Investigation of the effect of divertor geometry on the L-H transition using reflectometry diagnostics

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Abstract

The effect of divertor geometry on the L-H transition at ASDEX Upgrade has been investigated, revealing that the power threshold to access H-mode is inversely correlated to the magnetic X-point height at high density. Microwave reflectometry diagnostics were used to measure edge electron density profiles and fluctuations across the L-H transition in order to improve the physics understanding of the phenomenon. A steepening of the edge density gradients, a reduction of low frequency fluctuations and the appearance of a quasi-coherent mode were observed following the L-H transition. A fluctuation increase at high frequencies was also found, being consistent with turbulence suppression by sheared flow. The dependence of the L-H power threshold on the divertor configuration may be partly related to divertor detachment, which is deduced from the observation of a high field side high density front. Density gradients before the transition were found to be identical, so new experiments must be conducted to evaluate the importance of other key quantities, such as the ion temperature.

Keywords: Nuclear fusion, L-H transition, Power threshold, Divertor, Microwave reflectometry

1. Introduction

In the absence of instabilities, the confinement of a tokamak plasma is determined by Coulomb collisions and a theory for the transport of particles and energy which would occur under these circumstances has been developed [1]. Unfortunately, the real plasma losses often exceed the calculated values by an order of magnitude or more, due to turbulence driven by instabilities [2], making the achievement of high temperatures and pressures required for a desirable fusion reactor very difficult.

It was found, however, that under certain conditions there is a discontinuous improvement in confinement as the heating power is increased [3]. The regime of higher confinement is called the H-mode and the previous lower level is called the L-mode. The H-mode has been responsible for important accomplishments in the quest for fusion energy [4], but the physics of the L-H transition is not yet fully understood, despite numerous proposed theories [5].

One important aspect of the H-mode is that the confinement improvement is caused by a region of reduced transport at the edge of the plasma [6]. The appearance of this edge transport barrier is linked to the development of a radial electric field well [7], which is believed to decorrelate turbulent eddies by sheared $E \times B$ flow [8, 9]. However, the origin of the edge radial electric field remains a current topic of investigation.

The critical requirement to access H-mode in a fusion plasma is the application of a sufficiently high heating power, known as the L-H power threshold. Because auxiliary heating systems are expensive and constitute a technological challenge for future large scale experiments, such as ITER, reliably predicting and controlling the power threshold is essential for the development of high performance fusion devices. To take into account transient effects, it is defined as the loss power to the plasma boundary at the L-H transition [10], given by

$$P_{LH} = P_{ohm} + P_{heat} - \frac{dW}{dt},$$

where $P_{ohm}$ is the ohmic power, $P_{heat}$ is the absorbed auxiliary heating power, and $dW/dt$ is the rate of change of the stored plasma energy. The radiated power from the bulk plasma may also be subtracted in the definition, as the net heat power loss across the separatrix is more likely to be the relevant global physics parameter to characterize the H-mode threshold [11].

A widely used law for the power threshold, upon which current extrapolations for ITER are based, is the 2008 ITPA multi-machine scaling [10], which
for deuterium is given by

$$P_{LH} = 0.0488 \, n_e^{0.717} \, B_T^{0.803} \, S^{0.941},$$

(2)

where $P_{LH}$ is the power threshold in MW without subtracting radiation losses, $n_e$ is the line-averaged density in $10^{20} \text{m}^{-3}$, $B_T$ is the magnetic field in T, and $S$ the plasma surface area in m$^2$. While it is well known that the power threshold strongly depends on these quantities, there is a considerable scatter around the scaling law, which is caused by un-included hidden parameters, such as divertor configuration, triangularity and X-point position [12].

Studies at JET [11, 12], DIII-D [13] and MAST [14] have shown that the position of the X-point can vary the power threshold by up to a factor of 2 and may therefore have a large impact on future devices. These studies have demonstrated a significant decrease of the L-H power threshold with reduced X-point height. However, experiments at Alcator C-mod have shown the inverse dependence [15]. The involved physics in not fully understood because these geometric effects modify the divertor neutral recycling, plasma parameters around the X-point, pumping efficiency, scrape-off layer (SOL) flows and the aspects related with atomic physics are complex and may be relevant.

The L-H transition of the ASDEX Upgrade (AUG) tokamak is studied in this work using mainly reflectometry diagnostics, with focus on the effect of divertor geometry on the L-H power threshold. The next section briefly describes the machine and its main diagnostics, with emphasis on microwave reflectometry. Section 3 presents the developed methods of reflectometry data calibration and analysis to provide useful information about the plasma. The experiment conducted at AUG and its results regarding the L-H power threshold and evolution of density profiles and fluctuations are discussed in section 4, followed by a concluding section.

2. Experimental apparatus

ASDEX Upgrade is a divertor tokamak of major radius $R = 1.6 \text{m}$ and minor radii $a = 0.5/0.8 \text{m}$ whose overall goal is to prepare the physics base for ITER. It is equipped with neutral beam injection (NBI), ion cyclotron resonance heating (ICRH) and electron cyclotron resonance heating (ECRH). AUG possesses an extensive set of diagnostics for machine operation and scientific investigation. Some of the systems used in this work were the DCN interferometer to measure the line-averaged electron density along lines of sight through the core and edge of the plasma, Thomson scattering to measure the overall evolution of the electron temperature in the plasma core and edge, $D_\alpha$ radiation and divertor currents at the inner and outer divertor regions to monitor edge localized modes (ELMs) and help the identification of L-H transitions. Unfortunately, the charge exchange diagnostic could not be used to provide edge radial electric field and ion temperature data because the boron spectrum was perturbed by residual nitrogen.

Microwave reflectometry has been used as the main diagnostic for measurement of edge electron density profiles and fluctuations. Reflectometry has a modest requirement for plasma accessibility and the capacity of conveying microwaves to a remote location, making it an ideal method for a fusion reactor, finding extensive use in tokamak research [16, 17]. Its operating principle is the following: microwave radiation with a given frequency is launched into the plasma along the density gradient and reflected at the layer where a critical electron density is achieved. The reflected wave is received at an antenna and phase changes due to propagation and reflection in the plasma are measured by mixing the reflected radiation with a reference beam. The relative positions of the density layers in the density profile are determined by making the measurement with a range of different probing frequencies. Alternatively, movements of single layer can be studied by using a fixed probing frequency.

The current reflectometry system for density profile measurement at AUG [18] is based on O-mode frequency-modulated continuous-wave (FM-CW) probing. It has the unique capability of simultaneously measuring the high field side (HFS) and low field side (LFS) of the machine, allowing an extensive range of comparative studies that otherwise would be impossible to make. In the HFS, four channels are used to cover the density range $0.3 - 6 \times 10^{19} \text{m}^{-3}$, corresponding to probing frequencies in the range $17 - 70 \text{GHz}$, divided in the frequency bands K(17-25 GHz), Ka(25-37 GHz), Q(37-50 GHz) and V(50-70 GHz). In the LFS, an extra channel with the W frequency band (70-100 GHz) complements these four to cover densities up to $1.24 \times 10^{20} \text{m}^{-3}$. The reflectometer was built so that the plasma is probed in the equatorial plane, close to the magnetic axis. An automatic procedure has been developed over the years to minimize possible errors in the reconstruction of density profiles [19], resulting in a time resolution of 1 ms.

The AUG reflectometer for fluctuation measurements [20] consists of Q band (33–49.2 GHz) and V band (49.4–72 GHz) channels with heterodyne I/Q detection and 2 MHz sampling frequency. The system is designed to allow a fast frequency change for an arbitrary frequency step and therefore is called fast frequency hopping reflectometer. Its antennas are located inside the tokamak vessel to minimize spurious signals, as shown in figure 1. The lines of sight are aligned to be perpendicular to the density
cutoff layers in the plasma edge region.

Figure 1: Cross-sectional view of AUG showing the antennas of the hopping reflectometry system. The FM-CW antennas (not shown) are located at a height similar to the FLQ antenna but at different toroidal positions.

The heterodyne system allows separate measurements of amplitude and phase through the use of an I/Q detector. The reference and reflected signal are directly mixed and filtered to obtain the in-phase (I) signal. For the quadrature (Q) signal, the reference is $90^\circ$ phase shifted by a delay line prior to mixing and filtering. The output of the I/Q detector is therefore given by

$$I = A_1 A_2 \cos (\phi),$$

$$Q = A_1 A_2 \sin (\phi).$$

where $A_1$ and $A_2$ are the amplitude of the reference and reflected signal and $\phi$ is the phase difference between them. The reflectometry amplitude, $A$, and phase, $\phi$, are then computed with the expressions

$$A = \sqrt{I^2 + Q^2},$$

$$\phi = \text{atan2} (Q, I),$$

where atan2 is the two-argument inverse tangent function with values from $-\pi$ to $\pi$.

3. Methods of data analysis and validation

The outputs of the AUG microwave reflectometry systems need post processing mainly for calibration purposes, mitigation of deleterious turbulence effects and data interpretation, in order to provide robust and useful information about the plasma.

The FM-CW data undergoes a sophisticated procedure for the reconstruction of density profiles, but it is far from perfect in the presence of turbulence or fast events. To reduce the nonphysical features in the profiles due to these causes, several consecutive profiles are averaged. This is a trade-off between time resolution and accuracy, such that averaging 5 to 10 profiles is usually worthwhile.

The hopping reflectometer outputs I/Q data with no calibration, needing post processing to provide information about density fluctuations. I and Q offsets must be removed to separate reflectometry phase and amplitude, so an automatic algorithm based on iterative circular fitting for determining the offsets was developed. Its overall scheme is summed up in the following steps:

1. Average the 0.1% lowest and highest I and Q values for an initial estimate of the center and radius of the circle;
2. Choose all points whose distance from the center is above 90% of the estimated radius;
3. Fit a circle to the chosen points with an unnormalized orthogonal distance regression to get improved estimates of the center and radius;
4. Repeat from step 2 using the improved estimates until the variation of the center coordinates is less than 1%;
5. The coordinates of the circle center obtained with the last fit are the I and Q offsets.

This is an effective and robust way of determining the I/Q offsets, as can be seen from the final fit example of figure 2. The method works in cases where simple averages are not able to correctly determine the offsets and also in cases where a simple average or a single fit would suffice.

Figure 2: Final circle fit to determine I/Q offsets.
which are approximately constant for all frequencies. The average I and Q offsets were computed and subtracted from the signals, allowing the separation of reflectometry amplitude and phase. The unconstrained unwrapped phase was computed by adding ±2π to all phase values after a phase difference between successive samples exceeded ±π.

There are 1D analytical models relating the reflectometry phase to density fluctuations, valid for low density fluctuation levels and long wavelengths [17, 21, 22]. However, the phase of reflectometry signals alone rarely contains easily available information about density fluctuations. Figure 3 shows an example of the unwrapped phase time evolution of a single hopping frequency step. There are three phase jumps of 2π which are not linearly related to density fluctuations. At first one may think this is just a problem of the unwrapping algorithm, possibly due to a low sampling frequency. However this has been investigated and is not the case. In fact, phase jumps have been reported in many reflectometer systems [22–25] and reproduced in full-wave simulations [26] for high fluctuation levels.

Often the unwrapped phase presents a continuously increasing behavior which is inconsistent with a realistic motion of the reflecting layer. This phase drift or runaway has been observed in many devices [24, 27, 28]. The required condition for phase jumps and drifts is the existence of turbulence with large amplitude, which originates interference effects due to 2D density fluctuations in the cutoff layer [23, 28].

For the shots analyzed in this work, phase jumps and drifts are an almost ubiquitous phenomenon, so it is important to study the validity of reflectometry signals in high fluctuation regimes. Two extreme examples were chosen as a basis for this study. One is a frequency step without phase jumps from an H-mode with low fluctuation level whose I/Q plot is shown in figure 4a. The other is a frequency step with strong phase runaway from an L-mode with high fluctuation level whose I/Q plot is shown in figure 4b.

A statistical analysis of these examples showed that the low fluctuation level phase distribution is peaked, while the high fluctuation level distribution is almost uniform. The amplitude distribution is also very different, being almost Gaussian in the first case, but becoming very skewed in the high fluctuation regime due to a heavy tail at low amplitudes. Similar results have been obtained in full-wave simulations coupled to turbulence codes [26].

Power spectra of the unwrapped phase, highpass filtered at 5 kHz, and wrapped phase are shown in figure 5b. In the low fluctuation level case, the spectra are identical up to 200 kHz, above which there are wrapping artifacts. For high fluctuation levels, they are very different. The unwrapped phase spectrum is approximately inversely proportional to the squared frequency, while the wrapped phase spectrum is much flatter. This frequency dependence of the unwrapped phase has been observed in many reflectometer systems in cases of high turbulence [16] and also in full wave simulations, bearing no similarity with the turbulence spectrum generated by the used turbulence codes [26].

Since the reflectometry phase alone is not adequate to describe density fluctuations in a highly
turbulent plasma, power spectra of in-phase and amplitude signals are also shown in figure 5. In both fluctuation regimes the amplitude and in-phase power spectra are similar up to 200 kHz, after which the in-phase spectrum decays more rapidly with frequency. In the case of low fluctuation level, the in-phase spectrum is similar to the phase spectra, but in the case of high fluctuations levels they are very different. This behavior has also been observed in the CCT tokamak [29]. The wrapped phase spectrum is similar to the amplitude spectrum for high fluctuations. It was also found that the coherence between reflectometry amplitude and phase signals is generally very low, which means that they are not linearly related. The observed similarities and differences between phase, amplitude and in-phase signals indicate that amplitude in fact contains important information about density fluctuations in the plasma and must not be ignored.

One way of combining amplitude and phase signals is to define the complex signal $Ae^{j\phi}$ or equivalently $I + jQ$. Besides containing information from both quantities, the complex signal also has the advantage that no phase unwrap is needed and its power spectrum can be used to identify Doppler shifts. However, its interpretation is not as intuitive as that of phase signals and its relation to density fluctuations is not well investigated, especially with regard to full-wave simulations, so the information which can be retrieved from the complex signal is at the moment mostly qualitative. Double-sided complex power spectra and spectrograms are used in the rest of this work as the main method to study edge electron density fluctuations from fixed frequency hopping reflectometry data.

4. Evolution of density profiles and fluctuations

4.1. Experiment

To investigate the influence of the X-point position on the L-H transition, an experiment was performed at AUG in 2014 with deuterium plasmas, lower single null configuration and favorable ion $\nabla B$ drift towards the X-point. Figure 6 shows the magnetic configurations used in the experiment, which will be hereafter referred to as low, mid and high X-point configurations, according to their relative X-point heights. Besides having different distances between X-point and strike points, it must be noted that the outer strike point of the high X-point configuration is located on the vertical target, contrary to the low and mid cases, whose outer strike points are located on the horizontal target. This affects the pumping capability and may also have an impact on the L-H transition dynamics [30]. Several geometric parameters are also inevitably changed, such as upper and lower triangularity, $\delta_U$ and $\delta_L$, elongation, $\kappa$, and area of the last closed flux surface, $S$. Table 1 shows the main geometric parameters of the magnetic configurations before the L-H transition. There is no known influence of $\kappa$ on the L-H transition and it does not vary dramatically, so it should not affect this experiment. $\delta_U$ is very low on all configurations so its effect should also be negligible. $\delta_L$ is reduced in the high X-point configuration and may influence the L-H transition [11]. Finally, $S$ also varies, but its effect on the power threshold can be removed by normalization with the ITPA scaling law.

Table 1: Main geometric parameters of the magnetic configurations before the L-H transition.

<table>
<thead>
<tr>
<th>Shot</th>
<th>X-point</th>
<th>$\kappa$</th>
<th>$\delta_U$</th>
<th>$\delta_L$</th>
<th>$S$ (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30533</td>
<td>low</td>
<td>1.60</td>
<td>0.028</td>
<td>0.43</td>
<td>43.7</td>
</tr>
<tr>
<td>30534</td>
<td>mid</td>
<td>1.59</td>
<td>0.088</td>
<td>0.44</td>
<td>44.7</td>
</tr>
<tr>
<td>30545</td>
<td>high</td>
<td>1.54</td>
<td>0.068</td>
<td>0.39</td>
<td>41.7</td>
</tr>
</tbody>
</table>

Due to the limited number of available shots, the strategy for the experiment was to have two L-H transitions per discharge, the first one at a low density and the second one at a higher density. This
was achieved by puffing a large amount of gas between the two transitions. All shots were conducted at toroidal magnetic field $B_T = -2.4 \, T$ and plasma current $I_P = 0.83 \, \text{MA}$. At these conditions the L-H power threshold is expected to lie between 0.7 MW and 1.8 MW, so 0.3 MW of ECRH followed by an NBI power ramp up to 3.5 MW was applied in each density step. Ideally the power ramp would be a slow and continuously increasing function of time, but, due to the discrete nature of the NBI power steps, the power ramp had to be achieved by modulating the NBI sources and pulse widths.

4.2. Identification of transitions and power threshold

The typical time evolution of the main parameters used to identify the L-H transition is shown in figure 7. The time derivative of the line-averaged electron density suffers two significant increases which correspond to the transitions from L-mode to dithering H-mode and then to full H-mode, hereafter called L-D and D-H transitions, respectively. The outer and inner $D_\alpha$ and divertor current signals decrease at both transitions and exhibit ELMs after the D-H transition. The electron temperature does not show a sudden increase in either transition, just slowly increasing after the L-D transition in the edge and after the D-H transition in the core.

Not all transitions are as clear as the one just shown one and the $D_\alpha$ and divertor current signals often do not show easily detectable decreases at the transitions, especially when their values are already low in L-mode. Therefore the following criteria were used to systematically identify the L-D and D-H transitions of the experiment: there must be an increase in the time derivative of the density at each transition; between the transitions there must be fluctuations with few kHz in the $D_\alpha$ or divertor current which are reduced at the D-H transition, possibly with the emergence of ELMs; if there is a single density increase, only a single L-H transition is considered. The L-H power threshold was calculated with equation 1 after smoothing the absorbed NBI power and plasma energy signals to account for the slow energy transfer from the NBI to the bulk plasma. A boxcar window of 40 ms was used based on simple estimations of the typical fast ion slowing down time. Since the absorbed heating power needs time to reach the plasma edge, the power threshold was averaged over 60 ms to take into account the energy transport. This corresponds to about half of the energy confinement time and ensures that the maximum power loss is always included in the averaging procedure. The standard deviation of the power loss in this period was taken as an estimate of the uncertainty in the power threshold.

The power threshold for the D-H transition as a function of line-averaged electron density is shown in the top plot of figure 8. At low density there is only a small difference between the divertor configurations but the transitions at high density have very different power thresholds. The low X-point configuration has the highest power threshold, fol-
lowed by the mid X-point configuration. The high X-point configuration appears to be insensitive to density variations, having the lowest power threshold at high density. To allow the comparison of transitions at different densities, the power thresholds were normalized to the ITPA scaling (eq. 2) and are shown in the bottom plot of figure 8. This scaling is only valid for the high density branch of the power threshold and does not account for the rollover usually observed at low densities. Therefore the density region below the typical minimizing density for the power threshold at AUG is marked as yellow and the normalization of points inside this region is in principle invalid. The high density points of the three configurations have significantly different power thresholds.

Figure 8: D-H power threshold for all divertor configurations. The bottom plot shows the power threshold normalized to the ITPA scaling.

It has been shown that there is an increase of the L-H power threshold with X-point height at high density in AUG for the divertor configurations of this experiment. This result is similar to the one obtained at Alcator C-Mod [15] if it is interpreted in terms of outer divertor leg length instead of X-point height. However, this trend is contrary to what is observed in JET [12], DIII-D [13] and MAST [14] with both interpretations, since in these machines there a clear increase in power threshold with X-point height and outer divertor leg length, which are covariant in the experiments.

4.3. L-H transition

The typical evolution of reflectometry density profiles for a low density transition is shown in figure 9. The LFS SOL is identical at the different phases of the discharge, having a shoulder and a steep gradient around 2.155 m, due to the shadowing effect of a limiter. During the ohmic phase, there are no other sharp gradients and the plasma density increases towards the core. With the application of ECRH, a transport barrier is formed just inside the separatrix, causing a higher core density, but the gradients outside this region remain unchanged. NBI heating does not alter the profile noticeably until the L-D transition, after which the transport barrier gradient increases, leading to a clear edge pedestal and increase in core density. The fully developed H-mode profiles between ELMs have a much steeper edge gradient and higher densities from the transport barrier inwards. The L-H transition thus appears to be a phenomenon which directly affects only a small edge region inside the separatrix, but has a significant impact on the whole plasma. The LFS and HFS behaviors are similar, with the difference that the separatrix position at the HFS is not tightly controlled. It must be noted that for high density transitions the overall evolution of density profiles is the same, but there is a clear pedestal even in L-mode and the difference between L-mode and H-mode profiles is not as marked as in the low density transitions.

Figure 9: Typical evolution of reflectometry density profiles for a low density transition. The separatrix is indicated by vertical dashed lines.

Edge density fluctuations were studied with the fast frequency hopping reflectometer and the typical double-sided complex reflectometry spectrogram across a low density L-H transition is shown in figure 10. This is not a continuous spectrogram, but instead a sequence of Welch periodograms of 6 ms of continuous data from the same probing frequency separated by 64 ms of void time periods. During the ohmic phase, which lasts until 1.8 s, the spectrum is symmetric and the power decreases with frequency. After the application of ECRH heating at 1.8 s, the spectrum widens and there is a power increase at high frequencies. After the L-D transition, which is triggered by the application of NBI heating, there is a slight power decrease for frequencies below 50 kHz and a wide peak at about 70 kHz begins to develop.
With the D-H transition, there is a further power reduction at low frequencies, the peak is intensified, its frequency increases and its harmonics become more evident. This is the quasi-coherent mode often observed in H-mode, which is associated with steep edge gradients and is thought to play a key role in limiting the pedestal gradient [31].

Figure 10: Hopping reflectometry complex spectrogram across a low density L-H transition. The transition time intervals are indicated by dashed lines.

Discrete reflectometry complex spectra of several phases of a low density transition are shown in figure 11. The ohmic L-mode spectral power decreases with frequency, as expected from a spectrum of turbulence. With the application of ECRH the power increases for all frequencies and the spectrum becomes wider. This is also expected since ECRH increases plasma density and temperature, thereby leading to stronger turbulent fluctuations. The dithering H-mode spectrum exhibits higher power for frequencies above 50 kHz and a slight power reduction in frequencies below 50 kHz. The quasi-coherent mode is present in this spectrum, with a peak frequency of about 70 kHz and a total width of about 60 kHz. In the fully developed H-mode spectrum between ELMs, the quasi-coherent mode becomes more intense, its peak frequency increases to about 90 kHz and its harmonics become more evident. There is a further reduction in low frequency power, along with an increase at high frequencies, above 160 kHz. To explain these results, it is noted that cross-field turbulent transport is correlated with the radial size of turbulent structures and there is a general tendency in physics for large structures to associate with low frequencies and vice versa. Plasma turbulent structures seem to obey this rule [32, 33] and it is known that low frequencies are the most relevant for transport [32, 34]. Therefore a reduction of density fluctuations in the low frequency range, as suggested by reflectometry, may be sufficient for a confinement improvement in spite of the fluctuation increase at high frequencies. In fact, this observation is consistent with the breaking up of large turbulent structures into smaller ones, as suggested by the theory of reduced transport due to decorrelation of turbulent eddies by radially sheared $E \times B$ flow [8].

Figure 11: Reflectometry complex spectra of different phases of a low density transition. The total power of each spectrum in arbitrary units is indicated in the legend after the time interval.

The total power of each complex spectrum in arbitrary units is also indicated in the plot legend of figure 11 after each time interval. The ECRH L-mode spectrum has a higher power than the ohmic spectrum and a lower power than the dithering H-mode spectrum. For some transitions, however, the total power of the dithering H-mode spectrum is lower than the L-mode one. The total power of the fully developed H-mode spectrum between ELMs is lower than the dithering H-mode and ECRH L-mode powers, as expected. This is what usually happens, but a few exceptions were encountered in the transitions of this experiment and the temporal evolution of the total power presents large fluctuations. This may be due to the often overwhelming contribution of very low frequencies, below 5 kHz. It should also be noted that part of the difference between L-mode and H-mode complex spectra may be caused by different density gradients, as simple 1D reflectometry models predict a dependence of the phase fluctuations on the square root of the density gradient length scale in case of low fluctuation levels [21]. For these reasons, the total power of complex reflectometry spectra may not be the best quantity to characterize overall density fluctuation levels and the subject needs further investigation.

### 4.4. Influence of divertor configuration

Average electron density profiles before each L-D transition for the three divertor geometries are shown in figure 12. The low and high X-point configurations have very similar LFS and HFS profiles, while the mid X-point configuration has a broader SOL at the LFS and a very different profile at the

![Figure 12: Average electron density profiles before each L-D transition for the three divertor geometries.](image)
HFS. There is a clear high density region in the SOL which ends abruptly at 1.55 m due to the HFS limiter. The development of a HFS high density front associated with the inner divertor detachment has been reported at AUG [35] and it has recently been shown that there is a relation between the midplane density profiles and divertor detachment [36]. It has also been suggested that the inner divertor detachment state plays an important role in the L-H transition, possibly facilitating access to H-mode due to a higher SOL radial electric field [37]. This may explain the observed difference in power threshold between the low and mid X-point configurations, since the mid X-point configuration is closer to the inner divertor and HFS wall than the low X-point configuration. This could ease the detachment of the inner divertor at high density, contributing to the lower power threshold observed in the mid X-point configuration. The even lower power threshold of the high X-point case cannot, however, be explained by this hypothesis, since this configuration is farther from the divertor than the other two. The profile similarity of the low and high X-point configurations before the transition excludes the possibility of different critical density gradients to explain the power threshold dependence. This dependence is not a simple consequence of different particle confinement properties either, as it was found that the density profiles are also very similar for the same heating power. Therefore there must be other effects in play, possibly related to plasma-wall interaction and the ion temperature gradient, as has been suggested by other experiments [38].

A comparison of L-mode and H-mode complex spectra between the low and high X-point configurations at a reflectometry probing frequency of 36 GHz is shown in figure 13. The L-mode spectra are both asymmetric, but skewed towards opposite directions. This is consistent with antenna misalignment, since the flux surfaces of the two configurations are tilted in opposite directions with respect to the antenna. The H-mode spectrum of the high X-point configuration exhibits a power reduction at low frequencies along with the 60 kHz wide quasi-coherent mode with 90 kHz peak frequency. However, the quasi-coherent mode is absent in the low X-point spectrum, which has just a slight power reduction in the low frequency range. The quasi-coherent mode has been associated with edge temperature gradients [31], which may depend on the divertor configuration, but cannot be measured with reflectometry. The reduction in low frequency fluctuations is usually more evident when the quasi-coherent mode is present, but it is not clear if this reduction is affected by the quasi-coherent mode or if it just a consequence of an increased radial electric field associated with steep edge gradients, which also happen to be the driving mechanism of the quasi-coherent mode.

Figure 12: Reflectometry density profiles of LFS and HFS before the L-D transition for different configurations. The separatrix is indicated by vertical dashed lines.

A comparison of L-mode and H-mode complex spectra between the low and high X-point configurations at a reflectometry probing frequency of 36 GHz is shown in figure 13. The L-mode spectra are both asymmetric, but skewed towards opposite directions. This is consistent with antenna misalignment, since the flux surfaces of the two configurations are tilted in opposite directions with respect to the antenna. The H-mode spectrum of the high X-point configuration exhibits a power reduction at low frequencies along with the 60 kHz wide quasi-coherent mode with 90 kHz peak frequency. However, the quasi-coherent mode is absent in the low X-point spectrum, which has just a slight power reduction in the low frequency range. The quasi-coherent mode has been associated with edge temperature gradients [31], which may depend on the divertor configuration, but cannot be measured with reflectometry. The reduction in low frequency fluctuations is usually more evident when the quasi-coherent mode is present, but it is not clear if this reduction is affected by the quasi-coherent mode or if it just a consequence of an increased radial electric field associated with steep edge gradients, which also happen to be the driving mechanism of the quasi-coherent mode.

5. Conclusions and future work

An automatic I/Q calibration algorithm has been developed, revealing that reflectometry signals suffer from numerous phase jumps and considerable phase drift for high fluctuation levels. In such cases the reflectometry phase is not linearly related to density fluctuations and should be used together with the amplitude signal to best infer the characteristics of turbulence. The double-sided complex spectrum of reflectometry signals has been proposed and tested as a method of combining amplitude and phase measurements. Qualitatively, it is sensitive to the plasma conditions, but full-wave simulations coupled to turbulence codes and comparison with other diagnostics are needed to unlock its full potential and allow more quantitative measurements of density fluctuations with high turbulence levels.

A set of criteria for identifying transitions to
dithering H-mode and to full H-mode on AUG has been proposed. Robust methods were used to compute the L-H power threshold, revealing that it is sensitive to the divertor configuration only at high densities, exhibiting an inverse correlation with X-point height. Although this is consistent with results from C-Mod, the behavior is contrary to what is observed in most machines and cannot be attributed to overall plasma shaping parameters, so it should be related to more subtle edge physics.

The evolution of edge density profiles and fluctuations across the L-H transition has been studied with reflectometry. The profiles were found to steepen during the H-mode, leading to higher core density, which is expected. H-mode reflectometry spectra revealed a quasi-coherent mode that has been observed in other machines, where it is believed to play a role in limiting the pedestal gradients. The fluctuations after the L-H transition were found to decrease at low frequencies and increase at high frequencies. This may indicate turbulence modification at different scales, as predicted by the theory of turbulence suppression due to breaking up of large eddies into smaller ones by sheared flow. Experimental evidence of this phenomenon is limited and valuable, as it contributes to confirming the theory and improving knowledge on the subject. Reflectometry may therefore play an important role in understanding the L-H transition.

A comparison of density profiles at the L-H transition for different divertor geometries revealed that the mid X-point configuration, which is closer to the inner divertor and HFS wall, has a high density front in the HFS. This is associated with divertor detachment, which may influence the L-H transition, but it cannot explain the significant difference in power threshold between the low and high X-point configurations, where no high density front is observed. Nevertheless, the relation between divertor detachment and the L-H transition in this experiment should be further investigated by analyzing data from bolometry and Langmuir probes at the divertor. No significant differences in density gradients were found between the low and high X-point configurations, indicating that the ion temperature gradient may be the more relevant parameter for the L-H transition in these cases. New experiments must be conducted to evaluate the importance of this quantity and other key measurements not available in this experiment, such as the electric field and plasma flow. Hopping reflectometry revealed that the existence of the quasi-coherent mode depends on the divertor geometry, although this dependence may be a consequence of different temperature gradients. The reduction in low frequency fluctuations seen by reflectometry is more evident when the quasi-coherent mode is present, but this may be due to a stronger radial electric field associated with steep edge gradients, which also drive the quasi-coherent mode. Future experiments performed with adequate hopping settings may allow the measurement of the radial amplitude profile of the quasi-coherent mode and the investigation of its relation to edge gradients and fluctuations.

References