Inner versus outer $\mathbf{E} \times \mathbf{B}$ shear layer:
an attempt to radially localize the L-H transition

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The $\mathbf{E} \times \mathbf{B}$ shear stabilization of turbulence at the edge of fusion plasmas is the leading explanation for the transition from the low (L-) to the high (H-) confinement mode [1]. The $\mathbf{E} \times \mathbf{B}$ velocity ($\mathbf{v}_{E \times B}$) in the confined region may be generated by turbulence stresses [2], collisional (neoclassical) processes [3] or by any non-ambipolar transport mechanism, i.e. ion orbit losses [4]. For small toroidal velocity, neoclassical theory predicts that $\mathbf{v}_{E \times B}$ is dominated by the main ion temperature (T_i) and density (n_i) gradients and that it almost perfectly compensates the diamagnetic velocity $v_{\mathrm{dia}}^i = \nabla_r(n_i T_i)/(e Z_i n_i)$ [3]. Outside the Last Closed Flux Surface (LCFS), in the so-called Scrape-Off Layer (SOL), the radial electric field ($E_r = v_{E \times B}/B$) is determined by the non-ambipolar transport of ion and electron determining the plasma potential via a sheath region in front of the targets. The $\mathbf{E} \times \mathbf{B}$ velocity can be approximated from the electron temperature at the target $T_{e,\mathrm{t}}$ as $\mathbf{v}_{E \times B} \approx -3 k_B \nabla T_{e,\mathrm{t}}/(eB)$ as far as the electric connection along an open field line holds [5]. The resulting shape of the $\mathbf{v}_{E \times B}$ profile exhibits two shear layers: the "inner" one is located within the confined region while the "outer" layer connects the $\mathbf{E} \times \mathbf{B}$ well to the SOL. Both edge shear layers can in principle trigger the L-H transition and the knowledge of a dominant one might give the possibility to optimize the H-mode access and its prediction.

In the last years, several experimental and modelling results pointed to the influence of the SOL and divertor conditions on the L-H power threshold (P_{thr}). At the JET tokamak, it was observed that P_{thr} increases with the X-point height and decreases with the divertor closure [6]. Similar observation were obtained at the DIII-D and MAST tokamaks [7, 8]. On the same line, modelling results showed a correlation between P_{thr} and $\mathbf{v}_{E \times B}$ just outside the last closed flux surface highlighting the role of the outer shear layer in the L-H transition physics [9]. Moreover, zonal flows are shown to more strongly impact the outer shear layer [10]. On the other hand, a correlation between the edge ion heat flux and the H-mode onset has been found in ASDEX Upgrade and C-mod [11, 12] suggesting that the inner shear layer is the relevant one for the L-H transition. These are, however, all indirect and not conclusive indications since outer and inner shear layers are strongly coupled. For instance, an increase of the $\mathbf{v}_{E \times B}$ at the inner shear
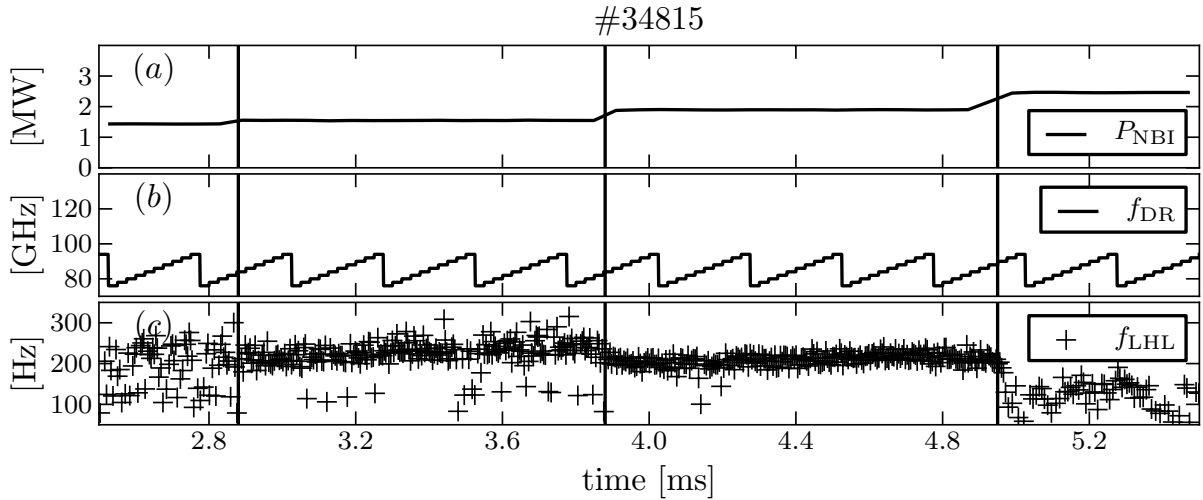
Figure 1: *Repetitive L-H-L dithers discharge scenario: (a) NBI heating power, (b) Outer separatrix position (blue) and DR probing frequency (black), (c) L-H-L dithers frequency.*

would at the same time steepens the outer one while a change in the divertor conditions might also affect the density and temperature gradients within the LCFS and in turn the inner $\mathbf{E} \times \mathbf{B}$ shear.

In this work, a direct radial localization of the turbulence suppression at the L-H transition via Doppler Reflectometry (DR) is performed. Dedicated discharges have been design to achieve stable L-H-L dithers at frequency of 200 Hz similarly as in [13]. Figure 1 shows the time traces of Neutral Beam Injection (NBI) power (1a), the probing frequency of one DR channel f_{DR} (1b) and the L-H-L dithers frequency f_{LHL} (1c) for the discharge analysed in this work. The vertical lines indicate the different power step obtained by changing the NBI duty cycle duration. Within one phase, f_{DR} is fully scanned four times to obtain repetitive measurements at different radial position. The following analysis focuses on the time window between 3.9 s and 4.9 s in which f_{LHL} is mostly stable at around 200 Hz. An algorithm based on the maximum cross-correlation of the poloidal magnetic fluctuation signature of a reference L-H-L dither with the other dithers has been employed to synchronize and select 100 out the total 200 L-H transitions within this phase [14]. Hence, the statistical relevance of this analysis is unprecedented compared to any earlier L-H transition study in which often one or, in best cases, few L-H transitions were considered.

Figure 2 shows the synchronized turbulence level for the X-mode DR channel (2a) and the O-mode channel (2b) during an L-H-L dither in function of $\rho_{pol,shear}$ and time. Darker colors indicate high turbulence level while brighter ones low turbulence level. The radial positions of the probing frequencies have been traced during the entire L-H-L cycle (see movement in time of measurements in figure 2) by using fast measurements of the electron density via the
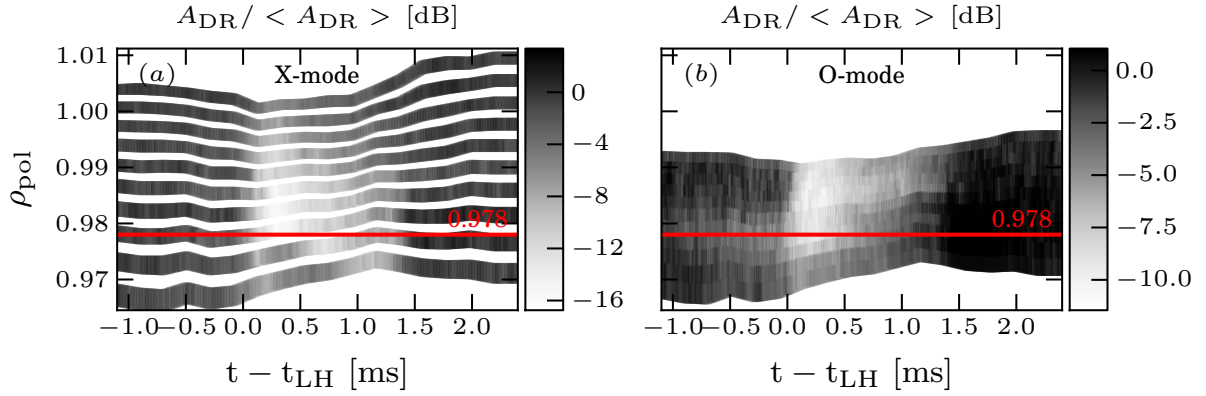
Figure 2: Synchronized normalized turbulence level A_{DR} during an L-H-L transition from (a) X-mode DR and (b) O-mode DR. High to low turbulence levels are color coded from dark to bright. The red horizontal line indicate roughly the initial turbulence suppression position.

Li-BES diagnostic. Note that the turbulence level measured by DR for a certain frequency A_{DR} is normalized by its mean value $\langle A_{DR} \rangle$ to emphasize relative changes and take into account the variation of the RF system response to the probing frequency. Both O-mode and X-mode channels show a localized initial turbulence decrease at $\rho_{pol} \approx 0.978$ at the L-H transition which extends towards the last close flux surface and the plasma center. This result indicates that the L-H transition takes place at a specific radial position. Note that the synchronized DR data in figure 2 are binned to a temporal resolution of $10\,\mu s$ which is the horizontal extension of the square pixels in 3 while the vertical one is radial resolution from the ray-tracing code.

To determine which $\mathbf{E} \times \mathbf{B}$ shear layer is responsible for the initial turbulence reduction, the $\mathbf{E} \times \mathbf{B}$ velocity needs to be determined. This can be done directly from the Doppler Reflectometry data to limit the uncertainty in the equilibrium reconstruction and in the relative alignment of different diagnostics. The E_r profiles from the X-mode (red) and O-mode (blue) channels are shown in figure 3. The position of the initial turbulence shear ($\rho_{pol,shear} \approx 0.978$) is indicated by the black vertical line and it is clearly located within the inner shear layer for both X- and O-mode. However, the value of E_r at the well is much lower than typical 13 to 15 kV/m observed in previous publication for similar plasma conditions [15, 16]. To clarify this point, E_r has been calculated from the fast edge CX diagnostic and it is shown in green in figure 3. The CX profile aligns to previous publications and still $\rho_{pol,shear}$ sits in the inner shear layer. However, the uncertainties on the mapping and relative alignment of the CX and the DR diagnostics are large making the localization not as robust as by only using the DR diagnostic. Different effects could explain the discrepancy between the E_r profiles measured by DR and CX. The presence of a large phase velocity or the loss of localization due to intense burst events are under investigation.

To conclude, a well radially localized turbulence suppression at the L-H transition has been identified via the Doppler Reflectometry diagnostic. Roughly hundred L-H-L dithers in similar conditions have been synchronized and averaged in the analysis. The evaluation of the $\mathbf{v}_{\text{E}\times\text{B}}$ from DR and CX shows that the turbulence reduction seems to start at the inner shear layer. However, the $\mathbf{E}\times\mathbf{B}$ velocity profiles do not agree with each other. Further analysis are required to clarify this discrepancy.
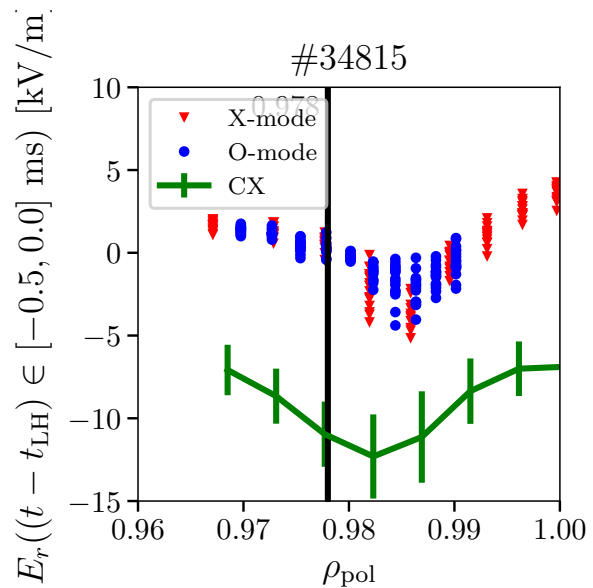

Figure 3: Synchronized E_r before the L-H transition ($t - t_{\text{LH}} \in [-0.5, 0.0]$ ms): X-mode DR (blue), O-mode DR (red) and Charge-Exchange (green).

References

[1] H. Biglari et al. *Phys. of Fluids B: Plasma Phys.* 2.1 (1990), p. 1. ISSN: 08998221.

[2] P H Diamond et al. *Plas. Phys. and Cont. Fusion* 47.5 (2005), R35.

[3] F. L. Hinton et al. *Rev. Mod. Phys.* 48 (2 1976), pp. 239–308.

[4] K. C. Shaing et al. *Phys. Rev. Lett.* 63.21 (Nov. 1989), pp. 2369–2372.

[5] P.C. Stangeby. Taylor & Francis, 2000. ISBN: 978-0-7503-0559-4.

[6] E Delabie et al. In: *IAEA Conference, Saint Petersburg, Russia*. 2014.

[7] P. Gohil et al. *Nuclear Fusion* 51.10 (2011), p. 103020.

[8] H. Meyer et al. *Nuclear Fusion* 51.11 (2011), p. 113011.

[9] A.V. Chankina et al. *Nuclear Materials and Energy* 12 (2017), pp. 273 –277. ISSN: 2352-1791.

[10] L. Schmitz et al. *Phys. Rev. Lett.* 108.15 (Apr. 2012), p. 155002. ISSN: 0031-9007.

[11] F. Ryter et al. *Nucl. Fusion* 54.8 (Aug. 2014), p. 083003. ISSN: 0029-5515.

[12] M. Schmidtmayr et al. *Nuclear Fusion* 58.5 (Mar. 2018), p. 056003.

[13] M. Cavedon et al. *Nucl. Fusion* 57.1 (2017), p. 014002.

[14] M. Cavedon et al. *Nuclear Materials and Energy* 18 (2019), pp. 275 –280. ISSN: 2352-1791.

[15] P. Sauter et al. *Nucl. Fusion* 52.1 (Jan. 2012), p. 012001. ISSN: 0029-5515.

[16] M Cavedon et al. In: *Proc. 44th EPS Conference on Plasma Physics, Ireland, Belfast*. 2017.