Study of the edge radial electric field during the L-H transition at ASDEX Upgrade

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In 1982, a regime with improved confinement (H-mode) was discovered at ASDEX [1]. The H-mode exhibits an edge transport barrier (ETB), a region of reduced particle and energy transport at the plasma edge. It is widely accepted that $\mathbf{E}\times\mathbf{B}$ velocity shear, caused by the local radial electric field E_r, is responsible for the suppression of turbulence and therefore for the establishment of the ETB. The formation of the ETB coincides with the transition from the low confinement mode (L-mode) to the H-mode and it is triggered when heating power exceeds a certain threshold P_{thr}, scaling in [2].

Neoclassical theory predicts E_r to be dominated by the diamagnetic velocity of the main plasma ions, as also suggested by experimental observations in H-mode [3] but not assessed yet in the transition from L-mode to H-mode. Recent observations at ASDEX Upgrade (AUG) have shown a correlation between the edge ion heat channel and the H-mode onset [4]. In line with that, a threshold for the E_r minimum, a proxy of ∇E_r, has been observed and is independent of density for a magnetic field of $B_t = 2.5\,\text{T}$ highlighting the importance of $\nabla p_i/(Z_i n_i e)$ in the L-H transition mechanism [5]. However, the triggering mechanism in the transition process is unclear. A pulsating phase of the edge E_r and of the turbulence amplitude, originally called dithering H-mode [6] and more recently limit cycle oscillation (LCO) or “I-phase” [7, 8] is often observed close the L-H transition where the role of turbulence induced flow shear is under investigation [8, 9]. Extensive effort has been directed to understanding the L-H transition, however, a first principle model which reproduces the experimental observations and predicts quantitatively the power threshold has not been developed yet. The aim of the present study is to provide a better understanding of the background $\mathbf{E}\times\mathbf{B}$ velocity shear necessary for the H-mode onset together with an analysis of the interplay between turbulence, flows and kinetic profiles in the dynamic evolution towards the L-H transition.

For this purpose, the edge charge exchange system at AUG has been upgraded. The new system has 30 toroidally (blue) and 20 poloidally (red) aligned lines of sight (LOS) focused at the low field side pedestal region (fig. 1) and permits accurate measurements of impurity density, velocity and temperature profiles.

The toroidal and poloidal projections of the LOS are shown respectively in figures 1 a and b. Through the ion radial force balance ($E_r = \nabla p_\alpha/(Z_\alpha n_\alpha) - v_{\theta,\alpha}B_\phi + v_{\phi,\alpha}B_\theta$, α : impurity species) it is possible to reconstruct the E_r profile from the impurity CXRS measurements, thus allowing the interaction between flows and kinetic profiles to be studied. Moreover a new spectrometer has been designed which, by means of an interference filter, allows the measurements of up to nine LOS at a sampling rate of 20 kHz. Such a time resolution is a fundamental requirement to investigate the fast dynamics close to the L-H transition which typically shows frequencies of a few kHz [6–9].

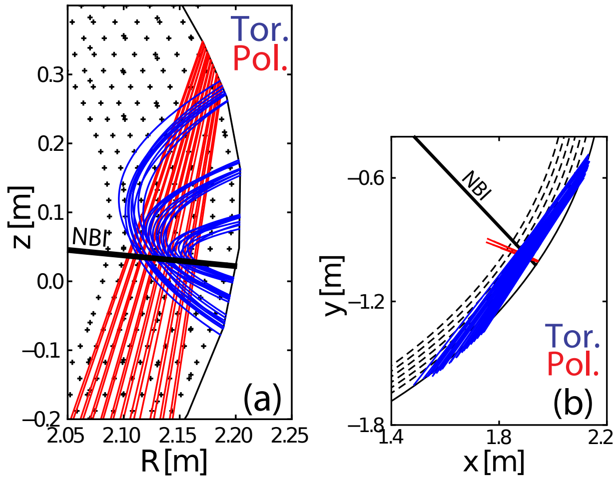

Figure 1: *Poloidal* (a) *and toroidal* (b) *projection of the upgraded edge charge exchange system at AUG*

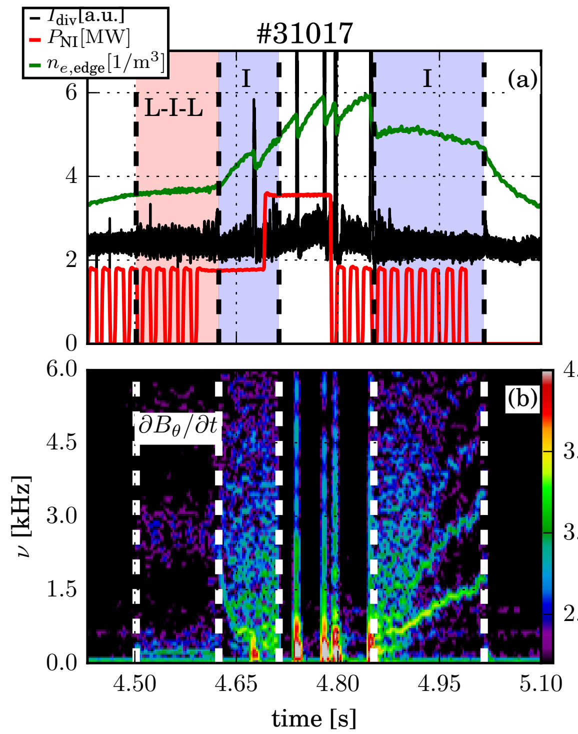

Figure 2: *Example of typical L-H transition:* (*a*) *time traces of the $n_{e,edge}$ (green), P_{NI} (red) and I_{div} (black),* (*b*) *spectrogram of the bottom inward Mirnov coil.*

In order to address the background $\mathbf{E}\times\mathbf{B}$ velocity shear condition for the H-mode onset, it is necessary to understand the dynamics of the L-H transition process and to define a time point where the plasma changes its confinement to enable a comparison of different discharges. In particular, correlations between the E_r profile just before the confinement change and the power threshold have to be investigated in order to experimentally relate the macroscopic effects on P_{thr} to the microscopic $\mathbf{E}\times\mathbf{B}$ shear of turbulence. A series of discharges with different plasma parameters has been performed where several L-H and H-L transitions have been induced by slowly ramping power up and down to allow active charge exchange measurements. In figure 2a, the time traces of the input power P_{NI} (red), the line integrated edge electron density $n_{e,edge}$ (green) and the divertor current I_{div} (black) are shown.

Close to the L-H and H-L transition the I-phase has been identified (fig. 2a, blue shaded area). This phase is clearly visible in the spectrogram of a poloidal Mirnov at the low inboard side coil (fig. 2b) and in the divertor shunt current I_{div} (black, fig. 2a) where the typical fluctuations in the range of a few kHz are detected. The appearance of the dithering phase at the back transition and their effect on $\partial B_\theta/\partial t$ has already been reported in other machines [10–12]. A zoom-in of this phase is plotted in figure 3a where the turbulence amplitude measured by Doppler reflectometry (black) shows the typical bursts which are correlated with the spikes in $\partial B_\theta/\partial t$. These spikes result in harmonics in the Fourier space (fig. 2b) and they show the same characteristics when the spectrogram is more blurry. In several of the analyzed transitions, the I-phase also extends in between type-I ELMs and it is connected with a density rise (fig. 2, blue shaded area) denoting a confinement closer to H-mode rather than L-mode. This is further confirmed by looking at the H-L transition where the plasma goes back to L-mode only when these fluctuations are vanishing.

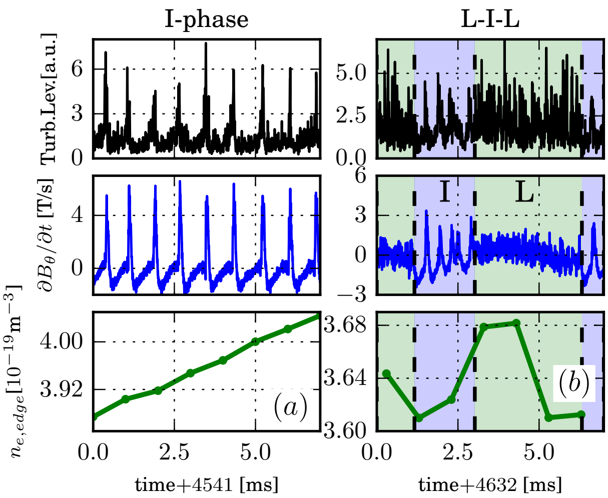

Figure 3: *Zoom-in of the I-phase* (a) *and of the L-I-L oscillations* (b) *comparing the turbulence level measured by Doppler reflectometry (black),* $\partial B_\theta/\partial t$ *from a Mirnov coil (blue) and the integrated edge electron density (green).*

Just before the onset of the I-phase another type of fluctuations is visible with a frequency of around 150 Hz (fig. 2, red shaded area). A zoom-in in one period (fig. 3b) shows that the plasma is shortly transiting from L-mode into the I-phase, indicated by a few bursts, and then it goes back to L-mode where the turbulence level (black) is higher. This rapid L-I-L transitions modulate also the edge electron density (green) which is increasing during the dithering and drops shortly after the plasma goes back into L-mode. These oscillations are only observed for electron densities above the minimum of the dependence of the power threshold on n_e. This suggests that the plasma goes back to L-mode due to the increased n_e and consequently increased P_{thr}. The final transition to the I-phase happens only when the input power is further increased, in this case only when the NI is switched on for a longer time (fig. 2).

In order to understand the background conditions for the H-mode onset, the radial electric field has been compared after the L-I-L oscillations but before the I-phase (in this case $t = 4.624$ s). It is however crucial to also understand the trigger of the H-mode by comparing the fast interplay of flows, kinetic gradients and turbulence during these fluctuations. Self induced turbulence flows, also called zonal flows (ZFs), are debated to be the actuator of these intermediate phases [8,9]. Due to the improved temporal resolution of the edge CXRS diagnostic (a few hundreds of μs) and by applying conditional averaging, the measured $\mathbf{E}\times\mathbf{B}$ velocity has been compared to the diamagnetic velocity of the main ions ($v_{\text{dia,i}} = \nabla p_i/(n_i B)$) just before the L-I and I-L transition and few bursts after the L-I transition. No strong deviation inside the error bar was found between the two values in these phases limiting a possible contribution from ZFs exactly at L-I transition and/or during the initial bursts. This is indeed where self induced turbulence flows are reported to be most active.

The E_r minimum just before the L-I transition is presented as a function of the magnetic field B in figure 4 for discharges with different B_t performed in deuterium (blue) and in hydrogen (red). E_r scales roughly linearly with B suggesting that a critical $\mathbf{E}\times\mathbf{B}$ velocity shear is necessary to get into H-mode. This also seems to be consistent with the almost linear dependence of the P_{thr} on B_t [2]. The minimum in the E_r measured in hydrogen also aligns with those measured in deuterium even if the power threshold changes by a factor of two between the two isotopes [13]. However, considering that the turbulence characteristics at the edge are similar in hydrogen and deuterium [14], this further supports the idea of a critical $\mathbf{E}\times\mathbf{B}$ velocity shear for L-H transition. These observations combined with those reported in [5] and [4] indicate that the background conditions for the H-mode onset are dominated by the diamagnetic velocity of the main ions.

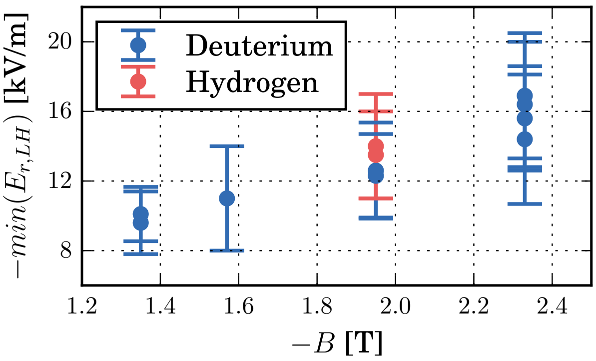

Figure 4: *Minimum of E_r just before the final L-I transition in function of B for deuterium (blue) and hydrogen (red) plasmas*

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.