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First Measurements of the Radial Electric Field with the Motional Stark Effect Diagnostic in ASDEX Upgrade

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The radial electric field plays an important role in tokamak transport theory as it determines the $\vec{E} \times \vec{B}$ shear flow which is one of the processes responsible for the suppression of micro turbulence [1]. To verify these theories various measurements of E_r have been developed in recent years: (A) From charge exchange recombination spectroscopy (CXRS) the different terms of the radial force balance are inferred and subsequently E_r is calculated [2]. (B) The change of the edge radial electric field in the H-mode transition has been derived by charge exchange measurements of high energy neutrals [3].(C) The measurement of the poloidal magnetic field by means of the motional Stark effect (MSE) is also sensitive to E_r [4], because the neutral beam atoms experience in their rest frame not only the Lorentz field due to their motion relative to the magnetic field, but also the radial electric field. Hence, the total electric field is given by

$$\vec{E} = \vec{v}_\mathrm{beam} \times \vec{B} + \vec{E}_\mathrm{r} \tag{1}$$

Here, $\vec{v}_\mathrm{beam}$ is the beam velocity, $\vec{B} = \vec{B}_\mathrm{pol} + \vec{B}_\mathrm{T}$ the total magnetic field, and $\vec{E}_\mathrm{r}$ the radial electric field vector. If $E_\mathrm{r}/v_\mathrm{beam}$ becomes of the order of B_pol then E_r can no longer be neglected. This is the case, in particular, for discharges with internal transport barriers (ITBs), where E_r can reach values of the order of 100kV/m. However, if two independent measurements of $\vec{E}$ are employed, this facilitates not only the deduction of B_pol but also of E_r. One possibility to measure E_r by means of MSE is to use two different lines of sight at the same radial position [4]. Another one is to use the same line of sight and to measure two different energy components of the neutral beam [5]. In ASDEX Upgrade the latter method is employed, which for machines with limited spatial access is easier to implement. In a non-planar viewing geometry the measured polarization angle of the Stark emission can be written as:

$$\tan\gamma_m = \frac{A_1 B_R + A_2 B_T + A_3 B_Z + A_4 E_R/v_b}{A_5 B_R + A_6 B_T + A_7 B_Z + A_8 E_R/v_b + A_9 E_Z/v_b} \tag{2}$$

where B_R, B_T, and B_Z are the magnetic field components in the cylindrical torus system (R: radial, T: toroidal, Z: vertical), E_R and E_Z the respective radial electric field components, v_b the beam velocity, and A_i geometrical coefficients which depended only on the viewing geometry. For the deduction of the current profile the above representation of γ_m is used as an additional constraint in the equilibrium code CLISTE [6]. To correct for the influence of E_r on the MSE polarimeter angle γ_m, E_R and E_Z are substituted by the values inferred from CXRS. For the self consistent determination of the current profile and the radial electric field, the polarimeter angles γ_m and $\gamma_{m/2}$ of the full and half energy fractions of the neutral beam are both used to constrain the equilibrium reconstruction by CLISTE. Spectroscopically the two polarization angles are distinguished by the different Doppler shifts of two energy components.

Neglecting the terms $A_5 B_R$, $A_7 B_Z$, $A_8 E_R/v_b$, and $A_9 E_Z/v_b$ in the denominator of (2), which are small compared to $A_6 B_T$, E_r can be approximated by

$$E_r = (\tan\gamma_m - \tan\gamma_{m/2}) B_T v_b \frac{A_6}{A_4(1-\sqrt{2})} \tag{3}$$

In figure 1 this method has been used to derive E_r from the measured γ_m's at $\rho_\mathrm{pol} \approx 0.6$.

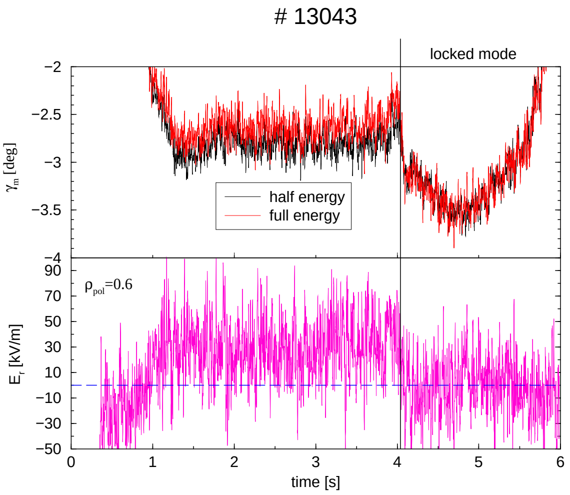

Figure 1: Time traces of γ_m,$\gamma_{m/2}$ (upper trace) and calculated E_r (not averaged,lower trace).

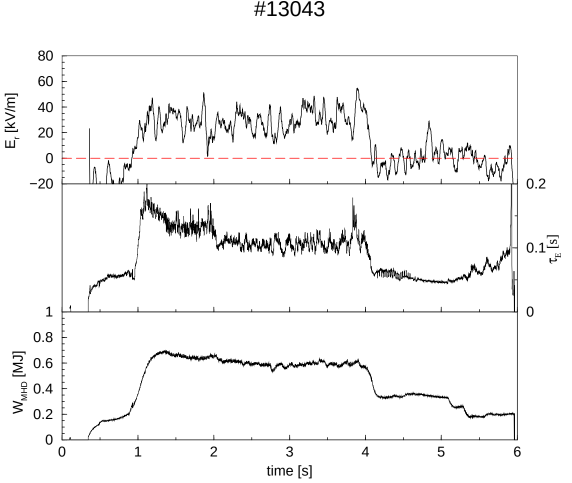

Figure 2: Time traces of E_r (upper trace), τ_E (middle trace), W_{MHD} (lower trace) of an H-mode with improved confinement. After reaching the β-limit, a locked mode occurs approximately at 4s.

This is the only system wich has been upgraded until yet. As the small difference $(\tan\gamma_m - \tan\gamma_{m/2})$ is multiplied by the large values of beam velocity and toroidal magnetic field, a large noise level is produced in the resulting E_r. Therefore, all E_r values from MSE shown below are averaged over 50ms, although the sampling rate is 1kHz. Another problem is the absolute value of γ_m. The calibration procedure results in a minimum error of about 0.2 deg, corresponding to an uncertainty of 40kV/m in E_r. To improve the absolute accuracy, the calibration factors of the half energy channels are adjusted to produce $E_\mathrm{r} = 0$ in the presence of locked modes. This assumption is justified, as the plasma toroidal rotation stops and the pressure gradient is balanced by the diamagnetic drift. In the example discharge of figure 1 a locked mode occurs at $t = 4$s.

In figure 2 the relation between the radial electric field measured by MSE (now averaged over 50ms) and the energy confinement is exemplified for a discharge with improved H-mode confinement [7]. While before 1s at 2.5MW of neutral beam heating power E_r is still small, a transition can be observed after 1s when the power is increased to 5MW and plasma energy, energy confinement time, and radial electric field start to rise simultaneously. However, for an analysis concerning turbulence suppression by $\vec{E} \times \vec{B}$ shear flow the measurement of the full E_r-profile is required. This extension of the MSE diagnostic is presently under construction.

ASDEX Upgrade is equipped with a CXRS diagnostic [2] which by means of poloidal and toroidal views measures the respective rotation velocities $v_{\mathrm{pol}}, v_{\mathrm{T}}$ and the radial pressure gradient $\nabla_r p$ of the impurity ion species C^{5+}. Substituted into the radial force balance equation, E_r is calculated:

$$E_r = \frac{1}{Zen_\mathrm{Z}} \nabla_r p_\mathrm{Z} - v_{\mathrm{pol}} B_\mathrm{T} + v_\mathrm{T} B_{\mathrm{pol}} \tag{4}$$

where B_{pol} and B_T are the poloidal and toroidal magnetic field components, n_Z the density, and Z the charge number of ion species used. In figure 3 the different E_r measurements are compared for the discharge presented in figure 2.

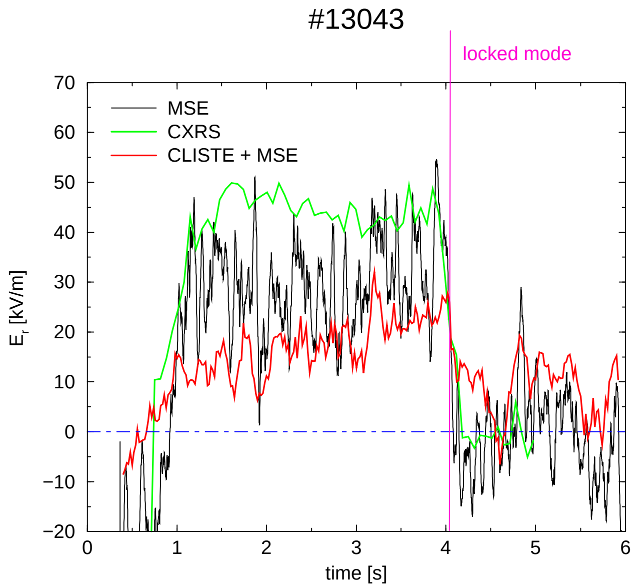

Figure 3: Time trace of E_r at $\rho \approx 0.6$ from MSE directly using the approximation of equation 3, from CXRS, and from MSE constraining the CLISTE equilibrium reconstruction with the polarimeter angles from the full and half energy components of the neutral beam.

The time evolution of E_r is qualitatively the same for all three methods. During the high confinement phase between 1s and 4s an increase of E_r can be observed. While E_r from MSE measurement is calibrated to be zero when a locked mode is present, the CXRS value drops to zero independently. Considering that the E_r value calculated from the MSE polarization angles directly is only an approximation, also the quantitative agreement is acceptable. Up to now two polarization angles of two energy components are only available at one radial location.

The systematic deviations of E_r calculated by CLISTE, a rather low E_r during the high confinement phase, and a small but finite value during the locked mode phase are unclear.

To study the influence of E_r on the q-profile evaluated by CLISTE using the MSE data, the radial electric field components in equation 2 are taken from the CXRS measurements. In figure 4 q-profiles without considering E_r and with the correction by CXRS are compared. In the first case, a discharge with reversed magnetic shear and an ITB is shown [8]. Including E_r the whole q-profile drops, but most prominently the central q-value (q_0). The minimum value of q (q_{min}) decreases less, but nevertheless improves the agreement between the appearance of a ($m = 2, n = 1$) double tearing mode and the time when q_{min} reaches 2. The same trend in the q-profile can be observed in the second case, which shows the monotonic q-profile of an improved confinement H-mode and is characterized by an extended low shear region in the plasma core. Here the central magnetic shear is not affected, but the absolute values of q in the core region of the plasma.

In summary, the possibility to determine the local radial electric field by means of MSE measuring the polarization angle of different energy fractions of the beam emission

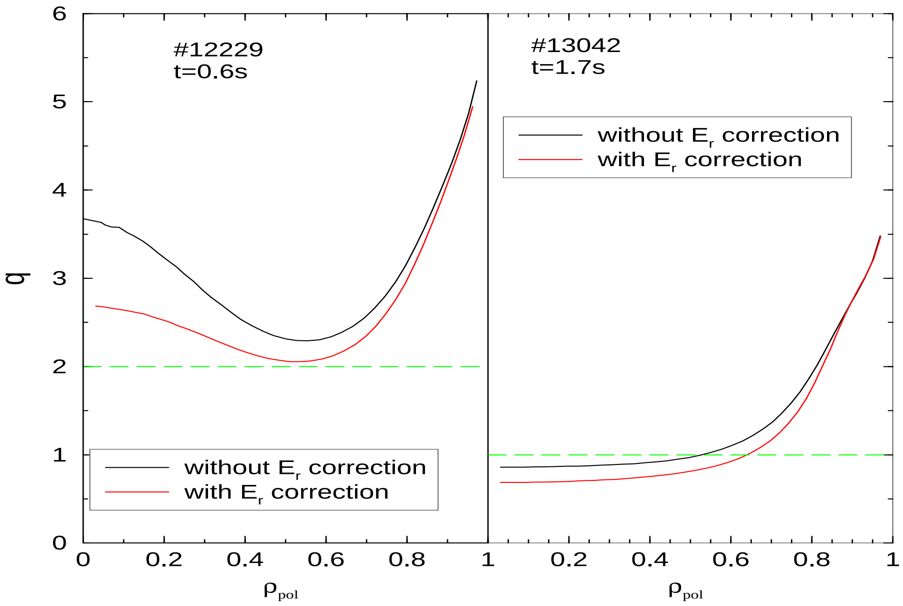

Figure 4: q-profiles without and with E_r correction, ITB and H-mode with improved confinement

spectrum has been demonstrated at ASDEX Upgrade. As observed in other tokamaks [9], the inclusion of E_r in the equilibrium reconstruction results in a drop of the q-profile over the whole radius. For the verification of transport theories based on $\vec{E} \times \vec{B}$ shear flow suppression of turbulence, the extension of this diagnostic to more radial channels is presently under construction.

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