Investigations on the edge radial electric field at ASDEX Upgrade

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The properties of the edge transport barrier (ETB) are a key parameter for determining the performance of an H-mode fusion plasma. The formation of the ETB is connected to the existence of a sheared plasma flow perpendicular to the magnetic field caused by a local electric field **E**. It is widely accepted that this **E**   **B** velocity shear is fundamental for suppressing edge turbulence and thus, aiding the formation of the ETB and leading to H-mode.

At ASDEX Upgrade (AUG), radial electric field (E_r) profiles are determined from charge exchange recombination spectroscopy (CXRS) measurements at a heating beam and from Doppler reflectometry (DR). Since 2011 the edge CXRS system has been equipped with a toroidal and a poloidal view of the neutral beam [1]. This enables the determination of E_r from CXRS using the radial force balance equation:

$$E_r \quad \frac{1}{n_\alpha Z_\alpha e}\frac{\partial p_\alpha}{\partial r} \quad v_{\theta\ \alpha}\ B_\phi \quad v_{\phi\ \alpha}\ B_\theta \tag{1}$$

where n_α denotes the density, Z_α the charge state, e the elementary charge, $\frac{\partial p_\alpha}{\partial r}$ the radial pressure gradient and $v_{\theta\ \alpha}$ and $v_{\phi\ \alpha}$ the poloidal and toroidal rotation velocities of the species α. B_ϕ and B_θ are the toroidal and poloidal magnetic field components, which are determined from the equilibrium reconstruction of the plasma. All the other quantities needed to derive E_r via the radial force balance equation (1) are measured with the edge CXRS diagnostics. In order to obtain full radial profiles of the ETB a radial sweep of the plasma is performed. Usually, the plasma is moved by   2 cm in about 800 ms during a steady-state phase of the discharge. This enables the alignment of the measurements from both edge CXRS diagnostics and also a relative alignment to the electron profiles and to the separatrix position. The accuracy of this relative profile alignment is estimated to be 2-3 mm [2].

Radial electric field profiles have been derived from charge exchange (CX) spectra measured on different impurity species including He^{2} , B^{5} , C^{6} and Ne^{10} . Within the uncertainties, E_r is found to be identical regardless of the impurity species used for the analysis [2]. This provides a consistency check of E_r and proves the validity of the diagnostic technique. A further cross-check of E_r has been performed by comparing CXRS with DR measurements. The depth of the E_r well is found to be consistent within the uncertainties of the systems. Figure 1 shows an inter-ELM (edge-localized mode) profile of E_r (black curve) derived from CX spectra of

B^5 in an H-mode plasma. In the ETB a negative E_r well, a narrow, localized minimum close to the separatrix position, is found. Towards the plasma core, the absolute magnitude of E_r decreases and E_r changes sign. The evaluation of the separate B^5 terms in equation (1), that contribute to E_r are shown in red (toroidal rotation contribution), green (diamagnetic term) and blue (poloidal rotation term). Note that at the edge the poloidal impurity ion rotation velocity is quite large and yields the dominant term in the evaluation of E_r. Towards the plasma core the toroidal rotation term becomes dominant. Since E_r is the same for every species, the profile shown in black in figure 1 represents the total E_r. A comparison between the E_r profile and an estimate of the diamagnetic term of deuterium (D) shows that for the main ions the diamagnetic term is the dominant contribution in the radial force balance (not shown), which is also in agreement with neoclassical theory. Thus, the main ion flow velocity perpendicular to the magnetic field, $v\ _i$, is very small in magnitude and approaches $v\ _i$ 0 inside the ETB, similar to results obtained at Alcator C-Mod [3].

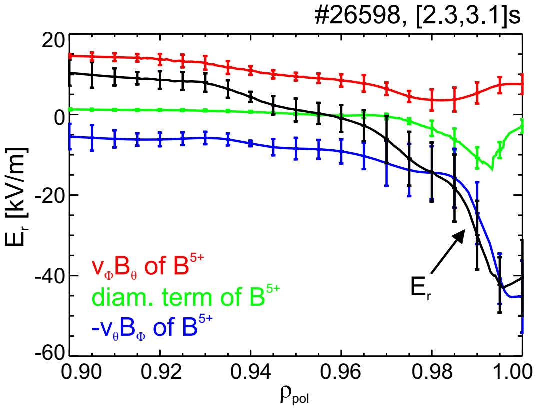

Figure 1: E_r profile obtained in H-mode: total E_r in black, toroidal B^5 rotation term in red, diamagnetic term of B^5 in green, poloidal B^5 rotation term in blue.

CXRS on main ions, i.e. D, is difficult to interpret due to large background emissions and Doppler shifted emission from neutral beam ions. However, helium plasmas provide the opportunity to obtain information on the main ion species. The main ion temperature, density and both poloidal and toroidal rotation velocities have been obtained from CXRS on He^2 in helium plasmas. From these measurements E_r is evaluated and is found to be dominated by the diamagnetic term of He^2. Note that at the plasma edge the plume effect [4] is small and therefore negligible. This is also confirmed by independent electron density measurements. The main ion density (i.e. the helium density) is half the electron density, while the gradients are the same. The poloidal rotation is found to be close to 0 and is in agreement with the prediction of NEOArt [5] (see figure 2), i.e. the main ion poloidal rotation is given by the ion temperature gradient scale length.

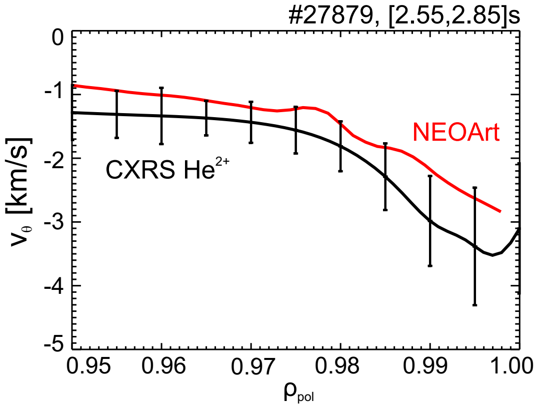

Figure 2: Measured and simulated main ion poloidal rotation velocity.

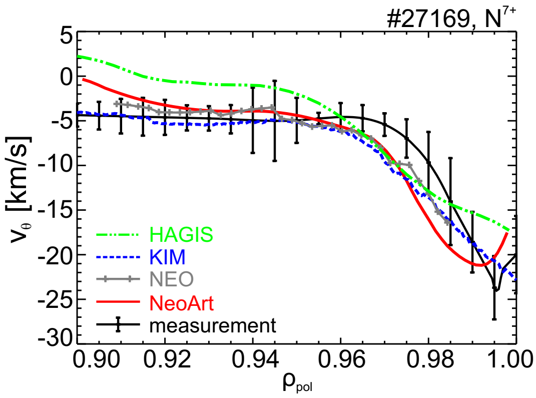

Figure 3: Comparison of measured and simulated nitrogen poloidal rotation velocity profile.

For an H-mode discharge performed in D the measured poloidal rotation of N^{7} is compared to conventional neoclassical predictions [6] and to several neoclassical codes including NEOArt, NEO [7] and HAGIS [8] (see figure 3). The neoclassical prediction using the analytic model [6] is shown in blue, while the simulated profiles using NEOArt, NEO and HAGIS are shown in red, gray and green. In H-mode plasmas both the sign and the magnitude of the neoclassical predictions are found to be consistent with the measured poloidal rotation profiles of both impurity ions and main ions (as measured in He plasmas).

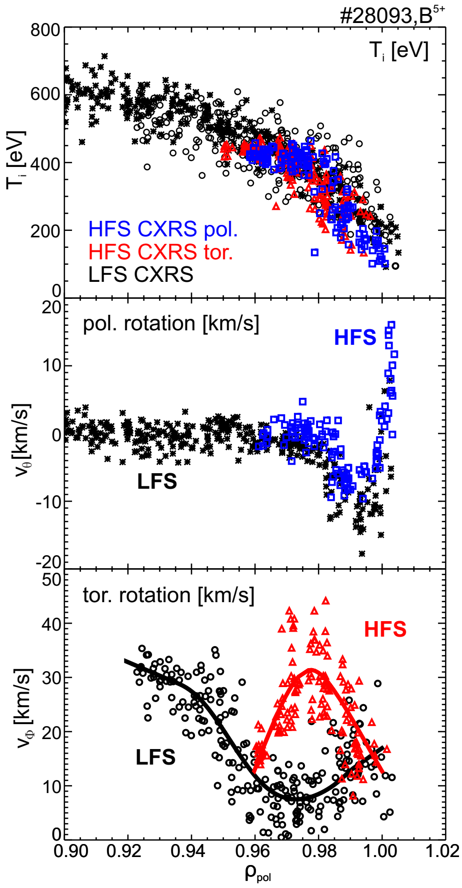

Figure 4: T_i and rotation velocities measured at the HFS and LFS.

Novel CXRS measurements based on a localized D gas puff at the inboard midplane of AUG enable the study of asymmetries on a flux surface. In the last opening two poloidal optical heads were installed at the inner wall to complement the pre-existing toroidal high-field side (HFS) diagnostics [9]. One optical head views the D gas puff while the other views the background plasma at the same poloidal location, but at a different toroidal location to avoid the active CX signal. Thus, the background signal measured in the active CX spectra can be subtracted. The resulting spectra give information on the HFS poloidal rotation, ion temperature (T_i) and intensity of the observed species. From these measurements, combined with those obtained from the toroidal HFS system, the E_r profile at the HFS is evaluated and compared to the beam-based measurements at the low-field side (LFS). Figure 4 shows inter-ELM profiles of T_i and rotation velocities at the HFS and LFS of AUG measured in an H-mode plasma. The HFS measurements are aligned to the LFS measurements via the T_i profile and thus, the E_r profiles are aligned relative to each other. For the evaluation of the HFS diamagnetic term two approaches are used: (i) the impurity density n_α is constant on a flux surface and (ii) the HFS n_α is higher than the LFS n_α as observed on Alcator C-Mod [10, 11] and postulated in [9].

Such a poloidal density asymmetry could explain the measured parallel flow velocities at the HFS [9]. For (ii) the neoclassical formalism for the total flow on a flux surface is used [10], thereby allowing for a poloidal n_α variation. This enables the evaluation of the HFS n_α using the measured poloidal rotation velocities and the LFS n_α. The resulting n_α asymmetry factor is similar to those found in [9]. In both cases the radial position of the minimum in E_r at the HFS and LFS coincides, while the absolute value of E_r differs depending on the flux surface. Preliminary analyses indicate that for the presented case, the electric potential in the ETB is up to 300 V lower at the HFS than at the LFS.

On the LFS, the E_r profile has also been measured in L- and I-mode [12] plasmas. In L-mode, E_r is small in magnitude and exhibits little shear. In this confinement regime both impurity ion velocity terms in equation (1) are dominant for the evaluation of E_r, while the diamagnetic term is almost negligible. In the I-mode regime the minimum of E_r is intermediate between L- and H-mode and dominated by the poloidal rotation term. Combining the results obtained in L-, I- and H-mode demonstrates that the minimum of the E_r profile is correlated with the pedestal top ion pressure (see figure 5). There is a clear correlation between deeper E_r wells and higher pedestal top pressures further confirming that E_r is mainly determined by the main ion diamagnetic term. Hence, the following picture develops from these measurements: For constant E_r well widths, deeper E_r wells have higher E_r shearing rates, thus increasing the efficiency of turbulence suppression. This leads to higher pedestal top pressures (i.e. higher heights of the ETB), which is connected to the global plasma confinement due to stiff T_i gradient scale lengths in the core. Hence, also the magnitude of the E_r shear (here defined as $\omega_{E\;\;B} = \nabla E_r/B_\phi$) should be correlated to the energy confinement and is confirmed by the measurements. In the low confinement regimes, i.e. L- and I-mode, the shear is small, while in the ETB of the H-mode the E_r shearing rate reaches values of up to 3 MHz.

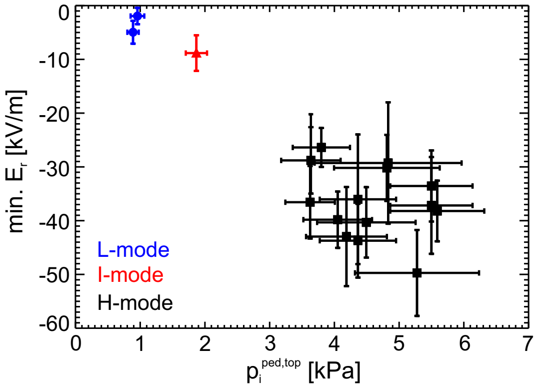

Figure 5: Depth of E_r well as a function of the pedestal top ion pressure $p_i^{ped\ top}$ (at ρ_{pol}=0.97).

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