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Effect of the radial electric field on transport at ASDEX Upgrade

H. Meister, A. Kallenbach, A. G. Peeters, J. Hobirk,
G. V. Pereverzev, F. Ryter, W. Ullrich and ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, EURATOM Assoziation
Boltzmannstr. 2, D-85748 Garching b. München

Introduction A promising operation regime for future tokamaks is the "advanced tokamak". Showing a good energy confinement and a high fraction of non-inductive driven plasma current, these scenarios have an internal transport barrier (ITB) which enables high ion temperatures in the plasma center. As heat diffusivity coefficients reach neoclassical levels in the plasma center in these scenarios, anomalous, turbulent transport is reduced. Similar to the transport reduction at the plasma edge in H-mode scenarios, theory explains the transport reduction in ITB regimes by $E \times B$ flow shear decorrelation of turbulence [1]: if the $E \times B$ shearing rate, $\omega_{E\times B} = \left| \frac{RB_\theta}{B_\phi} \frac{\partial}{\partial r} \left(\frac{E_r}{RB_\theta} \right) \right|$, exceeds the maximum linear growth rate of instabilities a stabilizing effect and hence transport reduction should be observed. The gyro-Landau fluid model used for the calculation of linear growth rates in this paper is based on the ion temperature gradient (ITG) instability, as this mode dominates the turbulent transport in the plasma center [2].

Diagnostic In order to experimentally test the prediction, whether $E \times B$ shear decorrelation is responsible for transport reduction in advanced tokamak regimes, one has to provide the radial electric field. It can be calculated from the radial force balance, $E_r = \frac{\nabla_r(p_i)}{Z_i e n_i} - v_{\phi,i} B_\theta + v_{\theta,i} B_\phi$. B_θ and B_ϕ denote the poloidal and toroidal magnetic field, $\nabla_r(p_i)$ the radial pressure gradient of the observed ion species i, Z_i, n_i, $v_{\phi,i}$ and $v_{\theta,i}$, their charge, density, toroidal and poloidal rotation velocity respectively.

At ASDEX Upgrade the charge exchange recombination spectroscopy (CXRS) has recently been extended with poloidal sight-lines and is now capable of providing all the quantities needed to calculate E_r, excluding the magnetic fields which have to be taken from equilibrium reconstruction. The most difficult quantity to measure is the poloidal rotation because its values are low and its uncertainties have to be kept as low as possible as v_θ is weighted with the large toroidal magnetic field when calculating E_r. Therefore not only the calibration has to be done very carefully, the geometry of the sight-lines with respect to the neutral beam on the one hand and to the magnetic field lines on the other hand have to be taken into account, because they give rise to apparent velocities due to the energy dependent cross-section for CXRS reactions.

Corrections due to cross-section effects As the effective charge exchange cross-section depends on the collision energy, the emissivity will show its effects on the observed spectra due to the average over the Maxwellian velocity distribution. Sight-lines which do not intersect the neutral beam perpendicularly will show lower intensities in the red part of the spectrum and higher intensities in the blue part. This results in shifted line-shapes with usually reduced line widths. The corresponding apparent rotation velocities and apparent temperatures are corrected for the toroidal sight-lines using an analytical procedure [3].

This effect of the energy dependent cross-section affects in principle the poloidal sight-lines, too. As these sight-lines are mainly perpendicular to the magnetic field lines, the gyration of the ions together with the finite life-time of the excited states also influences the spectral line shape as has been pointed out recently [4]. This effect can be explained as follows.

Due to the gyro motion, one half of the ions have a component of their velocity vector which is anti-parallel to the velocity vector of the beam neutrals. Therefore these ions have higher collision velocities during the charge exchange process than the other half. This leads to higher cross-sections and more hydrogen-like excited impurities for one half of the observed impurity ions. As the life-time of the excited states is finite, the ions will move along some fraction of the gyro orbit before emitting the photons which will be detected. This leads to a net velocity which will be observed at all radii by poloidal sight-lines.

In order to derive the apparent velocity $\vec{v}_{\text{app}}$ due to the finite life-time of the excited states one has to calculate the weighted average over the gyro motion of the observed hydrogen-like impurity:

$$\vec{v}_{\text{app}} = \frac{\sum_{jk} n^b_{jk} n^i \iiint d^3v \int dt \quad e^{-\frac{t}{\tau}} \cdot Q^{CX}_{jk}(v_{\text{col}}) \cdot f(\vec{v} - \vec{v}_{\text{rot}}) \cdot \vec{v}_{CX}(t)}{\sum_{jk} n^b_{jk} n^i \iiint d^3v \int dt \quad e^{-\frac{t}{\tau}} \cdot Q^{CX}_{jk}(v_{\text{col}}) \cdot f(\vec{v} - \vec{v}_{\text{rot}})} \tag{1}$$

The average is taken in time over the life-time τ on the one hand and on the other hand in velocity space over the Maxwellian distribution function f multiplied with the effective charge exchange cross-section $Q^{CX}_{jk}(v_{\text{col}})$. Together with the multiplication by the density of the beam neutrals n^b_{jk} and that of the fully ionized species n^i the average in velocity space corresponds to the charge exchange emission from an unit volume. The gyro motion $\vec{v}_{CX}(t)$ can be described in a coordinate system with its z-axis parallel to the magnetic field lines as follows:

$$\vec{v}_{CX}(t) = v_\perp \sin(\vartheta - \omega t)\vec{e}_{x'} - v_\perp \cos(\vartheta - \omega t)\vec{e}_{y'} + v_{||}\vec{e}_{z'} \tag{2}$$

The other quantities in the above equations are the gyro frequency ω, the velocity perpendicular and parallel to the magnetic field, $v_\perp$ and $v_{||}$, the collision velocity v_{col} and the bulk rotation of the plasma $\vec{v}_{\text{rot}}$. The sums take the different beam species k and beam sources j into account.

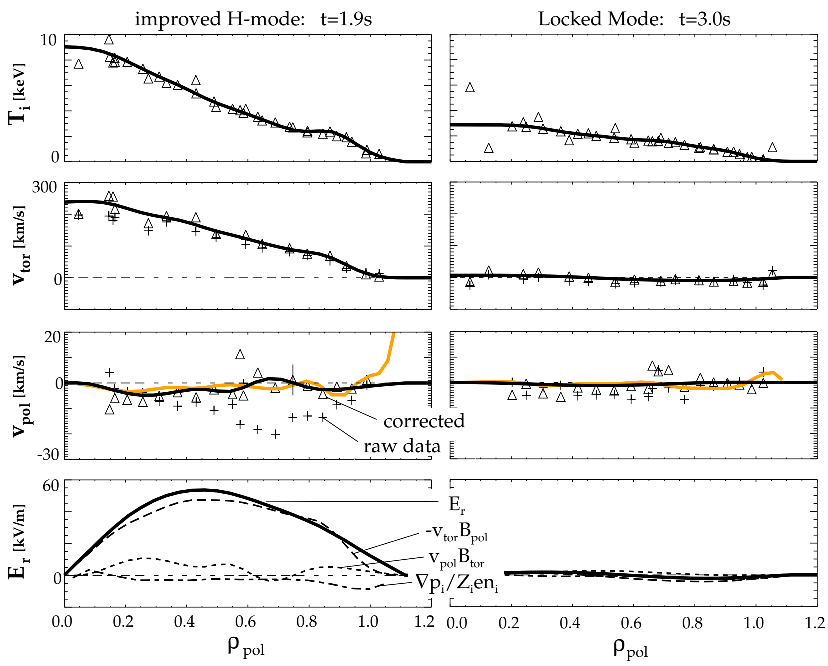


Figure 1: *CXRS data for an ASDEX Upgrade H-mode shot (#12957, $t = 1.9\,s$). Left column during improved confinement, right column during a locked mode later in the discharge (+ raw data, △ corrected data, — spline fit).*

Experimental results As an example for the application of the discussed corrections, the results of the evaluation of CXRS data for an ASDEX Upgrade H-mode shot with improved confinement are shown in figure 1. The left column shows the profiles during improved confinement. T_i and v_{tor} have high pedestal and central values. The corrections for the toroidal velocity are up to 20% of the raw value, depending on ion temperature. The raw values of v_{pol} are significantly higher than the error bars but correction reduces them to the low level of neoclassical expected values (—). E_r is, as is usually at ASDEX Upgrade, dominated by the contribution of v_{tor}, contributions of the carbon pressure gradient and v_{pol} are small. The right column on the other hand shows profiles of the same discharge somewhat later during a phase with a locked mode. T_i is much lower due to confinement loss from mode activity and the macroscopic rotation is stopped completely. Note that zero poloidal rotation is reached only after applying the corrections. In the case of a locked mode with $v_{\text{tor}} = 0$, $E_r = 0$ but finite pressure gradient one would expect to measure the diamagnetic drift in poloidal direction. But v_{dia} is approximately 2 $\frac{km}{s}$ and therefore inside the error bars.

Transport studies In order to decide whether experimental results at ASDEX Upgrade are compatible with the theoretical prediction of transport reduction via $E \times B$ shear decorrelation, $E \times B$ shearing rates $\omega_{E\times B}$, maximum linear growth rates for ITG modes γ_{max} and ion heat diffusivity coefficients χ_{ion} have been calculated from measurements for two different scenarios, an H-mode with improved confinement and an ITB discharge with L-mode edge.

The comparison of χ_{ion} in figure 2 shows that ion heat diffusivity profiles of a conventional H-mode and of the H-mode with improved confinement are similar but reduced in the latter. The profile of the discharge with ITB on the other hand exceeds the values of the H-mode in the outer part of the plasma according to its L-mode edge properties and reaches neoclassical expected values in the center. χ_{neo} has been calculated with the transport code ASTRA using two different models. The model giving the lower boundary included the effect of the finite gyro-orbit, whereas the upper boundary neglected it. This exemplifies the high uncertainties of χ_{neo} in the plasma center, as it is not yet clear, which theoretical model gives the best representation. Nonetheless, χ_{ion} reaches almost the lower boundary of χ_{neo} in the ITB discharge. This leads to the presumption that anomalous transport is suppressed inside the internal transport barrier, whereas transport reduction in the H-mode with improved confinement is achieved due to profile stiffness.

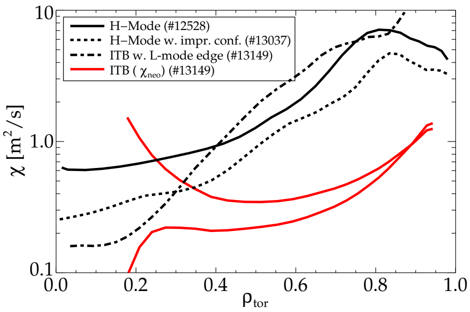
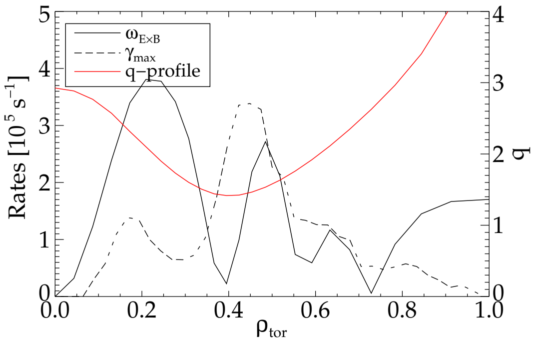


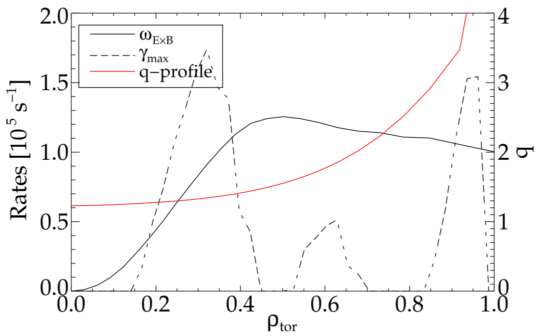
Figure 2:*Comparison of* χ_{ion}

In order to test this assumption $E \times B$ shearing rates and maximum linear growth rates have been calculated for these discharges. As shown in figure 3(a) $\omega_{E\times B}$ exceeds the linear growth rates by a factor of 3 inside the ITB which is located just inside the minimum of the reversed shear q-profile. $\omega_{E\times B}$ and γ_{max} in the H-mode with improved confinement on the other hand are similar across the whole profile (figure 3(b)). The deviations near the plasma edge are due to the poor resolution of the CXRS diagnostic in this region, which makes the calculation of gradients difficult.

As the presented calculations of γ_{max} are quasi stationary, no conclusion can be drawn for the cases where $\omega_{E\times B} \approx \gamma_{\text{max}}$. In these cases shear is not strong enough to prevent the growing of instabilities and because quasi stationary transport is the result of nonlinear saturated instabilities the calculated values of γ_{max} have no significance.



(a) *Discharge with ITB and L-mode edge (#13149, $t = 1.08$ s).*



(b) *H-mode with improved confinement (#13037, $t = 2.1$ s).*

Figure 3: *$E \times B$ shearing rates and maximum linear growth rates.*

On the other hand, even if one takes the rather high uncertainties of of $\omega_{E\times B}$ and γ_{max} into account, a clear trend can be observed in the plasma center of the discharge with ITB. The very high shearing rates and the low transport coefficients inside the reversed shear region support the assumption that ITG dominated turbulent transport is reduced in this region via $E \times B$ shear decorrelation.

Latest results from H-mode shots with improved confinement with NBI and ECRH show a sharp increase in T_e and a slower decrease in T_i during the phase with additional electron heating. As the criterion for stability of ITG-modes gets more restrictive with increasing T_e/T_i, these results may support ITG models. But a clear conclusion cannot be drawn yet, because together with the onset of ECRH mode activity is changed, too.

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