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The poloidal asymmetry in perpendicular plasma rotation and radial electric field measured with Correlation Reflectometry at TEXTOR.

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Introduction

Measurements of plasma rotation and electric field are crucial for the study of plasma confinement and transport. The radial electric field (E_r) in most tokamaks is derived either directly from potential measurements with a heavy ion beam probe or indirectly from measurements of the toroidal (υ_ϕ) and poloidal (υ_θ) plasma flow components. The measurements of plasma rotation perpendicular to magnetic field lines ($\upsilon_\perp^{plasma}$) allows to evaluate E_r from the radial force balance equation without knowledge of υ_ϕ and υ_θ components:

$$E_r = \nabla p/(Zen) - \upsilon_\theta \cdot B_\varphi + \upsilon_\varphi \cdot B_\theta = B \cdot (\nabla p/(ZenB) + \upsilon_\perp^{plasma}). \tag{1}$$

In magnetically confined plasmas the density perturbations are largely elongated along the magnetic field lines because of faster parallel conductivity. Due to such a topology of fluctuations such diagnostics as Correlation Reflectometry (CR) and Doppler Reflectometry (DR) which register the turbulence movement under the poloidal line of sight see the projection perpendicular the magnetic field lines $\upsilon_\perp^{turb}$: $\upsilon_{refl} \equiv \upsilon_\perp^{turb} = \upsilon_\perp^{plasma} + \upsilon_{phase}$, where υ_{phase} is the turbulence phase velocity in the plasma frame. For most cases of interest $\upsilon_{phase} \ll \upsilon_\perp^{plasma}$, therefore E_r can be expressed as:

$$E_r = B \cdot [\nabla p/(ZenB) + \upsilon_{refl}] \tag{2}$$

Recent results obtained with DR at ASDEX-U [1] have demonstrated the validity of this approach. In this paper we present results on the asymmetry of turbulence rotation found for two poloidal positions $\theta = 0^o$ and $\theta = 90^o$ in the same cross-section of TEXTOR (major radius R=1.75 m, limiter radius a_L=0.46 m). A heterodyne O-mode correlation reflectometer operates in a frequency range of $26 - 37$ GHz or critical density range of $0.8 - 1.7 \cdot 10^{13} cm^{-3}$ [2]. Two equivalent antenna systems each of five horns are focused to the center of vessel and placed in the same toroidal cross-section (Fig. 1). It provides the time delay measurements with an acquisition time of 1 μs.

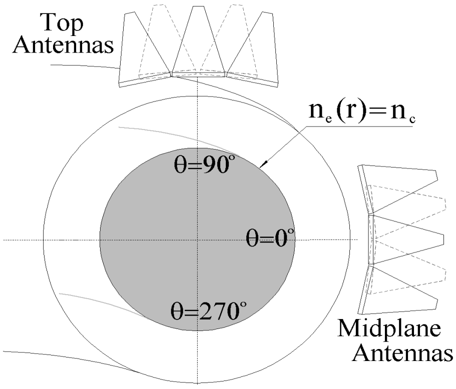

Figure 1: *Reflectometer antennae layout. For detailed view antennas are shown on larger scale.*

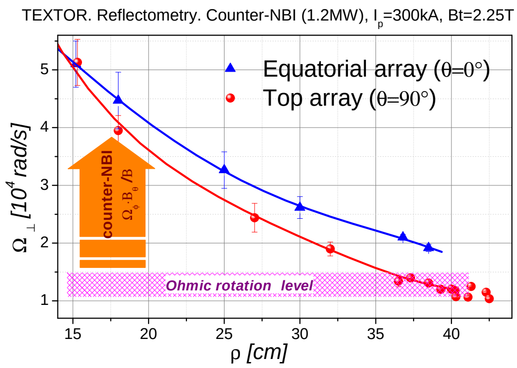

Figure 2: *Turbulence angular velocity for a regime with counter-NBI (∼1.2MW).*

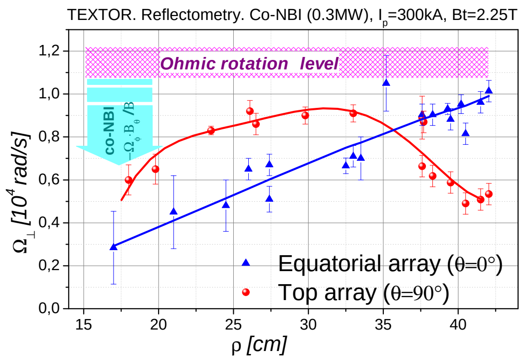

Figure 3: *Turbulence angular velocity for a regime with co-NBI (0.3MW).*

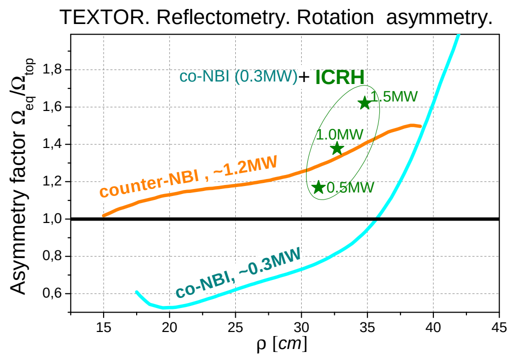

Figure 4: *Asymmetry in perpendicular plasma rotation measured with CR for* $\theta = 0^o$ *and* $\theta = 90^o$.

Experimental results

The results discussed in this paper have been obtained in a series of successive shots in two operating regimes. The first one: plasma current I_p=300kA, toroidal field B_t=2.25T, line averaged density $< n_e > \approx 1.5 - 2 \times 10^{19}$ m^{-3}, safety factor $q_{cyl}(a)$ ≈4.5, auxiliary heating with tangential neutral beam injectors (NBI) in co- and counter-current direction. The second regime: I_p=200kA, B_t=1.9T, $< n_e > \approx 2 \times 10^{19}$ m^{-3}, $q_{cyl}(a)$ ≈5.7, NBI and ion cyclotron resonance heating (ICRH) on the frequency of the 1st harmonic of hydrogen.

The rotation data as a function of the flux surface radius ρ for a counter-NBI ($\approx 1.2MW$) heated plasmas are presented in Fig. 2. A counter-NBI introduces toroidal momentum along the toroidal rotation of Ohmic heated plasmas thus accelerating it by several times. The data corresponding to the equatorial outer plane measurements exceed data obtained from top antennas measurements. Maximal asymmetry Ω_{eq}/Ω_{top} is ≈ 1.45 at the periphery ($\rho = 38\ cm$) and decreases gradually towards the center vanishing at $\rho \approx 15cm$. A rotation level for this

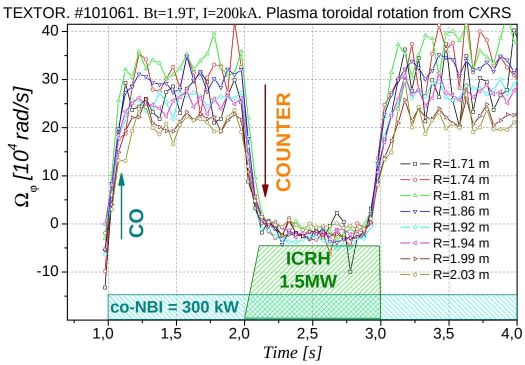

Figure 5: *Toroidal velocity vs time for a regime with ICRH application against co-NBI. Traces for different radii are shown in different colors and symbols.*

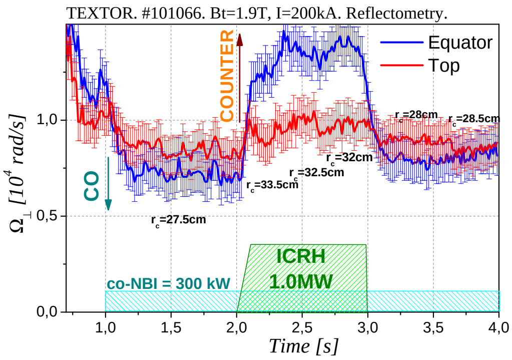

Figure 6: *Perpendicular rotation velocity from equatorial and top antennas in the regime with ICRH (2-3 s) application against a background of weak co-NBI.*

regime without NBI is shown as reference by the hatched rectangle. Fig. 3 represents the rotation data for a co-NBI heated plasmas with a power of $\approx 0.3\ MW$. All points lie below the Ohmic rotation level, since the injector introduces a toroidal momentum against the rotation of the Ohmic plasma. The rotation asymmetry for $\rho < 35$ cm is less than unit ($0.55 < \Omega_{eq}/\Omega_{top} < 1$) compare to the regime with counter-NBI. For periphery region, $\rho > 35cm$, asymmetry >1 and reaches its maximal value of ≈2 at $\rho \approx 42$ cm. The asymmetry factors for co- and counter-NBI heated plasmas are shown in Fig. 4. Note, the asymmetry in the counter-NBI scenario exhibits the monotonic behavior increasing to periphery. The asymmetry in the co-NBI regime being <1 in the range 20< ρ <35 cm decreases gradually, reverses around $\rho = 35$ cm and rises with radius towards a periphery reaching in the meanwhile the value for counter-NBI at $\rho \approx 39$ cm. One can see, that for periphery plasma region there is a tendency to have a similar asymmetry in rotation: $\Omega_{eq}/\Omega_{top} > 1$. Unfortunately, it is not possible to interpret the observed asymmetry of perpendicular rotation on the base of cylindrical equations (1,2), which does not take the toroidal effects (e.g. Shafranov' shift) into consideration.

The analysis of rotation for the 2^{nd} regime with different amounts of ICRH is presented below. Fig. 5 demonstrates time traces of toroidal rotation data for several radial positions measured with CXRS. The application of ICRH (1.5MW) between 2^{nd} and 3^{d} seconds of discharge makes the dramatic change in the toroidal plasma rotation in the counter-current direction. The reflectometry data on the perpendicular rotation for the same plasma conditions and for the same time scale are plotted in Fig. 6. It shows the decrease in perpendicular

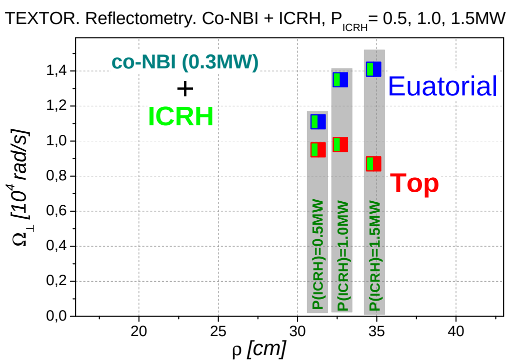

Figure 7: *Perpendicular rotation for $\theta = 0^o$ and 90^o measured with CR as function of ICRH power and radius.*

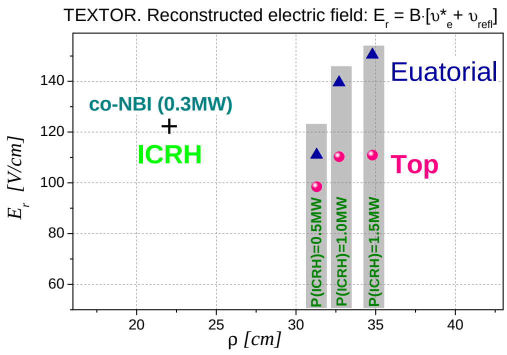

Figure 8: *Radial electric field calculated for $\theta = 0^o$ and $\theta = 90^o$ from reflectometry data and plasma pressure profiles.*

plasma rotation after application of co-NBI at t=1s and increase during the ICRH phase at t=2-3s. Note, that the reflection radius slightly decreases ($\approx$ 2 cm) after the ICRH application. The common analysis of CXRS and reflectometry data evidences that ICRH produces toroidal momentum in the counter-current direction either directly or through E_r modification. The spontaneous rotation of plasma caused by the additional RF heating was observed earlier in the several machines [3, 4] and also in TEXTOR [5]. A general explanation of phenomenon is wave-particle interactions leading to either direct toroidal momentum contribution or potential changing. From the point of view of rotation asymmetry ICRH acts similar to counter-NBI, resulting in $\Omega_\perp^{eq}/\Omega_\perp^{top} > 1$ (see green stars in Fig. 4). In Fig. 7 $\Omega_\perp(\rho)$ for different amounts of ICRH power is plotted. For this regime the evaluation of radial electric field was performed using the eq. 2 and taking into consideration experimental plasma pressure profiles. The results are shown in Fig. 8. In the frame of assumptions made above one can assert the top/equatorial asymmetry in E_r is an increasing function of P_{ICRH}.

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