The role of radial electric field and neoclassical transport in the establishment and sustainment of the edge transport barrier in the ASDEX Upgrade tokamak

M. Cavedon[1], T. Pütterich[1], E. Viezzer[2], G. Birkenmeier[1,3], M. G. Dunne[1], R. Dux[1], E. Fable[1], T. Happel[1], F.M. Laggner[4], P. Manz[1,3], F. Ryter[1], U.Stroth[1,3], E. Wolfrum[1], ASDEX Upgrade Team

[1] *Max-Planck-Institute for Plasma Physics, Boltzmannstr. 2, D-85748 Garching, Germany*

[2] *Dept. of Atomic, Molecular and Nuclear Physics, University of Seville, Spain*

[3] *Physik-Department E28, Technische Universität München, Garching, Germany*

[4] *Institute of Applied Physics, TU Wien, Fusion@ÖAW, 1040 Vienna, Austria*

Introduction

It is widely accepted that the $\mathbf{E}\times\mathbf{B}$ velocity shear is responsible for the suppression of the edge turbulence, thus leading to the formation of an edge transport barrier (ETB) and to the transition from the low confinement mode (L-mode) to the H-mode. However, the origin and the evolution of the edge radial electric field (E_r) profile and the accompanying $\mathbf{E}\times\mathbf{B}$ flow ($v_{E\times B}$) is still very much disputed in the scientific community. The $\mathbf{E}\times\mathbf{B}$ flow may be generated by turbulence stresses or collisional (neoclassical) processes and it must follow the radial force balance equation. For small toroidal velocity, neoclassical theory predicts that $v_{E\times B}$ is dominated by the main ion temperature (T_i) and density (n_i) gradients. It is predicted to almost perfectly compensate the diamagnetic velocity $v^i_{\mathrm{dia}} = \nabla_r(n_iT_i)/(eZ_in_i)$ [1] . Note that neoclassical theory can only predict E_r if the profiles of density and temperature are given. Still, turbulence may design the shape of these profiles.

The neoclassical contribution to the $v_{E\times B}$ velocity is always present and it is found to be the dominant in H-mode [2, 3]. However, its importance has not been assessed yet in the transition from L- to H-mode at ASDEX Upgrade (AUG). In particular, zonal flows (ZFs) have often been invoked as a possible triggering mechanism for the L-H transition [4, and references therein]. However, a direct measurement of the energy transfer from turbulence to the ZF via Reynolds stress, which has been made in low temperature plasmas [5], is not possible in fusion plasmas. Hence, additional sources of the $\mathbf{E}\times\mathbf{B}$ flow can only be determined if the radial electric field can be measured with high accuracy and compared to the neoclassical prediction at the edge of the plasma where the toroidal rotation is observed to be small. Deviations of the measurements from the predictions would clearly point to the importance of additional driving mechanisms such as turbulence driven flow. A better understanding of the generation of the edge transport barrier and its sustainment is of crucial importance to enable a better control of the L-H transition process and of the transport at the plasma edge.

The role of $\mathbf{E_r}$ for the L-H transition

Recent studies demonstrated a correlation between the ion heat channel and the H-mode onset highlighting the importance of the main ions in the L-H transition mechanism [6, 7]. Due to the close interconnection between main ions and the $\mathbf{E}\times\mathbf{B}$ flow via the diamagnetic velocity,

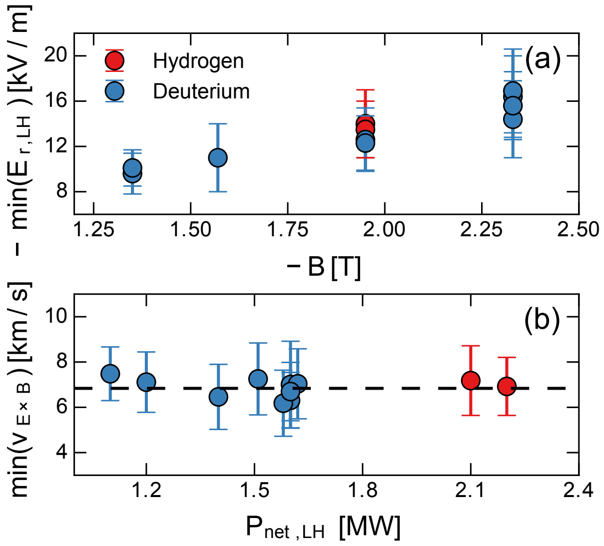

Figure 1: (a) E_r minimum at the L-H transition as a function of the local magnetic field B in hydrogen (red) and deuterium (blue) plasmas. (b) $v_{E\times B}$ minimum dependence on the L-H transition power threshold.

it is natural to investigate to what extent the macroscopic L-H power threshold dependencies correlate with the **E**×**B** shear at the L-H transition. To that end the E_r minimum, a proxy of the E_r shear [8], has been measured at the L-H transition at various B-fields, electron densities, and in both hydrogen and deuterium plasmas. In figure 1a the absolute value of the E_r minimum just before the final L-H transition is shown as a function of the magnetic field B at the measurement position for deuterium (blue) and for hydrogen (red) discharges. The minimum of E_r scales roughly linearly with B, explaining the almost linear dependence of P_{thr} on B. In other words, a constant $v_{E\times B} = E_r/B$ is found at the L-H transition independently on the required power threshold (see figure 1b). This is remarkable, because the related power threshold varies between 1.1 MW and 2.2 MW. These findings suggest that, for the investigated plasma configurations (LSN, $0.2 < \delta < 0.25$), a critical $v_{E\times B}$ shear is required to access the H-mode.

Fast dynamics of E_r during the L-H transition

In search of a situation where discrepancies from neoclassical theory could appear, the dynamics of the L-H transition has been investigated with a time resolution of down to 100 µs. In particular, a pulsating phase of the edge E_r and of the turbulence amplitude, originally called dithering H-mode [9] and more recently limit cycle oscillation (LCO) or "I-phase" [10, 11], is often observed close to the L-H transition where the role of turbulence induced flow shear is under investigation [11, 12]. In the present work, the I-phases of several L-H transitions have been analyzed during which the measurements of the **E**×**B** velocity and the main ion diamagnetic velocity have been compared by means of conditional synchronization over the turbulence pulsations. The result is presented in figure 2 where the time-traces of $v_{E\times B}$ (a) and v^i_{dia} (b) are shown at different radial locations. The flows are compared to the turbulence level at the edge measured by Doppler Reflectometry (c). A quantitative agreement within the error bars is found between v^i_{dia} and

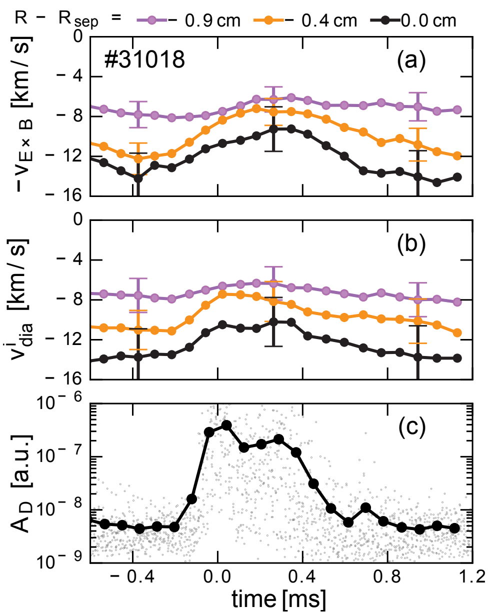

Figure 2: Comparison during a constant I-phase between the measurements of the **E**×**B** velocity (a) and the main ion diamagnetic velocity (b) at different radial positions with the turbulence level at the edge (c).

$v_{E\times B}$. As a result, while the physics of the zonal flows has been largely demonstrated in previous studies [4, and references therein], here it is shown, that their contribution to the total **E**×**B** flow is small compared to the neoclassical one. Note that in the present work particular effort is dedicated to the measurements of v^i_{dia} which combined with the **E**×**B** flow, provides the only way to quantitatively estimate the amplitude of the turbulence induced flows. In previous studies, the neoclassical flows are often poorly documented due to the demanding diagnostic requirements.

A correlation analysis reveals that the evolution of the edge gradients, flows and turbulence is, within the experimental resolution (100 µs), simultaneous during the whole transition from L- to H-mode [13]. In particular, the interconnection between the pressure gradient and the flow holds at the L-I transition and during the following initial I-phase bursts. The latter observation suggests more an ELM-like behavior: Particles and energy are expelled during each turbulent phase [14]. Note that a significant contribution to the **E**×**B** velocity from turbulence induced flows would induce a phase difference in the evolution of $v_{E\times B}$ and v^i_{dia}.

E_r during Edge Localized Modes (ELMs)

To clarify the nature of the radial electric field after the establishment of the edge transport barrier, E_r has been compared to its neoclassical prediction throughout an ELM cycle. While E_r has been shown to be neoclassical just before the ELM onset [2, 3], the present analysis aims to investigate the fast dynamics within one ELM cycle with a time resolution of 100 µs. Such a comparison was so far inaccessible due to the demanding diagnostic requirements. The results are shown in figure 3 where the minimum of E_r (a) is compared to its neoclassical prediction $E_{\mathrm{r,neo}}$ (b). The measurements are synchronized relatively to the onset of the ELM (t_{ELM}) which is indicated by the vertical dashed line. Both time-traces show a similar trend: the E_r shear is strongly reduced at the ELM onset and the pre-ELM conditions are re-established within 4 ms after the crash. Despite the qualitative similarities, E_r and $E_{\mathrm{r,neo}}$ present quantitative differences after the ELM crash, between 2 and 4 ms, as shown in figure 3c. Several reasons could lead to this discrepancy, e.g. turbulence induced flows or ion orbit loss effects. The deviations are however in the phase where the scatter of measurements increase due to the uncertainties in the mapping and in the normalized gradient ($\nabla n/n$). Hence, further investigations are required to confirm this observation.

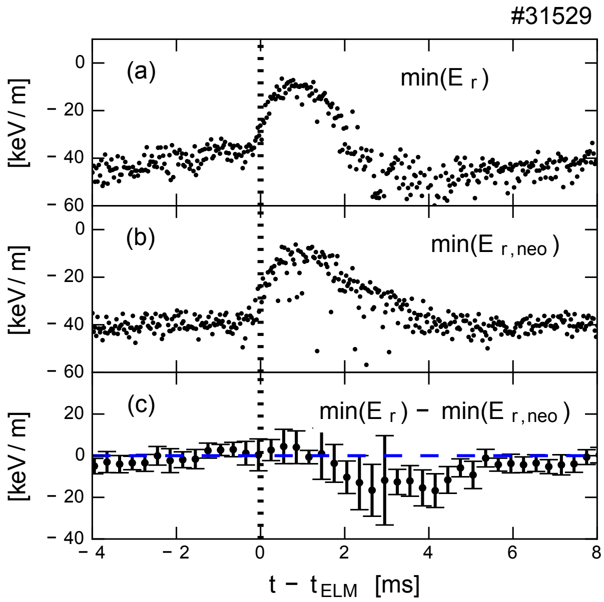

Figure 3: Comparison during an ELM cycle between the measurements of the E_r minimum (a) and its neoclassical prediction (b). The discrepancy between the time-traces is shown in (c) where the error bars are derived from the standard deviation of the measurements binned every 300 µs.

As the fast CXRS measurements were carried out during a type-I ELMy H-mode it was possible to compare the recovery of the electron and ion channels after the ELM crash for the first time. The comparison reveals that the maximum of the ion temperature gradient recovers on a much shorter timescale than the electron temperature gradient, confirming the hypothesis in ref. [15] where the reconstructed edge current density has been found to deviate from the calculated one assuming $T_i = T_e$ suggesting a faster recovery of ∇T_i. The implication of such an asymmetry on the stability and formation of the pedestal is under investigation.

Summary

The edge CXRS system at ASDEX Upgrade has been upgraded to provide temporally and radially resolved measurements of the ion temperature, density, fluid velocity and hence E_r via the radial force balance equation with unprecedented temporal resolution. The new system enables measurements with a frequency of up to 20 kHz and a radial resolution of down to 3 mm. Together with knowledge of n_e, the CXRS measurements can be used to test the limit of the neoclassical prediction of the $\mathbf{E}\times\mathbf{B}$ velocity. A comparison between $v_{E\times B}$ and v^i_{dia} during a constant I-phase shows no deviations between the measurements within the temporal resolution of 100 µs. Within the same timescale, the edge gradients and flows are found to evolve together during the whole transition from L- to H-mode. Hence, $v_{E\times B}$ seems to be dominated by the collisional (neoclassical) contribution because a substantial contribution from turbulence induced flows should induce delays or differences between $v_{E\times B}$ and v^i_{dia}. A constant $\mathbf{E}\times\mathbf{B}$ shear is observed at the H-mode onset across a large database of L-H transitions under different conditions, including hydrogen and deuterium plasmas. This result is in agreement with [6, 7] and identifies $E_{r,\text{neo}}$ as a key role for the L-H transition. Finally, E_r and $E_{r,\text{neo}}$ have been compared during an ELM cycle. Good agreement has been observed throughout the ELM cycle, except for the phase 2 to 4 ms after the ELM crash. However, due to the relatively large error bars in this phase further investigations are needed to confirm this observation.

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