



**HAL**  
open science

## Formation of the radial electric field profile in the WEST tokamak

L. Vermare, P. Hennequin, C. Honoré, M. Peret, Guilhem Dif-Pradalier, X. Garbet, J. Gunn, C. Bourdelle, F. Clairet, R. Varennes, et al.

► **To cite this version:**

L. Vermare, P. Hennequin, C. Honoré, M. Peret, Guilhem Dif-Pradalier, et al.. Formation of the radial electric field profile in the WEST tokamak. Nuclear Fusion, 2022, 62 (2), pp.026002. 10.1088/1741-4326/ac3c85 . hal-03441556

**HAL Id: hal-03441556**

**<https://hal.science/hal-03441556v1>**

Submitted on 22 Nov 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Formation of the radial electric field profile in the**  
2 **WEST tokamak**

3 **L. Vermare, P. Hennequin, C. Honoré**

4 Ecole Polytechnique, LPP, CNRS UMR 7648,91128 Palaiseau, France

5 **M. Peret, G. Dif-Pradalier, X. Garbet, J. Gunn, C. Bourdelle,**  
6 **F. Clairet, R. Varennes, J. Morales, R. Dumont, M. Goniche,**  
7 **P. Maget and WEST Team <http://west.cea.fr/westteam>**

8 CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France

## 1. Abstract

Sheared flows are known to reduce turbulent transport by decreasing the correlation length and/or intensity of turbulent structures. The transport barrier that takes place at the edge during improved regimes such as H mode, corresponds to the establishment of a large shear of the radial electric field. In this context, the radial shape of the radial electric field or more exactly of the perpendicular  $E \times B$  velocity appears as a key element in accessing improved confinement regimes. In this paper, we present the radial profile of the perpendicular velocity measured using Doppler back-scattering system at the edge of the plasma, dominated by the  $E \times B$  velocity, during the first campaigns of the WEST tokamak. It is found that the radial velocity profile is clearly more sheared in Lower Single Null configuration (with the  $B \times \nabla B$  magnetic drift pointing toward the active X-point) than in Upper Single Null configuration for ohmic and low current plasmas ( $B = 3.7T$  and  $q_{95} = 4.7$ ), consistently with the expectation comparing respectively “favourable” versus “unfavourable” configuration. Interestingly, this tendency is sensitive to the plasma current and to the amount of additional heating power leading to plasma conditions in which the  $E \times B$  velocity exhibits a deeper well in USN configuration. For example, while the velocity profile exhibits a clear and deep well just inside the separatrix concomitant with the formation of a density pedestal during L-H transitions observed in LSN configuration, deeper  $E_r$  wells are observed in USN configuration during similar transitions with less pronounced density pedestal.

## 2. Introduction

The shear of the radial electric field at the edge is widely accepted to be responsible for turbulence reduction in edge transport barriers [Bur+89] and thought as a key ingredient of the improved confinement of H-mode plasmas [Wag+82]. Experimental evidence that shear flow plays a crucial role in triggering and maintaining edge transport barrier in H-mode regime has been largely demonstrated (for example in DIII-D [BDT90], ALCATOR C-MOD [McD+09], TJ-II [Est+09], ASDEX Upgrade [Vie+13], JET [And+08], JT60 [Kam+11], and for a review see [Bur20]. The radial electric field measured just inside the separatrix is found to be dominated by the diamagnetic contribution in ALCATOR C-MOD H mode [McD+09] as well as in ASDEX Upgrade both in H-mode [Vie+13] and during I-phase [Cav+16]. In the other hand, approaching the L-H transition, contributions related to turbulence generated flows are reported to enter at play [Con+11; Sch+12; Est+11].

Nevertheless, a full understanding of how the  $E_r$  profile builds up at the edge is still lacking. It can be formulated either as the result of a competition between several mechanisms that generate and damp flows or as the result of a non-ambipolar particle flux, which enhances radial charge separation imposing a radial electric field profile. In neoclassical theory, in an axisymmetric plasma, the thermal radial fluxes are intrinsically ambipolar. As a result, the radial electric field  $E_r$  is undetermined.

48 The toroidal  $v_\varphi$  and the poloidal  $v_\theta$  velocities can be determined by projecting  
 49 the momentum balance equations in the toroidal (or equivalently parallel) and poloidal  
 50 directions, admitting that the radial force balance equation is satisfied on a short time  
 51 scale. Standard neoclassical theory predicts the parallel component of a collisional  
 52 stress tensor. The parallel force balance equation then leads to a prediction on the  
 53 poloidal velocity proportional to the main ion temperature gradient- more precisely  $v_\theta =$   
 54  $-\frac{K}{m_i \Omega_i} \frac{dT_i}{dr}$  [KDG91], valid when impurities are trace. However the toroidal component  
 55 of the neoclassical stress tensor is vanishingly small. As a consequence, ambipolarity  
 56 is automatically satisfied and the toroidal velocity cannot be determined separately  
 57 from the radial electric field. Therefore, in this context (no external momentum source,  
 58 axisymmetric plasma), the neoclassical theory does not predict an independent toroidal  
 59 rotation. The contribution from the perpendicular velocity  $v_{s,\perp} = v_{s,\theta} \frac{B_\varphi}{B} - v_{s,\varphi} \frac{B_\theta}{B}$  is  
 60 then not expected to be negligible.

61 At this point, two equations remain: the time evolution of the radial electric field,  
 62 which can be written as

$$\epsilon \frac{\partial E_r}{\partial t} = -j_r \quad (1)$$

63 where  $\epsilon$  is the dielectric constant in toroidal plasmas and  $j_r$  the total radial current  
 64 which includes several contributions such as the neoclassical viscosity current related  
 65 to collisions, the orbit loss current and the current related to the turbulent Reynolds  
 66 stress.

67 In addition, the radial force balance couples the ion toroidal velocity and the radial  
 68 electric field at given poloidal velocity and pressure gradient and reads :

$$E_r = v_{s,\varphi} B_\theta - v_{s,\theta} B_\varphi + \frac{\nabla p_s}{n_s q_s} \quad (2)$$

69 Therefore, from here one can see this equation as an expression of the toroidal  
 70 velocity as a function of the radial electric field and then use the equation 1 to determine  
 71 the radial electric field. Another way to proceed, and the one chosen in this paper, is  
 72 to see the radial electric field as the sum of three contributions : one coming from the  
 73 toroidal rotation, one from the poloidal rotation and the diamagnetic contribution.

74 In some specific cases, the diamagnetic contribution is found to be dominant (as  
 75 mentioned above [Vie+13; Cav+16]. This is the the so-called "neoclassical prediction"  
 76 , which is also obtained when assuming a strong neutral friction force, as mentioned  
 77 for example in [SMR11]. In this regime, the neutral friction force  $F_{nj} = -nm_j^{1/2} \nu_{nj} u_{\perp j}$   
 78 that creates a radial drift which combined with the ambipolarity leads to a  $E_r$  such  
 79 that  $F_{ni} = -F_{ne}$ . This balance leads to an expression for  $E_r$  that depends on  $\nu_{ni}/\nu_{ne}$ ,  
 80  $\nabla P_e/\nabla P_i$  and the mass ratio  $\epsilon = m_e/m_i$ . The case of  $T_e \approx T_i$ ,  $\nu_{ni} \approx \nu_{ne}$  leads to a  
 81 zero perpendicular velocity. As a result, the radial electric field can be reduced to the  
 82 diamagnetic radial electric field :

$$E_{r,dia} = \frac{\nabla p_i}{n_i q_i} \quad (3)$$

However, it should be emphasized that this approximation/prediction is based on strong assumptions and by consequence its validity domain holds as long as the friction force dominates. A full self-consistent prediction of plasma rotation requires an independent theoretical prediction for  $E_r$ , which is typically the result of momentum transport on time scales longer than the ion collisional time. Among possible mechanisms to be taken into account, one can think in terms of neoclassical effects from one side, such as ion orbit losses [CKW02; dMB11; Brz+19], toroidal magnetic ripple [Gar+10; Nav+10; Ura+11; Fen+11] and as already mentioned the effect of neutral friction [Mon+97; SMR11] at the edge or, on the other side, turbulent generation of poloidal momentum [DK91; Dif+09; Gri+13].

In addition, magnetic drift toward the X-point is commonly considered as the favourable configuration to access an H-mode regime with the lowest power threshold. While there are multiple proposed explanations [Fed+12; Cha+17], there is no clear consensus on the reason of such favourable versus unfavourable configuration and systematic experimental comparisons of velocity profiles in USN and LSN are scarce.

The present contribution gives a first review of radial electric field profiles at the edge of the WEST tokamak in both LSN and USN configurations during its first campaigns that may bring some complementary elements helping in the understanding of  $E_r$  formation, while approaching the L-H transition.

The WEST tokamak is an upgrade of Tore Supra from a limiter-based tokamak with carbon PFCs into an X-point divertor tokamak with full-tungsten armour while keeping its long pulse capability [Buc+14]. As a result, WEST is a large aspect ratio machine ( $A=5-6$ ) with a magnetic ripple around 3% at the plasma outboard edge, lower than in Tore Supra (around 6%). Additional heating is based on RF systems (both Lower Hybrid and Ion Cyclotron Resonance Heating systems); divertors are symmetric with active X-point either at the bottom or at the top and the  $B \times \nabla B$  drift always pointing down (as visible in Figure 1).

In order to place the context, previous results obtained on Tore Supra show that the radial profile of the perpendicular flow could be separated in three spatial areas. Inside  $r/a = 0.8$ , the radial electric field is dominated by losses of thermal ions due to the magnetic ripple [Tri+08] while between  $0.7 < r/a < 0.95$ , a competition between the latter and the generation of large scale flows by turbulence appears as a possible explanation of the measured poloidal asymmetry of the mean perpendicular velocity [Ver+18]. In addition, edge conditions such as contact points and parallel dynamics in the scrape-off-layer (SOL) influence the edge profiles beyond  $r/a = 0.9$  [Hen+10].

The velocity profiles presented and discussed in the following are obtained from Doppler BackScattering (DBS also called Doppler reflectometry) measurements in X-mode polarisation [Hen+06]. This system probes the plasma using microwaves launched in oblique incidence and stepped in frequency. The signal collected by the antenna

122 corresponds mainly to the signal backscattered by density fluctuations in the vicinity  
 123 of the cut-off layer. The detected density fluctuations are selected at a spatial scale  
 124 given by the incidence angle (and by the propagation in the plasma toward the cut-off  
 125 layer). In the context of velocity measurements at the edge, density fluctuations act as  
 126 tracers to access the  $E \times B$  velocity. The phase velocity that corresponds to the velocity  
 127 of fluctuations in the plasma frame is found negligible in the area of interest here (for  
 128  $\rho_{pol} > 0.9$ ) by performing probing wavenumber scans. In the standard measurements set-  
 129 up, each radial point of the profile corresponds typically to an averaged velocity over 7ms  
 130 leading to an entire profile (i.e 12 probing frequency steps) evaluated on approximately  
 131 80ms. For the reconstruction of velocity profiles, the measurements location and the  
 132 wavenumber selected at the turning point are computed using a beam tracing code  
 133 [Hon+06] ; the input density profile is measured using using fast sweep reflectometry in  
 134 X-mode polarization [Cla+17] in burst mode (ie. each probing frequency ramp is swept  
 135 in  $1\mu s$  and each burst contains around 8000 profiles) and it corresponds to an average  
 136 over 200 profiles regularly distributed in a full burst (i.e average over 10ms) with an  
 137 input equilibrium constrained using the equilibrium reconstruction code NICE (Newton  
 138 direct and Inverse Computation for Equilibrium) [Fau20].

139 The paper is organized as follows. The first section is devoted to the comparison of  
 140 the radial profile of the perpendicular velocity in Lower Single Null (LSN) configuration  
 141 versus Upper single Null (USN) configuration in low power plasmas. Then, the evolution  
 142 of these velocity profiles during L-H transition in both, LSN and USN, configurations  
 143 are presented respectively in section 3 and 4. These first observations in WEST plasmas  
 144 are finally discussed in the last section.

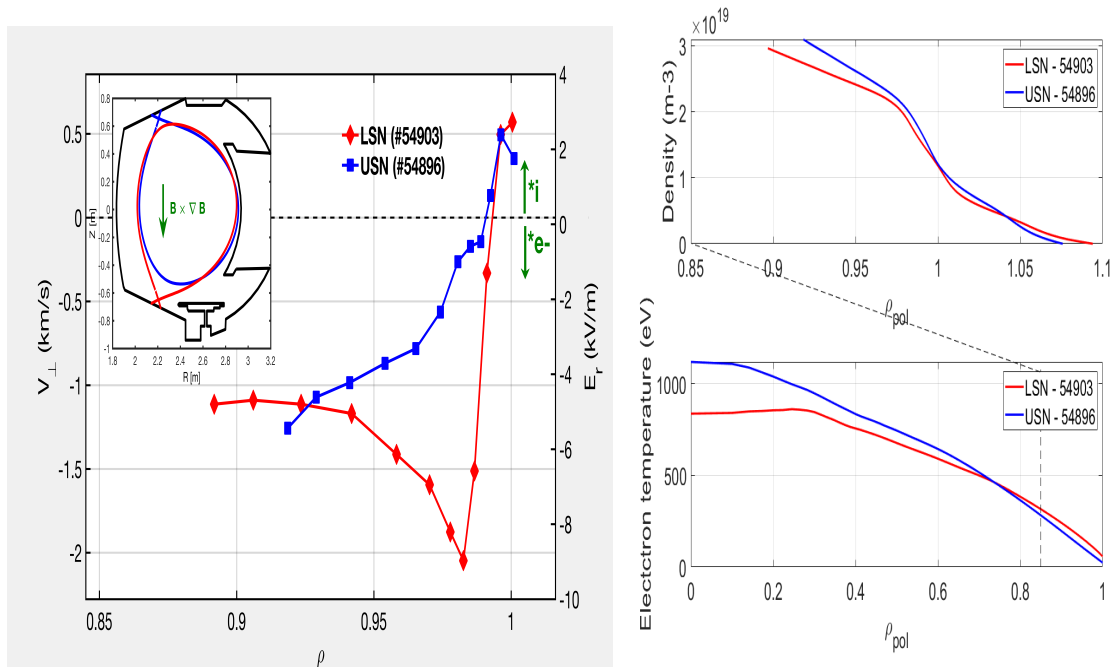
### 145 3. Velocity profile in LSN and USN configurations during ohmic discharges

146 This section is dedicated to ohmic discharges which allows investigations on the radial  
 147 electric field profiles with long stationary phases and scanning properly several plasma  
 148 parameters (magnetic configuration, plasma current, density...). The comparison  
 149 between low and high power discharges in different magnetic configurations brings  
 150 elements to understand the balance and the weight of each mechanisms at work in the  
 151 formation of the  $E_r$  profile. One can argue that the plasma conditions in ohmic phases  
 152 are far from those of L-H transition but it should be noted that the set of possible  
 153 mechanisms that come into play for generating  $E_r$  are not expected to change between  
 154 both regimes, only their respective weights are.

155 In WEST plasmas, with no heating power (also valid at low power), the radial  
 156 profile of the  $E \times B$  velocity between LSN and USN plasmas shows an impressive  
 157 difference (see Fig 1 (left)). In LSN configuration, the  $E \times B$  velocity profile exhibits a  
 158 “standard shape” : a positive velocity outside the separatrix (i.e. in the ion diamagnetic  
 159 direction), changing sign across the separatrix and forming a well in the edge of the  
 160 confined plasma with a velocity that decreases in absolute value toward the core region.  
 161 In contrast, the radial profile for USN configuration does not show a well and exhibits

a smooth decay from the edge to the core. Interestingly, the density and electron temperature  $T_e$  profiles (no ion temperature  $T_i$  measurement are available at this stage) for these discharges, which are presented in Figure 1 (right), are very similar at the edge. The energy content,  $W_{MHD}$  is also identical for both discharges. However, it should be mentioned that the safety factor  $q$  and the internal inductance are slightly different ; in the LSN configuration,  $q$  at the edge (as inferred from magnetic equilibrium reconstruction constrained by polarimetry) is higher by about 20% while  $l_i$  is lower by about 30%.

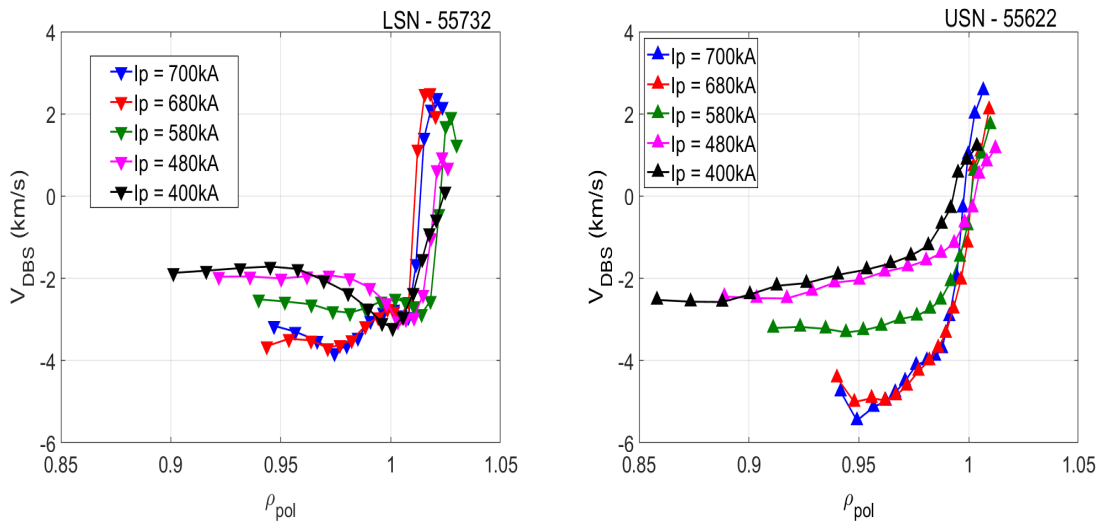
Approximating the diamagnetic radial electric field (i. e.  $E_r \approx \nabla P_i / en_i$ , eq. 3) using the electron pressure, it appears that this contribution is not the dominant contribution, as least in the USN configuration. Especially, the shape of the density gradient exhibits a well suggesting that the velocity profile deviate from this approximation.



**Figure 1.** Radial profiles of perpendicular velocity and corresponding  $E_r$  profiles measured using DBS in LSN (red) and in USN (blue) configurations during ohmic plasmas (left). Radial density profiles measured using fast sweep reflectometry [Cla+17] and electron temperature measured using ECE radiometer during the same discharges (right).

Concerning the difference in the shape of the velocity profile, a similar observation has been obtained in pure ICRH heated ASDEX Upgrade plasmas [Sch+06] and interestingly also in Tore Supra circular plasmas during low current ohmic discharges [Fed+13; Hen+10]. In the latter, the contact point with this limiter is rolled from  $\theta_X \approx 35^\circ$  below the midplane (equivalent to LSN) to  $\theta_X \approx +35^\circ$  above the midplane (equivalent to USN). The modification of the velocity shape has been shown to be

181 compatible with a simplified model based on the dynamical interaction between potential  
 182 eddies and shear flow [Fed+13]. When eddies are tilted in the velocity shear direction,  
 183 the system is favourable to shear increase while when they are tilted in the opposite  
 184 direction, the shear flow is damped. Therefore, depending of the position of the contact  
 185 point, the balance between both contributions (associated with the change of the tilting  
 186 direction between upper and lower section of the low field side part of the plasma) is  
 187 modified and the averaged velocity profile is modified. It is important to notice that  
 188 this mechanism depends on the magnetic shear.



**Figure 2.** Radial profiles of perpendicular velocity  $V_{E \times B}$  measured using DBS varying the plasma current  $I_p$  in LSN (left) and in USN (right) configurations during ohmic plasmas.

189 Even if plasma conditions are far from L-H transition, the difference observed in  
 190 the velocity shear between LSN versus USN may appear consistent with the fact that  
 191 the configuration with the  $B \times \nabla B$  magnetic drift pointing toward the active X-point,  
 192 designated as the 'favourable configuration', is more favourable to reach the H-mode as  
 193 compared to the opposite case when  $B \times \nabla B$  magnetic drift points away from the active  
 194 X-point.

195 However, this tendency is sensitive to the plasma parameters. In particular,  
 196 experiments have been performed to compare the DBS velocity profiles at the edge  
 197 in both USN and LSN at different plasma current  $I_p$  keeping  $B = 3.7T$ . During this  
 198 scan the safety factor is varying by a factor 1.7 with a small difference between USN  
 199 and LSN discharges in the safety factor covered range such as  $q_{95} = [3.3 - 5.8]$  in LSN  
 200 while  $q_{95} = [2.85 - 4.7]$  in USN. Note that during these scans, it is found from the radial  
 201 profiles of the safety factor that the magnetic shear does not change significantly. As  
 202 visible in Figure 2, it appears that the plasma current impacts significantly the velocity  
 203 profile in the USN discharges. When increasing the plasma current, the  $E \times B$  velocity  
 204 starts to form a well to end up with a deeper profile than in LSN at high current. Indeed,



in LSN configuration, the increase of the plasma current also deepens the radial electric field well ; however, the effect is less pronounced than in USN. While the density profile also slightly changes during the  $I_p$  scan, it is found that the dominant effect comes from the plasma current variation. These results suggest that, at least one dominant mechanism entering in the  $E_r$  profile formation in USN depends on the plasma current or the safety factor.

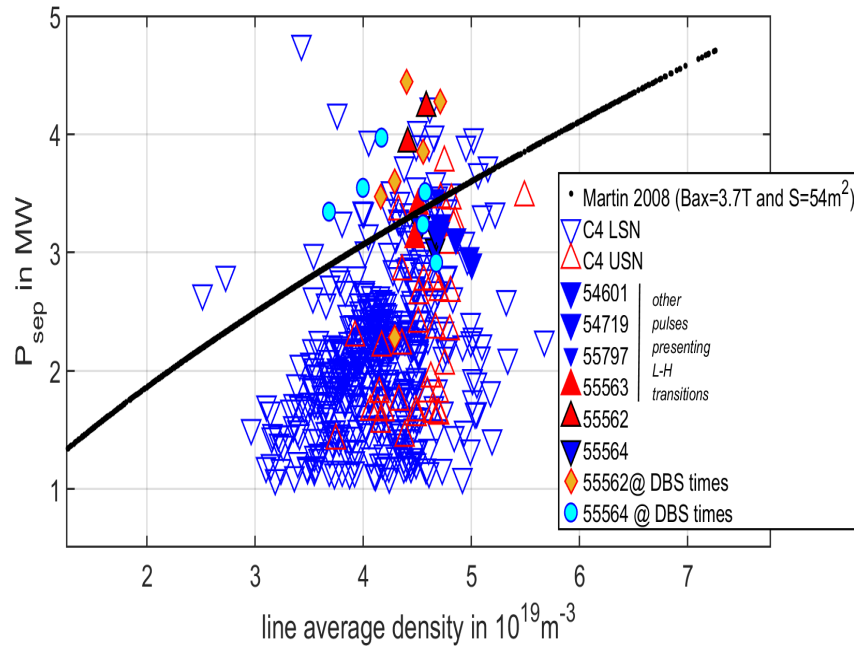
Interestingly, for fixed plasma current and moderate to high heating power, the velocity profile ends up deeper in the USN configuration for the same plasma conditions. This result leads to an unexpected situation in which the "unfavourable configuration" seems more favourable, at least from the point of view of mechanisms for improved confinement based on vortex shearing. This situation is addressed in the next session, in the context of L-H transitions.

#### 4. Evolution of the radial electric field profile during L-H transition

##### 4.1. L-H transition observed in LSN configuration

In WEST, up to now, L-H transitions have been observed after fresh boronization (when the radiated fraction inside the separatrix is lower than 40%) with heat power crosses the separatrix  $P_{sep}$  close to the ITPA scaling law prediction [MTI08], as visible in the Figure 3. While no sign of an established H-mode regime is visible (such as ELMs), transitions have been identified by simultaneously observing expected changes in both the confined and SOL plasmas. Time traces of this discharge in LSN configuration (i.e. with 'favourable  $B \times \nabla B$ ' directed towards the lower divertor) with an L-H transition occurring at  $t = 6.45s$  are shown in Figure 4. This is a discharge using both LHCD and ICRH additional power  $P_{sep} = 3.8MW$  with  $B_T = 3.7T$ ,  $I_p = 0.5MA$  and  $q_{95} = 4.5$ . In the confined plasma, edge steepening of the density profile (from both reflectometry and interferometry measurements), increase of the total energy content  $W_{MHD}$ , decrease internal inductance (as expected in case of increased edge bootstrap current) and a deepening of the  $E_r$  well measured by Doppler Back Scattering are simultaneously observed.

In the SOL, concurrently to the changes mentioned above in the confined plasma, several modifications are observed. A reduced transport flux was measured such as reduced D-gamma signal on the divertor target. In the same time, the density measured by the SOL interferometer chord exhibits a reduction as well as the flux measured on the Langmuir probes at the divertor targets (measurements available in LSN only for this experiment) and the gas puff rate. Note for now that no measurements of the pedestal electron temperature are available since the ECE signal is polluted by the fast electrons from LHCD for  $\rho_{pol} > 0.5$ . In the four LSN discharges presenting an L-H transition, the power crossing the separatrix remains close to the threshold leading to a more or less pronounced oscillatory phase. In the present work, we focused on one LSN discharge during which fast reflectometry measurements are available to access high-resolution

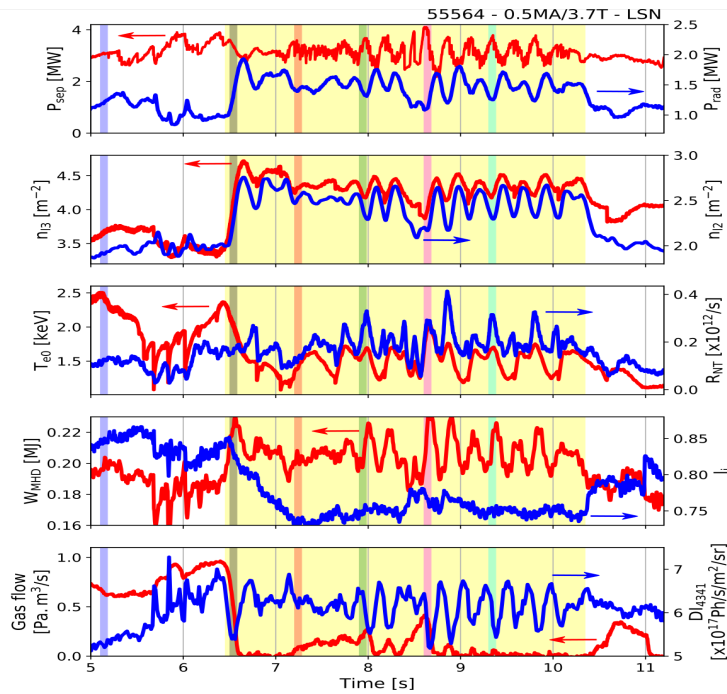


**Figure 3.** Heat power crossing the separatrix as a function of the line average density of WEST campaign C4 discharges for  $I_p = 0.5MA$  and  $B = 3.7T$ . Time sequences in LSN configuration (red) and in USN configuration (blue), symbols with black line corresponding to the discharges, respectively 55564 and 55562, and full symbols corresponding to other L-H transition discharges

244 density profiles and with moderate density at the edge in order to probe a sufficient  
 245 wide edge area. During this discharge, the increment in the total energy content  $W_{MHD}$   
 246 is about 20% between time phase just before and the one just after the transition. The  
 247 confinement time normalized to the ITER scaling law (which gives the confinement time  
 248  $\tau_{ITER-98(y,2)}$  [CCE99]), known as the H factor labelled as  $H_{98}$  is around 0.6. This rather  
 249 low value is explained by the high level of radiated power. Computing this H-factor  
 250 subtracting the radiated power to the total power gives  $H_{98, P_{tot} - P_{rad}} = 0.8$ . Note that  
 251 the transitions presented in this paper are probably in the low-density branch [Ryt+13].

252 As mentioned above and visible in Figure 4, the transition leads to an oscillatory  
 253 phase that can be explained by the fact that, at the transition at  $t = 6.45s$ , the density  
 254 and the power radiated ( $P_{rad}$ ) rises leading to a reduction of the power crossing the  
 255 separatrix and then to a reduction of the density. Then while the density is reduced,  
 256 the radiated power reduces as well, allowing for the power crossing the separatrix to  
 257 rise again and for the pedestal to form again, etc. Similar oscillatory H-L transitions  
 258 are reported in Deuterium plasmas in JET-ILW on the low density branch where the  
 259 radiated fraction power is larger (40%) [Vin19] as well as on AUG when operating well  
 260 after a boronization [Put20].

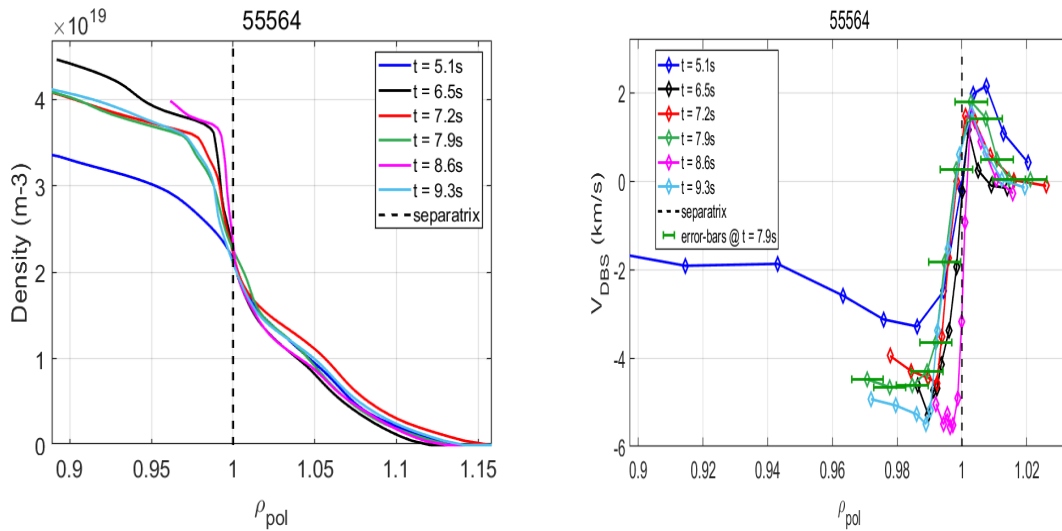
261 Figure 5 shows that, from the transition time, the density profile exhibits a pedestal  
 262 at the edge. At the same time, a clear deepening of the radial profile of the  $E \times B$  velocity



**Figure 4.** Time traces of radiated power  $P_{rad}$  and power crossing the separatrix  $P_{sep}$ , central line integrated densities  $n_{l2}$  and  $n_{l3}$ , central electron temperature and neutrons rate  $R_{NT}$ , total energy content  $W_{MHD}$  and internal inductance  $l_i$ , gas flow rate and D-gamma signal on the divertor target  $D_{I4341}$  for a LSN discharge with an L-H transition at  $t = 6.45s$ . The yellow area shows the L-H transition phase and colored vertical lines show the times of the DBS measurements

is visible. The radial electric field well remains deep during the oscillatory phase, at least at the time of DBS measurements. The radial profiles of the velocity are measured before ( $t = 5.1s$ ) and just after the transition ( $t = 6.5s$ ) and during the oscillatory phase ( $t = 7.2s, 7.9s, 8.6s$  and  $9.3s$ ).

Before discussing the specifics of the radial profiles presented in Figure 5, it is necessary to mention that the sensitivity of the initialization of density profiles to pollution by fast electrons radiation (due to LHCD heating which generates suprathermal electrons which create a broadband ECE stray radiation affecting the signal to noise ratio of the fast sweep reflectometer [Cla+01]) and the equilibrium uncertainties (that can vary between LSN and USN configurations), can lead to a radial shift of the density profiles, varying from one sweep to another. In order to compensate this shift, averaged density profiles were slightly shifted. Choice has been made to align the profiles in order to get the main inflection point close to the separatrix for all profiles. While this hypothesis is far from satisfactory, it helps in making both figures (density and velocity profiles) more readable. However, it is important to notice that the radial shift applied modifies the reconstruction of the velocity profiles from DBS since the determination of the radial position and the probing wavenumber selected at the turning point are computed using these profiles in a beam tracing code [Hon+06].



**Figure 5.** Radial profiles of electron density measured using fast sweep reflectometry [Cla+17] during an L-H transition phase in LSN starting at 6.45s (left). Associated radial profiles of the  $E \times B$  velocity measured using DBS [Hen+06] (right)

281 However, the radial shift applied to the density profile has a negligible impact on the  
 282 value in term of velocity (i.e the amplitude of the velocity is not sensitive the shift of  
 283 the density profile).

284 Coming back to the evolution of density profiles, it can be seen that a pedestal is  
 285 formed from  $t = 6.5s$  for which  $P_{sep} = 3.3MW$ ; it remains visible on each DBS time  
 286 measurements during the whole sequence, even if it evolves slightly with small changes  
 287 in additional heating power. Notably, the gradient weakly decreases at  $t = 7.2s$ , and  
 288  $t = 7.9s$  while it is recovered at  $t = 8.6s$  to finally decreases slightly again at  $t = 9.3.s$ .  
 289 Note that from  $t = 7.9s$  density starts to strongly oscillate. While this behaviour is  
 290 visible in the time traces showed in Figure 4, it is not on density profiles (averaged  
 291 on  $10ms$ ) since the time of the DBS measurements does not resolve a full cycle of the  
 292 oscillation. However, due to the time resolution of the DBS system (one entire profile  
 293 requires approximatively  $80ms$ ), the density evolves during the velocity measurements.  
 294 In order to evaluate the error-bars on the radial position (influence of the density profile  
 295 in the velocity values through the wavenumber is negligible) of DBS measurements due  
 296 to these oscillations, beam tracing has been performed for extreme density profile (at the  
 297 extrema of the closet density oscillation) for one DBS time acquisition (see Figure 5).

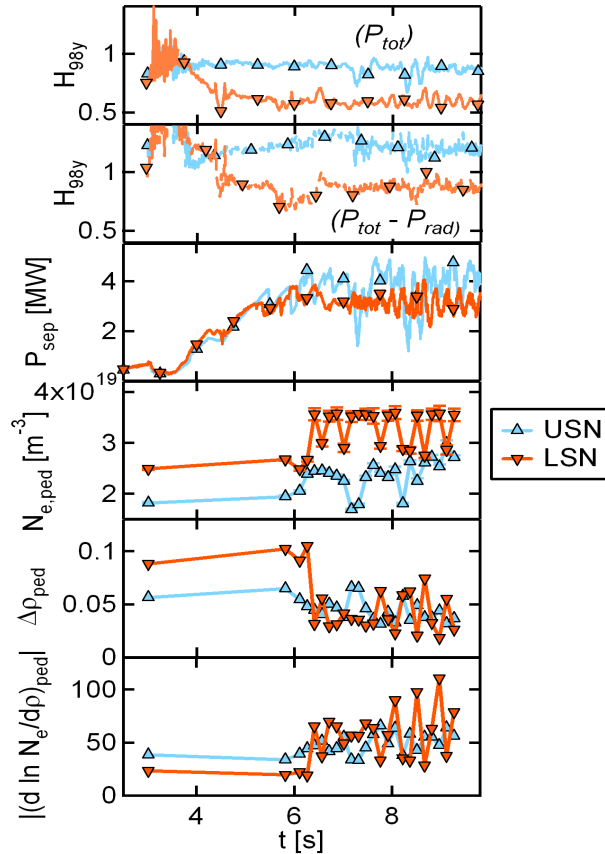
298 On the velocity profiles, concomitantly to the formation of the density pedestal  
 299 and as expected considering contribution  $\nabla P$ , a deeper and narrower well is formed as  
 300 compared to the profile before the transition. While the well remains deep for all the  
 301 measurements time (in several locations), the depth of the well and the shape change  
 302 softly for the three times during which the density gradient slightly decreases. On  
 303 the contrary, at  $t = 8.6s$  ( $P_{sep} = 4MW$ ), the well is the deepest one and its position  
 304 appears shifted closer to the separatrix. The velocity shear is stronger at  $t = 8.6s$  when

the density gradient is also stronger. Therefore, these density and velocity profiles are consistent with a strong contribution of the  $\nabla n/n$  to the formation of the  $E_r$  profile in this radial area. This tendency is also visible in Figure 9 which is commented in the discussion section. Although it remains rather shallow, the  $E \times B$  velocity shear also increases in the inner branch (between  $\rho_{pol} = 0.94$  and  $\rho_{pol} = 0.985$ ) when the density gradient is the largest. This part of the profile is under investigation, especially to evaluate the contribution of toroidal magnetic ripple (which is about 3% at the edge in WEST) and its competition with turbulence in generating radial electric field [Var21].

The pedestal in density has been characterized using a fit with a modified tanh function [GO98]. The fit is applied on the inner side of the pedestal only, with no offset in the edge density. From this fitting procedure, the density at the pedestal and the pedestal width can be determined when reflectometry profiles are available (note that reflectometry profiles measurements are more frequent than DBS). The pedestal width is defined here as twice the half-width determined from the fit. The temporal evolution of the energy normalized confinement time  $H_{98,y2}$ , the power crossing the separatrix, pedestal density, pedestal width and normalized density gradient is shown in Figure 6 for the pulse 55564 (in LSN) and for the pulse 55562 in USN that is discussed in the next section. Error bars on  $P_{sep}$  represent the standard deviation over a time window of 100ms. We have a reference during the ohmic part of the discharge ( $t = 3s$ ), and the next points are recorded during the high power phase. The transition occurs after the power crossing the separatrix has reached a value above the expected power threshold for L-H transition [MTI08]. Then the pedestal density increases abruptly and the pedestal width falls, leading to a sharp increase of the normalized density gradient. Concerning the H-factor  $H_{98,y2}$  which corresponds to the energy confinement time normalised to the confinement time predicted by the scaling law IPB98 [CCE99] and is valuable only for the H-mode phases; values are around  $H_{98,y2} = 0.6$  for the LSN and  $H_{98,y2} = 0.8$  for the USN case. These low values come from the high level of radiated power which lead to a reduction of the central electron temperature. In order to compensate this effect, the H-factor computed using a net power  $P_{tot} - P_{rad}$  obtained by subtraction the radiated power  $P_{rad}$  to the total power  $P_{tot}$  is also given in Figure 6. However, it should be noted that the use of the  $IP98P(y, 2)$  may be questionable in WEST due to its large aspect ratio A (around 5-6) and to the relatively narrow range of the available A parameter in the database.

#### 4.2. L-H transition observed in USN configuration

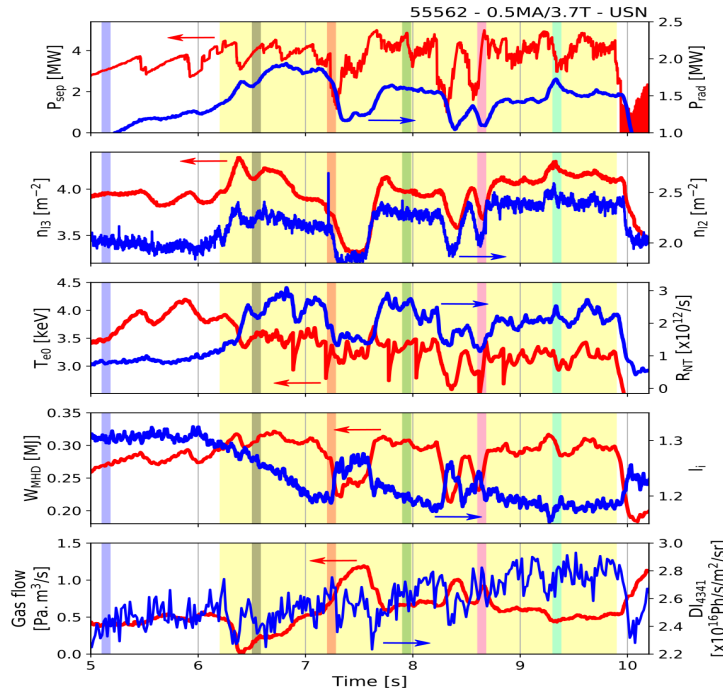
Interestingly, a transition is also observed in the so called 'unfavourable  $B \times \nabla B$ ', direction therefore in the USN configuration in WEST. This transition appears similar in some points to the L-H transitions occurring in LSN configuration. Notably, an increase of total energy content  $W_{MHD}$  (which is weaker than in the LSN transition), a decrease of the internal inductance, a reduction of the D-gamma signal on the divertor target as well as a reduction of the density measured by the SOL interferometer chord



**Figure 6.** Evolution of  $H_{98,y2}$  computed using total power and subtracting the radiated power,  $P_{sep}$ , pedestal density, pedestal width and normalized density gradient for an H-mode transition in LSN (55564) and in USN (55562).

345 and a deepening of the  $E_r$  well are simultaneously observed. However, contrary to  
 346 transitions in LSN discharges, no oscillatory phase takes place during these discharges  
 347 (see Figure 7). Another difference, which explains the latter, comes from the fact that  
 348 while the gradient of the density profile clearly increases at the transition, the pedestal  
 349 in density appears less pronounced than in the LSN case. The reduction in the width  
 350 of the pedestal density shown in Figure 8 is moderate compared to the LSN case, and  
 351 the change in the normalized density gradient is also less pronounced (see Figure 6).

352 Concerning the radial profiles of the  $V_{E \times B}$ , visible in Figure 8, similarly to the  
 353 behaviour of the LSN discharge described above, a well is formed in the velocity profile  
 354 just inside the separatrix at the transition occurring during the ICRH ramp up. The  
 355 first measurement ( $t = 6.5$  s) after the transition, exhibits a well reaching  $-9.5$  km/s.  
 356 Since the heating power is not stationary ( $P_{sep}$ ) changing between  $2$  MW and  $4.5$  MW,  
 357 this discharge is eventful. The 'weakly improved confinement regime' is lost a first time  
 358 around  $t = 7.3$  s and this loss starts during the DBS measurements recorded at  $t = 7.2$  s.  
 359 However, the velocity profile is deeper at this time as compared to the previous time.



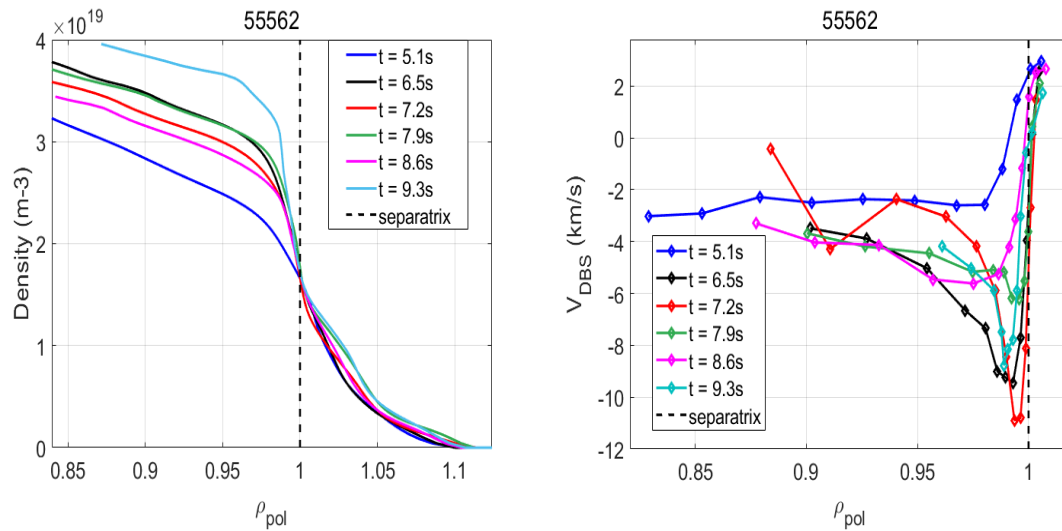
**Figure 7.** Time traces of radiated power  $P_{rad}$  and power crossing the separatrix  $P_{sep}$ , central line integrated densities  $n_{l2}$  and  $n_{l3}$ , central electron temperature and neutrons rate  $R_{NT}$ , total energy content  $W_{MHD}$  and internal inductance  $l_i$ , gas flow rate and D-gamma signal on the divertor target  $D_{I4341}$  for a USN discharge with an L-H transition at  $t = 6.2s$ . The yellow area shows the L-H transition phase and colored vertical lines show the times of the DBS measurements

When enough additional power is recovered ( $t = 7.55s$ ), the density increases again and the velocity profile shows anew a well. As compared to the previous one, this velocity well appears weaker while the density profile is similar and  $P_{sep}$  higher. Looking more in details into the DBS data, it is found that at this time the velocity profile has a particular behaviour, which is discussed just below. At  $t = 8.6s$ , again the additional power is perturbed and both density profile and velocity profile seem affected by the change in plasmas condition. After a quieter period in term of heating power, the density profile exhibits the strongest gradient at the edge of this discharge at  $t = 9.3s$  and the velocity profile has a deep well, which remains, however, less pronounced than for the deepest one (corresponding at  $t = 7.2s$ )

Therefore, a puzzling result is that during this transition the radial profile of the velocity shows the deepest well observed so far in WEST plasmas. For comparable heating power (mainly  $P_{sep} = 3.5MW$ ), the  $E_r$  well is significantly deeper during the transition in USN than during the one in LSN presented in the previous section, since the velocity well reaches  $-11km/s$  (against around  $-6km/s$  in LSN). Another interesting aspect is related to the fact that in the same time, the density gradient close to the separatrix is weaker than in the transitions occurring in LSN.

Note that the observation of an  $E_r$  well formation without a clear density pedestal





**Figure 8.** Radial profiles of electron density measured using fast sweep reflectometry [Cla+17] during an L-H transition phase in USN starting at  $t = 6.45\text{s}$  (left). Associated radial profiles of the  $E \times B$  velocity measured using DBS [Hen+06] (right). Time measurements are plotted in time traces of the discharge Fig. 7

378 may suggest that a strong pedestal is formed in the temperature profile. Unfortunately,  
 379 no measurements of the temperature at the edge are available to verify it. In addition,  
 380 one could think that this situation suggests an I-mode regime since this configuration is  
 381 favorable to such mode during which a pedestal forms in temperature only. Especially,  
 382 WEST operating at high B field, it is expected to have an-I mode significant operational  
 383 window [Hub+16]. However, in addition to the increase in density, which is not expected  
 384 during I-mode, no clear signs of a Weakly Coherent Mode typically, considered as the  
 385 signature of I-mode, is reported on fast sweeping reflectometry.

386 Concerning the surprising shape of the averaged velocity profile at  $t = 7.9\text{s}$  as  
 387 compared to the other time measurements, time evolution of the velocity has been  
 388 analysed more in details. As already mentioned above, the velocity profiles discussed  
 389 here are averaged profiles, over typically 80ms that may not be representative in cases  
 390 of a specific dynamics. In particular, during this USN discharge (Figure 7), at  $t = 7.9\text{s}$ ,  
 391 the DBS amplitude signal exhibits burst events with a frequency around 4kHz, in a  
 392 radial zone which extends across the well and inner branch. This bursty dynamics is  
 393 associated with bursts of high (resp. low) Doppler velocities. Therefore, as mentioned  
 394 just above, the averaged profile (Figure 8, green profile) does not resolve properly the  
 395 peculiar shape of the velocity profile at this time. This behaviour explains the less deep  
 396 well. In addition, the dynamics observed both in the velocity and in the amplitude  
 397 of density fluctuations has strong similitude with observations made in DSB signal on  
 398 ASDEX Upgrade during I-phase [Med+17]. Note that however, in WEST, no sign of  
 399 this I-phase dynamics has been detected so far in other signals (such as Dalphi or fast  
 400 sweep reflectometry). For comparison, during the other measurement times, the velocity



(at a given probing frequency step, i.e. radial position) also shows a dynamics, which corresponds more to oscillations around a certain value. This behaviour appears similar to the presence of Geodesic Acoustic Modes (GAMs). The frequency of these oscillations is around  $15kHz$  which is higher but of the same order of magnitude of GAMs observed in Tore Supra [Ver+12]. As no temperature measurements are available, the expected GAM frequency cannot be evaluated for this specific discharge and then does not allow to confirm or exclude GAMs related oscillations. It should be mentioned that the amplitude of the DBS appears also modulated suggesting a modulation of the density in the equatorial plane while this feature is not expected for GAMs (GAMs perturbation in density is such as  $m=1$ ). However, the modulation of DBS amplitude may also result from an interaction between turbulence at the probing wavenumber and GAMs.

## 5. Discussion

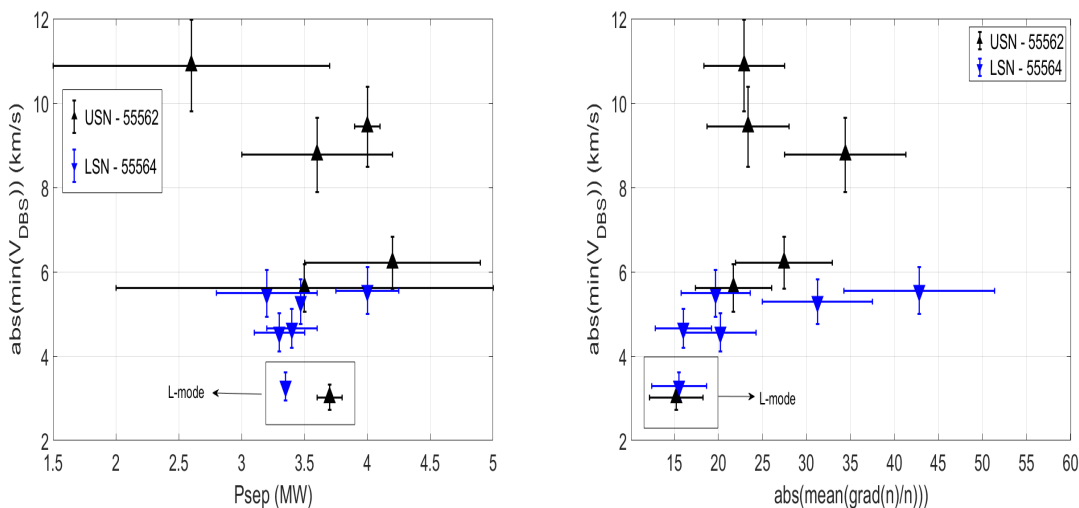
In WEST, differences in the shape of the radial profile of  $E_r$  are observed between LSN and USN configurations. During Ohmic and low heating power discharges, the difference is remarkable ; the  $E_r$  profile does not exhibit a well in USN while it has a standard shape in LSN. This behaviour changes when increasing the plasma current during Ohmic plasmas or when increasing the additional heating power at fixed plasma current. While the result in Ohmic plasma is consistent with previous observations [Sch+06] and may appear in line with the common belief that configuration with magnetic drift toward X-point is the favourable configuration to access H-mode, it remains unexplained.

First, while no ion temperature measurements are available, the density and electron temperature profiles for these two configurations remain almost identical. Considering the diamagnetic contribution to the radial electric field  $\nabla P_i/en_i$ , taking  $T_i=T_e$ , the shape of the  $E \times B$  velocity profile should be strongly influenced by the density gradient (in L-mode,  $n_e \approx n_i$  is reasonable). Therefore, at least in one configuration (looking at both density and velocity profiles it is probably in the USN configuration), the observed difference suggests that the  $E_r$  profile cannot be described using the diamagnetic approximation.

Secondly, when increasing the additional RF heating power, the radial electric field profile becomes more sheared in USN discharges. On this aspect, it should be noted that RF waves generates a toroidal torque that in turn produces a radial current of particles. This effect was computed in [Cho+15] and appears quite small in the plasma edge. In the same way, direct losses of energetic particles generated by RF waves are small in the edge. This reversed situation (deeper well in USN than in LSN) while reaching plasma conditions for a potential L-H transition is not anymore consistent with the idea of LSN been a favourable configuration, at least considering that the shear of  $E_r$  is a key ingredient of the L-H transition. Indeed this thumb rule would advocate an LSN configuration as more propitious to a transition, and hence more sheared  $E_r$  than in USN. The comparison of the behaviour of  $E_r$  profile in Ohmic and high power discharges is not straightforward since conditions are largely different. However, it brings new

441 pieces of understanding in the formation of the  $E_r$  profile. Especially, the observation  
 442 of a clear dependence of the velocity shear with the plasma current, stronger in USN  
 443 than in LSN, is interesting.

444 The power threshold for the L-H transition does not depend on the plasma current  
 445 [MTI08], suggesting a weak role of the current in the physics of the  $E_r$  well formation  
 446 and sustainment. The sensitivity of the  $E_r$  profile in Ohmic plasmas with the plasma  
 447 current may be interpreted as a sign of a substantial change in the physical mechanisms  
 448 dominating the  $E_r$  formation. In fact, the plasma current, or more precisely the safety  
 449 factor, is expected to play some role in the establishment of the radial electric field.  
 450 Indeed increasing the safety factor (i.e. lowering the current at constant magnetic  
 451 field) increases the connexion length, and therefore decreases the ability of the plasma  
 452 to balance charge separation via the particle motion along the field lines (Pfirsch-  
 453 Schlüter mechanism). Correlatively the orbit width increases with the safety factor,  
 454 thus presumably leading to a wider  $E_r$  shear layer if orbit losses (including prompt  
 455 losses as well as thermal and fast particles losses) are to play a role in the formation  
 456 of the  $E_r$  well. This mechanism is also sensitive to the ion  $\nabla B$  drift which comes into  
 457 play when comparing LSN versus LSN configuration. Also the competition between  
 458 neoclassical viscous damping and turbulent drive plays a role in some models of the  
 459 L-H transition [Chô+14]. This competition introduces an explicit dependence on the  
 460 safety factor. In particular, considering the turbulent drive, the breaking of the poloidal  
 461 symmetry of the magnetic shear with X-point or contact point with a limiter, can induce  
 462 significant contribution on the  $E_r$  profile [Fed+13; Man+18]. In this spirit, investigation  
 463 on edge turbulence generating flows via both magnetic and velocity shear, based on a  
 464 reduced model [Per+21] are in progress.



**Figure 9.** Comparison of the evolution of the depth of the  $E_r$  well in LSN and USN during L and H-mode phases as a function of the heating power crossing the separatrix  $P_{sep}$  (left) and as a function of the density gradient at the edge (right)

Concerning the evolution of the velocity profile with increasing the RF heating power, in addition to the fact that the  $E_r$  well is deeper in USN than in LSN, it is also found that the correlation between the density gradient and the velocity gradient changes between LSN and USN configuration. To illustrate this point, Figure 9 shows the evolution of the velocity gradient by mean of the depth of the velocity well with both the heating power and the density gradient at the edge. It shows that the evolution of the depth of the velocity well with the normalized density gradient, after the transition, seems to follow a linear trend in the case of LSN but not in the USN configuration (Figure 9 right). This observation suggests, in addition to the others already mentioned, that the dominant mechanism that rules the radial electric field is different from one configuration to the other. In particular, this behaviour appears not in line with a dominant diamagnetic contribution (see eq. 3) suggesting that other effects must be considered, at least in the USN case. The dynamical interaction between eddies and shear flow discussed just above appears not compatible since in this model, the USN configuration leads to a weaker flow. Competition between neoclassical mechanisms such as orbit losses and magnetic ripple with turbulence related effects may be responsible for this complex behaviour.

*This work has been carried out within the framework of the EUROfusion Consortium and the French Research Federation for Fusion Studies and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.*

## References

- [Bur+89] K H Burrell et al. “Confinement physics of H-mode discharges in DIII-D”. In: *Plasma Physics and Controlled Fusion* 31.10 (Aug. 1989), pp. 1649–1664. DOI: 10.1088/0741-3335/31/10/012. URL: <https://doi.org/10.1088/0741-3335/31/10/012>.
- [Wag+82] F. Wagner et al. “Regime of Improved Confinement and High- $\beta$  in Neutral-Beam-Heated Divertor Discharges of the ASDEX Tokamak”. In: *Phys. Rev. Lett.* 49 (19 Nov. 1982), pp. 1408–1412. DOI: 10.1103/PhysRevLett.49.1408. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.49.1408>.
- [BDT90] H. Biglari, P. H. Diamond, and P. W. Terry. “The Influence of Sheared Poloidal Rotation on Edge Turbulence”. In: *Phys. Fluids B* 2.1 (1990), pp. 1–4.
- [McD+09] R. M. McDermott et al. “Edge radial electric field structure and its connections to H-mode confinement in Alcator C-Mod plasmas”. In: *Physics of Plasmas* 16.5 (2009), p. 056103. DOI: 10.1063/1.3080721. eprint:

<https://doi.org/10.1063/1.3080721>. URL: <https://doi.org/10.1063/1.3080721>. 501  
502

[Est+09] T Estrada et al. “Sheared flows and transition to improved confinement 503  
504 regime in the TJ-II stellarator”. In: *Plasma Physics and Controlled Fusion*  
505 51.12 (Nov. 2009), p. 124015. DOI: 10.1088/0741-3335/51/12/124015.  
506 URL: <https://doi.org/10.1088/0741-3335/51/12/124015>.

[Vie+13] E. Viezzer et al. “High-accuracy characterization of the edge radial electric  
507 field at ASDEX Upgrade”. In: *Nuclear Fusion* 53.5 (2013), p. 053005. URL:  
508 <http://stacks.iop.org/0029-5515/53/i=5/a=053005>.  
509

[And+08] Y. Andrew et al. “Evolution of the radial electric field in a JET H-mode  
510 plasma”. In: *EPL (Europhysics Letters)* 83.1 (June 2008), p. 15003. DOI:  
511 10.1209/0295-5075/83/15003. URL: [https://doi.org/10.1209/0295-](https://doi.org/10.1209/0295-5075/83/15003)  
512 [5075/83/15003](https://doi.org/10.1209/0295-5075/83/15003).  
513

[Kam+11] K. Kamiya et al. “Spatio-temporal structure of the edge radial electric field  
514 during H-mode in JT-60U”. In: *Nuclear Fusion* 51.5 (Apr. 2011), p. 053009.  
515 DOI: 10.1088/0029-5515/51/5/053009. URL: [https://doi.org/10.](https://doi.org/10.1088/0029-5515/51/5/053009)  
516 [1088/0029-5515/51/5/053009](https://doi.org/10.1088/0029-5515/51/5/053009).  
517

[Bur20] K. H. Burrell. “Role of sheared  $E \times B$  flow in self-organized, improved  
518 confinement states in magnetized plasmas”. In: *Physics of Plasmas* 27.6  
519 (2020), p. 060501. DOI: 10.1063/1.5142734. eprint: [https://doi.org/](https://doi.org/10.1063/1.5142734)  
520 [10.1063/1.5142734](https://doi.org/10.1063/1.5142734). URL: <https://doi.org/10.1063/1.5142734>.  
521

[Cav+16] M. Cavedon et al. “Interplay between turbulence, neoclassical and zonal  
522 flows during the transition from low to high confinement mode at ASDEX  
523 Upgrade”. In: *Nuclear Fusion* 57.1 (Oct. 2016), p. 014002. DOI: 10.1088/  
524 0029-5515/57/1/014002. URL: [https://doi.org/10.1088/0029-](https://doi.org/10.1088/0029-5515/57/1/014002)  
525 [5515/57/1/014002](https://doi.org/10.1088/0029-5515/57/1/014002).  
526

[Con+11] G. D. Conway et al. “Mean and Oscillating Plasma Flows and Turbulence  
527 Interactions across the L-H Confinement Transition”. In: *Phys. Rev. Lett.*  
528 106 (6 Feb. 2011), p. 065001.  
529

[Sch+12] L. Schmitz et al. “Role of Zonal Flow Predator-Prey Oscillations in  
530 Triggering the Transition to H-Mode Confinement”. In: *Phys. Rev. Lett.*  
531 108 (15 Apr. 2012), p. 155002. DOI: 10.1103/PhysRevLett.108.155002.  
532 URL: <https://link.aps.org/doi/10.1103/PhysRevLett.108.155002>.  
533

[Est+11] T. Estrada et al. “Spatiotemporal Structure of the Interaction between  
534 Turbulence and Flows at the L-H Transition in a Toroidal Plasma”.  
535 In: *Phys. Rev. Lett.* 107 (24 Dec. 2011), p. 245004. DOI: 10.1103/  
536 [PhysRevLett.107.245004](https://doi.org/10.1103/PhysRevLett.107.245004). URL: [https://link.aps.org/doi/10.1103/](https://link.aps.org/doi/10.1103/PhysRevLett.107.245004)  
537 [PhysRevLett.107.245004](https://link.aps.org/doi/10.1103/PhysRevLett.107.245004).  
538

[KDG91] Y. B. Kim, P. H. Diamond, and R. R. Groebner. “Neoclassical poloidal and  
539 toroidal rotation in tokamaks”. In: *Physics of Fluids B: Plasma Physics* 3.8  
540 (1991), p. 2050.  
541

- [SMR11] U Stroth, P Manz, and M Ramisch. “On the interaction of turbulence and flows in toroidal plasmas”. In: *Plasma Physics and Controlled Fusion* 53.2 (Jan. 2011), p. 024006. DOI: 10.1088/0741-3335/53/2/024006. URL: <https://doi.org/10.1088/0741-3335/53/2/024006>.
- [CKW02] C. S. Chang, Seunghoe Kue, and H. Weitzner. “X-transport: A baseline nonambipolar transport in a diverted tokamak plasma edge”. In: *Physics of Plasmas* 9.9 (2002), pp. 3884–3892. DOI: 10.1063/1.1490348. eprint: <https://doi.org/10.1063/1.1490348>. URL: <https://doi.org/10.1063/1.1490348>.
- [dMB11] J.S. deGrassie, S.H. Müller, and J.A. Boedo. “Plasma flow due to a loss-cone distribution centred around the outboard edge in DIII-D”. In: *Nuclear Fusion* 52.1 (Dec. 2011), p. 013010. DOI: 10.1088/0029-5515/52/1/013010. URL: <https://doi.org/10.1088/0029-5515/52/1/013010>.
- [Brz+19] Robert W. Brzozowski et al. “A geometric model of ion orbit loss under the influence of a radial electric field”. In: *Physics of Plasmas* 26.4 (2019), p. 042511. DOI: 10.1063/1.5075613. eprint: <https://doi.org/10.1063/1.5075613>. URL: <https://doi.org/10.1063/1.5075613>.
- [Gar+10] X. Garbet et al. “Entropy production rate in tokamaks with nonaxisymmetric magnetic fields”. In: *Physics of Plasmas* 17.7 (2010), p. 072505. DOI: 10.1063/1.3454365. eprint: <https://doi.org/10.1063/1.3454365>. URL: <https://doi.org/10.1063/1.3454365>.
- [Nav+10] M. F. F. Nave et al. “Influence of Magnetic Field Ripple on the Intrinsic Rotation of Tokamak Plasmas”. In: *Phys. Rev. Lett.* 105 (10 Sept. 2010), p. 105005. DOI: 10.1103/PhysRevLett.105.105005. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.105.105005>.
- [Ura+11] H. Urano et al. “Edge pedestal characteristics in JET and JT-60U tokamaks under variable toroidal field ripple”. In: *Nuclear Fusion* 51.11 (Oct. 2011), p. 113004. DOI: 10.1088/0029-5515/51/11/113004. URL: <https://doi.org/10.1088/0029-5515/51/11/113004>.
- [Fen+11] C. Fenzi et al. “On plasma rotation with toroidal magnetic field ripple and no external momentum input”. In: *Nuclear Fusion* 51.10 (Sept. 2011), p. 103038. DOI: 10.1088/0029-5515/51/10/103038. URL: <https://doi.org/10.1088/0029-5515/51/10/103038>.
- [Mon+97] P Monier-Garbet et al. “Effects of neutrals on plasma rotation in DIII-D”. In: *Nuclear Fusion* 37.3 (Mar. 1997), pp. 403–412. DOI: 10.1088/0029-5515/37/3/i09. URL: <https://doi.org/10.1088/0029-5515/37/3/i09>.
- [DK91] P. H. Diamond and Y.-B. Kim. “Theory of mean poloidal flow generation by turbulence”. In: *Phys. Fluids B* 3.7 (1991), pp. 1626–1633.

- [Dif+09] G. Dif-Pradalier et al. “Interplay between Gyrokinetic Turbulence, Flows, and Collisions: Perspectives on Transport and Poloidal Rotation”. In: *Phys. Rev. Lett.* 103 (6 Aug. 2009), p. 065002. DOI: 10.1103/PhysRevLett.103.065002. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.103.065002>.
- [Gri+13] B.A. Grierson et al. “Collisionality scaling of main-ion toroidal and poloidal rotation in low torque DIII-D plasmas”. In: *Nuclear Fusion* 53.6 (May 2013), p. 063010. DOI: 10.1088/0029-5515/53/6/063010. URL: <https://doi.org/10.1088/0029-5515/53/6/063010>.
- [Fed+12] N. Fedorczak et al. “Shear-induced Reynolds stress at the edge of L-mode tokamak plasmas”. In: *Nuclear Fusion* 52.10 (Sept. 2012), p. 103013. DOI: 10.1088/0029-5515/52/10/103013. URL: <https://doi.org/10.1088/0029-5515/52/10/103013>.
- [Cha+17] A V Chankin et al. “EDGE2D-EIRENE modelling of near SOL E r: possible impact on the H-mode power threshold”. In: *Plasma Physics and Controlled Fusion* 59.4 (Mar. 2017), p. 045012. DOI: 10.1088/1361-6587/aa5ecc. URL: <https://doi.org/10.1088/1361-6587/aa5ecc>.
- [Buc+14] J. Bucalossi et al. “The WEST project: Testing ITER divertor high heat flux component technology in a steady state tokamak environment”. In: *Fusion Engineering and Design* 89.7 (2014). Proceedings of the 11th International Symposium on Fusion Nuclear Technology-11 (ISFNT-11) Barcelona, Spain, 15-20 September, 2013, pp. 907–912. ISSN: 0920-3796. DOI: <https://doi.org/10.1016/j.fusengdes.2014.01.062>. URL: <https://www.sciencedirect.com/science/article/pii/S0920379614000635>.
- [Tri+08] E. Trier et al. “Radial electric field measurement in a tokamak with magnetic field ripple”. In: *Nuclear Fusion* 48.9 (Aug. 2008), p. 092001. DOI: 10.1088/0029-5515/48/9/092001. URL: <https://doi.org/10.1088/0029-5515/48/9/092001>.
- [Ver+18] L. Vermare et al. “Poloidal asymmetries of flows in the Tore Supra tokamak”. In: *Physics of Plasmas* 25.2 (2018), p. 020704. DOI: 10.1063/1.5022122. eprint: <https://doi.org/10.1063/1.5022122>. URL: <https://doi.org/10.1063/1.5022122>.
- [Hen+10] P. Hennequin et al. “The effect of SOL flows on edge and core radial electric field and rotation in Tore Supra”. In: *37th EPS Conference on Plasma Physics, Dublin* 34A, P1.1040 (2010).
- [Hen+06] P. Hennequin et al. “Fluctuation spectra and velocity profile from Doppler backscattering on Tore Supra”. In: *Nuclear Fusion* 46.9 (2006), S771.
- [Hon+06] C. Honoré et al. “Quasi-optical Gaussian beam tracing to evaluate Doppler backscattering conditions”. In: *Nuclear Fusion* 46.9 (2006), S809–S815.

- 620 [Cla+17] F. Clairet et al. “1  $\mu$ s broadband frequency sweeping reflectometry for  
plasma density and fluctuation profile measurements”. In: *Review of* 621  
*Scientific Instruments* 88.11 (2017), p. 113506. DOI: 10.1063/1.4991789. 622  
eprint: <https://doi.org/10.1063/1.4991789>. URL: [https://doi.org/](https://doi.org/10.1063/1.4991789) 623  
[10.1063/1.4991789](https://doi.org/10.1063/1.4991789). 624
- [Fau20] Blaise Faugeras. “An overview of the numerical methods for tokamak 625  
plasma equilibrium computation implemented in the NICE code”. In: 626  
*Fusion Engineering and Design* 160 (2020), p. 112020. ISSN: 0920-3796. DOI: 627  
<https://doi.org/10.1016/j.fusengdes.2020.112020>. URL: <https://www.sciencedirect.com/science/article/pii/S0920379620305688>. 628  
<https://www.sciencedirect.com/science/article/pii/S0920379620305688>. 629
- [Sch+06] J Schirmer et al. “The radial electric field and its associated shear in the 630  
ASDEX Upgrade tokamak”. In: *Nuclear Fusion* 46.9 (Aug. 2006), S780– 631  
S791. DOI: 10.1088/0029-5515/46/9/s13. URL: <https://doi.org/10.1088/0029-5515/46/9/s13>. 632  
[1088/0029-5515/46/9/s13](https://doi.org/10.1088/0029-5515/46/9/s13). 633
- [Fed+13] N Fedorczak et al. “Dynamics of tilted eddies in a transversal flow at the 634  
edge of tokamak plasmas and the consequences for L–H transition”. In: 635  
*Plasma Physics and Controlled Fusion* 55.12 (Nov. 2013), p. 124024. DOI: 636  
10.1088/0741-3335/55/12/124024. URL: [https://doi.org/10.1088/](https://doi.org/10.1088/0741-3335/55/12/124024) 637  
[0741-3335/55/12/124024](https://doi.org/10.1088/0741-3335/55/12/124024). 638
- [MTI08] Y R Martin, T Takizuka, and the ITPA CDBM H-mode Threshold Data 639  
Group. “Power requirement for accessing the H-mode in ITER”. In: *Journal* 640  
*of Physics: Conference Series* 123 (July 2008), p. 012033. DOI: 10.1088/ 641  
1742-6596/123/1/012033. URL: [https://doi.org/10.1088/](https://doi.org/10.1088/1742-6596/123/1/012033) 642  
[1742-6596/123/1/012033](https://doi.org/10.1088/1742-6596/123/1/012033). 643
- [CCE99] ITER Physics Expert Group on Confin Transport, ITER Physics Expert 644  
Group on Confin Database, and ITER Physics Basis Editors. “Chapter 2: 645  
Plasma confinement and transport”. In: *Nuclear Fusion* 39.12 (Dec. 1999), 646  
pp. 2175–2249. DOI: 10.1088/0029-5515/39/12/302. URL: [https://doi.](https://doi.org/10.1088/0029-5515/39/12/302) 647  
[org/10.1088/0029-5515/39/12/302](https://doi.org/10.1088/0029-5515/39/12/302). 648
- [Ryt+13] F. Ryter et al. “Survey of the H-mode power threshold and transition 649  
physics studies in ASDEX Upgrade”. In: *Nuclear Fusion* 53.11 (Sept. 2013), 650  
p. 113003. DOI: 10.1088/0029-5515/53/11/113003. URL: [https://doi.](https://doi.org/10.1088/0029-5515/53/11/113003) 651  
[org/10.1088/0029-5515/53/11/113003](https://doi.org/10.1088/0029-5515/53/11/113003). 652
- [Vin19] P. Vincenzi. In: *Private Communication* (2019). 653
- [Put20] T. Putterich. In: *ITPA Transport and confinement, June 2020* (2020). 654
- [Cla+01] F Clairet et al. “Edge density profile measurements by X-mode 655  
reflectometry on Tore Supra”. In: *Plasma Physics and Controlled Fusion* 656  
43.4 (Mar. 2001), pp. 429–441. DOI: 10.1088/0741-3335/43/4/305. URL: 657  
<https://doi.org/10.1088/0741-3335/43/4/305>. 658  
<https://doi.org/10.1088/0741-3335/43/4/305>. 658
- [Var21] R. Varennes. In: *Private Communication* (2021). 659

- 661 [GO98] R. J. Groebner and T. H. Osborne. “Scaling studies of the high mode 660  
662 pedestal”. In: *Physics of Plasmas* 5.5 (1998), pp. 1800–1806. DOI: 10 .  
663 1063/1.872849. eprint: <https://doi.org/10.1063/1.872849>. URL:  
<https://doi.org/10.1063/1.872849>.
- 664 [Hub+16] A.E. Hubbard et al. “Multi-device studies of pedestal physics and  
665 confinement in the I-mode regime”. In: *Nuclear Fusion* 56.8 (July 2016),  
666 p. 086003. DOI: 10.1088/0029-5515/56/8/086003. URL: <https://doi.org/10.1088/0029-5515/56/8/086003>.
- 668 [Med+17] A Medvedeva et al. “Density profile and turbulence evolution during L-  
669 H transition studied with the ultra-fast swept reflectometer on ASDEX  
670 Upgrade”. In: *Plasma Physics and Controlled Fusion* 59.12 (Nov. 2017),  
671 p. 125014. DOI: 10.1088/1361-6587/aa9251. URL: <https://doi.org/10.1088/1361-6587/aa9251>.
- 673 [Ver+12] L Vermare et al. “Detection of Geodesic Acoustic Mode oscillations , using  
674 MULTiple Signal Classification analysis of Doppler backscattering signal on  
675 Tore Supra”. In: *Nuclear Fusion* 52.6 (2012), p. 063008.
- 676 [Cho+15] B Chouli et al. “Investigations of LHCD induced plasma rotation in Tore  
677 Supra”. In: 57.12 (Oct. 2015), p. 125007. DOI: 10.1088/0741-3335/57/  
678 12/125007. URL: <https://doi.org/10.1088/0741-3335/57/12/125007>.
- 679 [Chô+14] L. Chôné et al. “L-H transition dynamics in fluid turbulence simulations  
680 with neoclassical force balance”. In: *Physics of Plasmas* 21.7 (2014),  
681 p. 070702. DOI: 10.1063/1.4890971. eprint: <https://doi.org/10.1063/1.4890971>.  
682 URL: <https://doi.org/10.1063/1.4890971>.
- 683 [Man+18] P. Manz et al. “Magnetic configuration effects on the Reynolds stress in  
684 the plasma edge”. In: *Physics of Plasmas* 25.7 (2018), p. 072508. DOI:  
685 10.1063/1.5037511. eprint: <https://doi.org/10.1063/1.5037511>.  
686 URL: <https://doi.org/10.1063/1.5037511>.
- 687 [Per+21] M. Peret et al. “A spectral model for interchange transport in tokamak  
688 scrape-off layers”. In: *Nuclear Fusion* 61.4 (Mar. 2021), p. 046045. DOI:  
689 10.1088/1741-4326/abe6b3. URL: <https://doi.org/10.1088/1741-4326/abe6b3>.
- 690