q_{edge}) correlation is found between the inversion radius and the location where the profile starts to flatten. The B_θ dependence of v_ϕ was tested by inverting I_p resulting in an inverted v_i profile, in agreement with the standard fluid theory, confirming the negligible beam induced rotation (always positive) (Fig. 4).

For densities up to 5×10^{19} m^{-3} the absolute value of v_ϕ was usually found to increase with n_e as an indirect effect of the T_i increase due to equipartition [5]. For higher densities, a new regime was observed in which central v_ϕ reversed to become co-current. Transition to this regime was

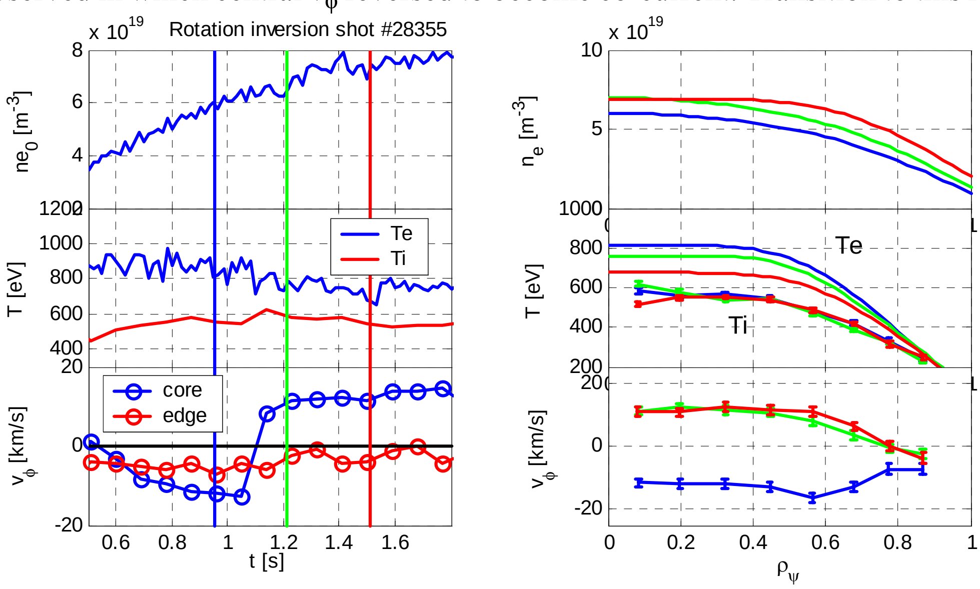

Figure 5. Rotation inversion during a density ramp; n_e and T_e profiles are fitted on Thomson data. Vertical lines indicate the times of the corresponding profiles.

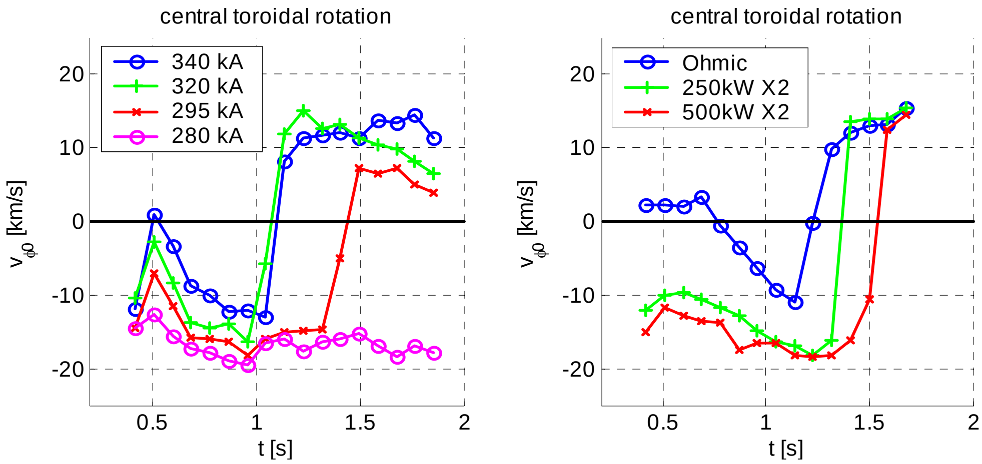

Figure 6. Central toroidal rotation (mean of 3 central chords) during the same density ramp for different plasma currents and different heating schemes.

very reproducible with ramping plasma density, occurring at n_{e0} ~$5x10^{19}$ m^{-3} (Fig. 5). After transiting, the rotation profile is positive inside ρ=0.7, with values comparable with the previous values but slightly more peaked. The edge rotation for ρ>0.8 was unaffected. Across the transition n_e and T_e profiles were similar, and, apart from sawteeth, MHD activity was low. A smooth transition could be obtained by reducing the fuelling rate: intermediate rotation profiles confirm that the phenomenum is not linked to a torque located in the edge.

In n_e ramp down experiments a back transition was obtained but at a lower density indicating some hysteresis. The dependence of the transition on plasma parameters has been explored. The n_e threshold is found to strongly increase when decreasing I_p and no transition was attained for I_p<280kA. The separate influence of T_e profile has been studied with ECH heated plasmas showing that higher T_e increases the density at which the transition occurs (Fig. 6).

These observations suggest that the quantity determining the transition is at least a combination of n_e and T_e: so a parameter such as collisionality is tempting, although this only provides some interpretation of the reported trends, not a physical understanding.

Conclusions

The new adopted λ calibration arrangement and spectra deconvolution analysis, has been used to measure v_ϕ with an uncertainty better than 2 km/s with n_e from 1 to $8x10^{19}$ m^{-3}. Rotation behaviour in limited configuration Ohmic plasmas has been characterised as function of I_p and n_e, indicating the key role played by the sawtooth instability in determining the steady state v_ϕ profile. A transition to an inverted rotation profile regime at a reproducible density has been identified and a scaling with I_p and T_e reported.

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