

Indirect measurement of the poloidal rotation in the core of ASDEX Upgrade plasmas with charge exchange recombination spectroscopy

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The radial electric field (E_r) is a critical parameter to understand the physics of microinstabilities and turbulent transport in fusion plasmas [1]. While difficult to measure, it can be calculated by evaluating the radial force balance equation for a given ion species α :

$$E_r = \frac{\nabla p_\alpha}{eZ_\alpha n_\alpha} - u_{\text{pol},\alpha} B_{\text{tor}} + u_{\text{tor},\alpha} B_{\text{pol}}, \quad (1)$$

where ∇p_α denotes the radial pressure gradient, eZ_α the charge, n_α the density and $u_{\text{pol},\alpha}$ and $u_{\text{tor},\alpha}$ the poloidal and toroidal rotation velocities of the species α . B_{pol} and B_{tor} are the poloidal and toroidal magnetic field components determined from the magnetic equilibrium reconstruction. One of the most commonly used diagnostic to evaluate the ion quantities is active charge exchange recombination spectroscopy (CXRS), which measures the line-emission resulting from the charge exchange process between fully stripped impurity ions with neutrals from the highly energetic neutral beam injection (NBI) sources.

At the plasma edge, where the temperatures are low, the direct observation of u_{pol} is a standard technique (see e.g. [2]). In the plasma core, however, the direct measurement of u_{pol} is more challenging due to practical geometry and signal to noise issues associated with the poloidal lines-of-sight (LOS) as well as atomic physics issues. The energy dependence of the charge exchange cross-sections [3] in combination with the finite lifetime of excited atomic states lead to an apparent rotation in the poloidal direction [4] exceeding the desired poloidal rotation at high temperatures and magnetic fields.

Indirect measurement principle

A promising method to obtain more accurate measurements of the poloidal rotation, which is less sensitive to the atomic physics effects, is the evaluation of the inboard-outboard asymmetry of u_{tor} . This method is based on the neoclassic description of the plasma flow, i.e. the plasma flow can be expressed as a sum of a component parallel to the magnetic field and a purely solid body rotation:

$$\vec{u} = \hat{u}(\psi) \vec{B} + \hat{\omega}(\psi) R \vec{e}_{\text{tor}}, \quad (2)$$

where \hat{u} and $\hat{\omega}$ are flux functions [5]. This means that by evaluating the plasma rotation, preferably u_{tor} , at two distinct locations on the same flux surface, \hat{u} and $\hat{\omega}$ can be evaluated and, therefore, the poloidal rotation can be measured indirectly. In order to have a precise estimation of the rigid body component, the two points with the largest separation are ideally taken, i.e. on the low-field side (LFS) and the high-field side (HFS). In reality, the measurement points are given by the injection geometry of the NBI sources. A big advantage of this measurement technique is additionally that the toroidal rotation asymmetry caused by a poloidal flow is amplified

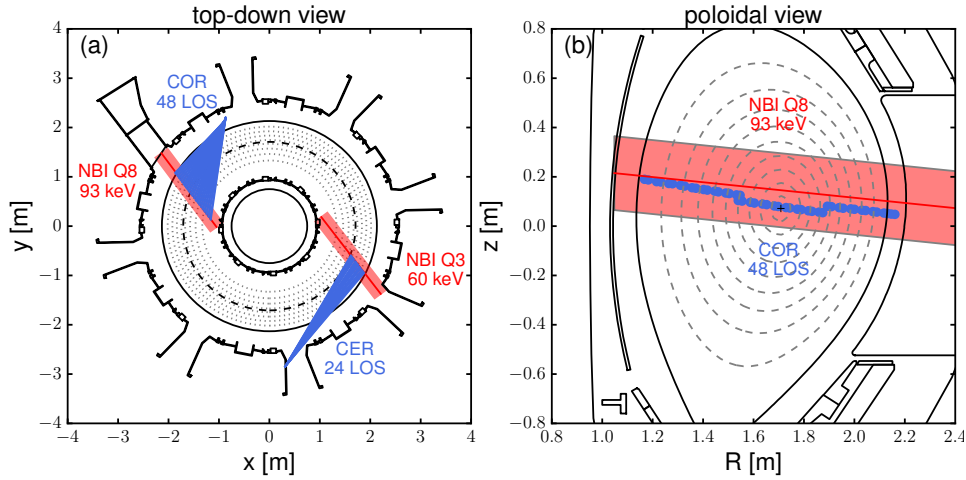


Figure 1: Upgrade of the core CXRS systems at ASDEX Upgrade.

by the safety factor q [8].

Equation (2) has been derived under the assumption that $|u_{\text{tor}}| \ll u_{\text{therm}}$, i.e. without HFS-LFS asymmetries in the impurity density (n_{imp}) profile so that n_{imp} is a flux function. If the toroidal rotation approaches the thermal velocity then a more general form of the plasma flow has to be considered [6]. However, in this work only plasmas with an impurity mach number below 0.5 were considered so that n_{imp} can be assumed to be a flux function.

The described indirect measurement technique has been applied as well at DIII-D [7] and TCV [8]. Compared to the direct measurement technique they were able to reduce the uncertainty in u_{pol} by a factor of 2 (from 2 km s^{-1} to 1 km s^{-1}). At higher ion collisionalities ($v_i^* > 0.2$), good agreement between the experimentally observed poloidal rotation and the expected one from neoclassics are reported. However, in discharges with an internal transport barrier (ITB) or at very low ion collisionalities, deviations of u_{pol} from neoclassic are reported [9]. These findings are also consistent with previous results reported from direct measurement of u_{pol} [3, 10–13].

Upgrade of the core CXRS systems at AUG and initial profile comparison

A new core CXRS system (COR, see figure 1) has been installed at ASDEX Upgrade (AUG) in order to measure the HFS-LFS profiles of the CXRS quantities and, thus, enable the indirect measurement of u_{pol} . This new system has in total 48 toroidal LOS aligned along the NBI source 8, which has an injection energy of 93 keV. The system measures the ion temperature (T_i), u_{tor} and n_{imp} from the pedestal top on the LFS to the pedestal top on the HFS. Figure 1a shows a top-down view of AUG and illustrates the geometry of the two NBI sources being used for core CXRS measurements as well as the toroidal LOS geometry of the new core CXRS diagnostic and the pre-existing one (CER). Figure 1b illustrates the alignment of the new CXRS system along NBI source 8 in the poloidal plane. All 48 LOS are imaged simultaneously by two F/2.8 flexible wavelength spectrometers. The systems use Princeton Instruments ProEM 512×512 $16 \mu\text{m}$ pixel cameras that, with the 25 regions of interest defined on each camera, are capable of a maximum readout rate of 2.4 ms. The standard time resolution, however, is between 5 and 10 ms due to signal to noise considerations.

Figure 2 compares the measured profiles of T_i and u_{tor} for the two systems (CER in black; COR in blue and red) in a typical H-mode plasma with a core line-integrated density of

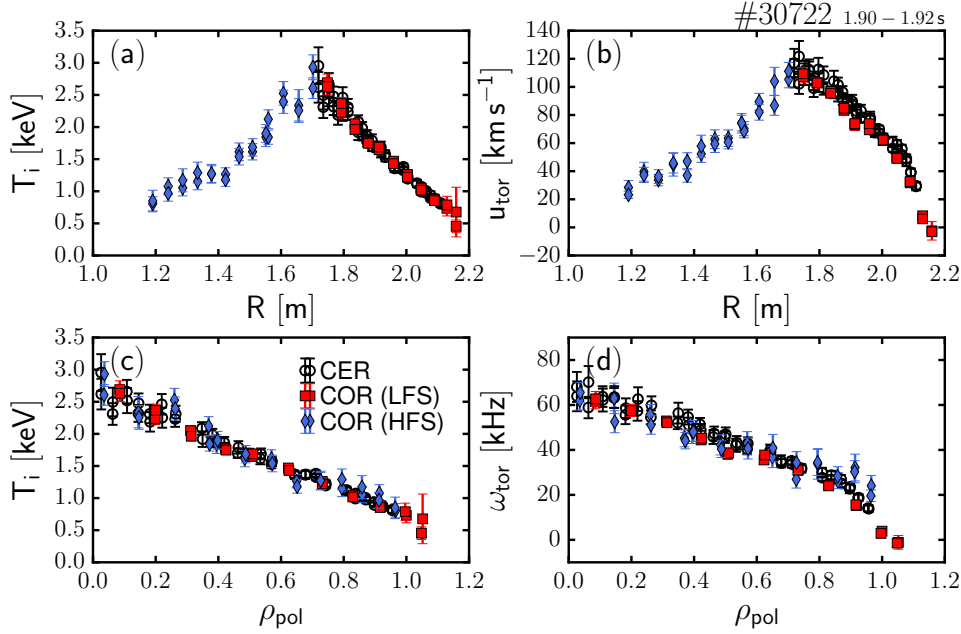


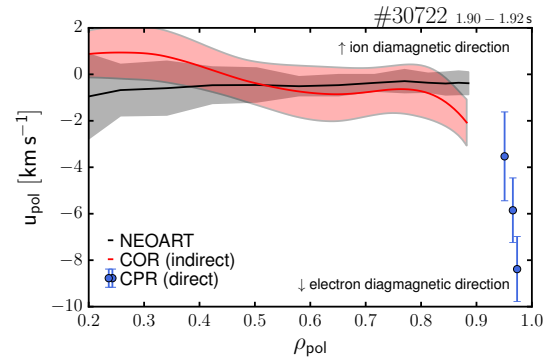
Figure 2: Comparison of HFS-LFS CXRS profiles.

$n_e = 7.4 \times 10^{19} \text{ m}^{-2}$ and 5 MW of NBI heating. A maximum of 3.0 keV for T_i and 120 km s^{-1} for u_{tor} were measured by both diagnostics in the plasma core. These profiles are shown in figure 2a and b as function of the major radius R . There is overlap between the CER and COR on the LFS such that the measurements of these two systems can be compared directly in this region. There is a very good agreement of the ion temperature on the LFS (see figure 2a) indicating that the dispersion of the spectrometers are well understood. The toroidal rotation of the two systems also agrees within error bars on the LFS.

When mapping the measurement locations to the normalized poloidal flux function ρ_{pol} , good agreement between the HFS and LFS ion temperatures is generally found. In the 2014 campaign, however, there were some cases where the LFS and HFS T_i did not agree completely. This could be due to uncertainties in the magnetic equilibrium which effects the mapping of these measurements in flux coordinates. This possibility is being investigated.

Comparing u_{tor} (see figure 2b) on HFS and LFS, one can see that u_{tor} is higher on the LFS. This is because the rotation is, to first order, a solid body rotation, meaning that the toroidal rotation frequency $\omega_{\text{tor}} = u_{\text{tor}}/R$, is the flux function and not the rotation velocity. By plotting ω_{tor} on HFS and LFS (see figure 2d) one can identify deviations away from a solid body rotation and, hence, identify the presence of a poloidal flow. In the plasma shown, the good agreement of ω_{tor} on HFS and LFS indicates that u_{pol} is small in the plasma core.

Figure 3 shows the calculated poloidal rotation (blue curve) from the asymmetry in the rotation frequency shown in figure 2d. The method reveals a poloidal rotation in the electron diamagnetic direction in the region $0.4 < \rho_{\text{pol}} < 0.9$. The magnitude and direction of u_{pol} for that

Figure 3: Initial u_{pol} profile.

area is in very good agreement with the neoclassical predictions from NEOART [14]. Towards the plasma center, the indirect method reveals a change in the sign of the poloidal rotation. In this region, the reconstructed rotation agrees within the error bars with the neoclassical prediction. In figure 3 also direct measurements of the impurity poloidal velocity from the edge CXRS system (CPR) are displayed. While the directions and magnitudes measured by the core and edge systems agree, they can not be compared directly as there is no radial overlap between the diagnostics.

The errors on the poloidal rotation are calculated by a Monte-Carlo approach. The measured toroidal rotation and measurement location of the LOS are varied within their uncertainties and their resolutions, respectively. Each "new" profile is fit with a spline to create a distribution of calculated poloidal velocities which provides the error estimate of this quantity. In total this measurement technique can resolve poloidal flows with an accuracy of $\pm 1 \text{ km s}^{-1}$.

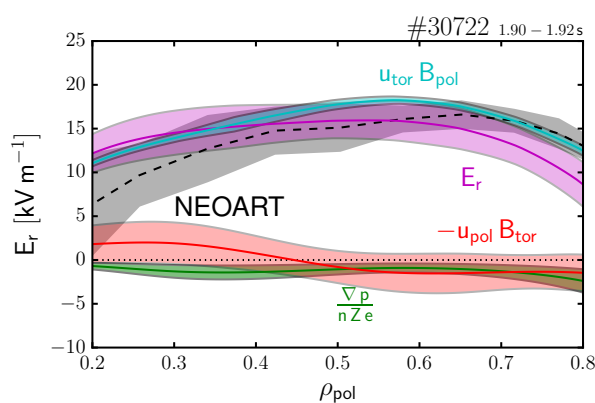


Figure 4: Initial E_r profile and comparison to the neoclassical prediction from NEOART.

Being able to measure T_i , u_{tor} , u_{pol} and n_{imp} , one can evaluate the radial force balance equation and calculate E_r . Figure 4 shows the calculated E_r in purple and the single contributions to the radial electric field shown in equation (1) in blue, green and red. It reaches a maximum value of 18 kV m^{-1} at $\rho_{\text{pol}} \sim 0.6$ and is dominated by the contribution of the toroidal rotation times the poloidal magnetic field component.

Summary

The new core CXRS system measures T_i , u_{tor} and n_{imp} from the pedestal top on the LFS to the pedestal top on the HFS. This enables first HFS-LFS comparisons of the CXRS quantities in the core of ASDEX Upgrade plasmas. In general, good agreement between the LFS and HFS profiles is found. The poloidal rotation can be measured indirectly by evaluating the asymmetry of u_{tor} on LFS and HFS, which means that this new diagnostic can provide measurements of E_r in the core of AUG plasmas.

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