Edge instabilities across the L-H transition and in H-mode of ASDEX Upgrade

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Introduction

The H-mode is currently the preferable operational regime for a fusion reactor but the physics of the L-H transition and confinement enhancement is not yet fully understood. Turbulence suppression is responsible for the formation of the edge pedestal, whose growth is believed to be limited by the onset of instabilities. The L-H transition in ASDEX Upgrade (AUG) is often accompanied by the appearance of edge coherent [1] or quasi-coherent modes (QCMs) [2] in density fluctuations. QCMs have also been detected in other devices [e.g. 3-4], but the underlying instabilities of these modes are mostly an open question, despite their relevance for understanding edge transport and pedestal physics. This contribution reports on the main results of an experiment at AUG dedicated to the study of edge instabilities.

Description of the experiment

Slow power ramp shots at different densities have been conducted in AUG to study edge instabilities across the L-H transition and in H-mode, including the intermediate I-phase. The following scenario was chosen: toroidal magnetic field $B_t = -2.5$ T; plasma current $I_p = 0.8$ MA; lower single null configuration (favourable L-H configuration with $B\times\nabla B$ towards the X-point); constant deuterium gas puff and central ECRH with steps of about 0.2 MW, up to a total of 1.5 MW. Three shots were performed with densities $\overline{n_e} = 2.3$, 4.0 and 4.6×10^{19} m^{-3} at the L-H transition, corresponding to the low density, minimum threshold and high density branches of the L-H power threshold curve. These will be hereafter referred to as low, medium and high density shots. Reflectometry is one of the main diagnostics used in this work, both for density profile and fluctuation measurements. Since the frequency modulated continuous wave reflectometer [5], which probes both the low-field side (LFS) and the high-field side (HFS) of the plasma, cannot simultaneously measure profiles and fluctuations, each shot was consecutively repeated with different diagnostic configurations. Fast frequency hopping (FFH) [6] and poloidal correlation reflectometry (PCR) [7] were also used to obtain more detailed information about the density fluctuations at the LFS.

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Characterization of the observed instabilities

Figure 1 (a)-(d) shows an overview of the medium density shot from L-mode to H-mode, with the transitions marked by vertical dashed lines. From 1.97 s to 2.13 s the plasma undergoes an alternation period between L-mode and I-phase with a slight confinement improvement, after which it enters a continuous I-phase until 2.48 s with a higher confinement improvement, as seen in the line-averaged electron density traces (figure 1(c)). Instabilities start to develop during the I-phase and their amplitude grows and saturates when the plasma enters the ELM-free H-mode, as shown in the FFH reflectometry phase (figure 1(a)) and radial magnetic field (figure 1(b)) spectrograms, which feature strong edge coherent modes with a multi-peak structure from 50 to 80 kHz. Similar modes have been previously observed in AUG [1]. Correlation analysis between different coils, including lower frequency peaks, reveals toroidal and poloidal mode numbers $n = -(2\text{-}8)$ and $m = 16\text{-}64$, with propagation in the electron diamagnetic direction in the lab frame, corresponding to a safety factor $q = m/n \sim 8$ if resonance is assumed. These modes are visible by LFS reflectometry in the pedestal ($\rho_{pol} \geq 0.97$), near the separatrix and weakly visible in the scrape-off layer (SOL). In this shot they are only visible on the HFS for brief periods of time because there is a high-field side high density front (HFSHD) which prevents reflectometry measurements in the confined

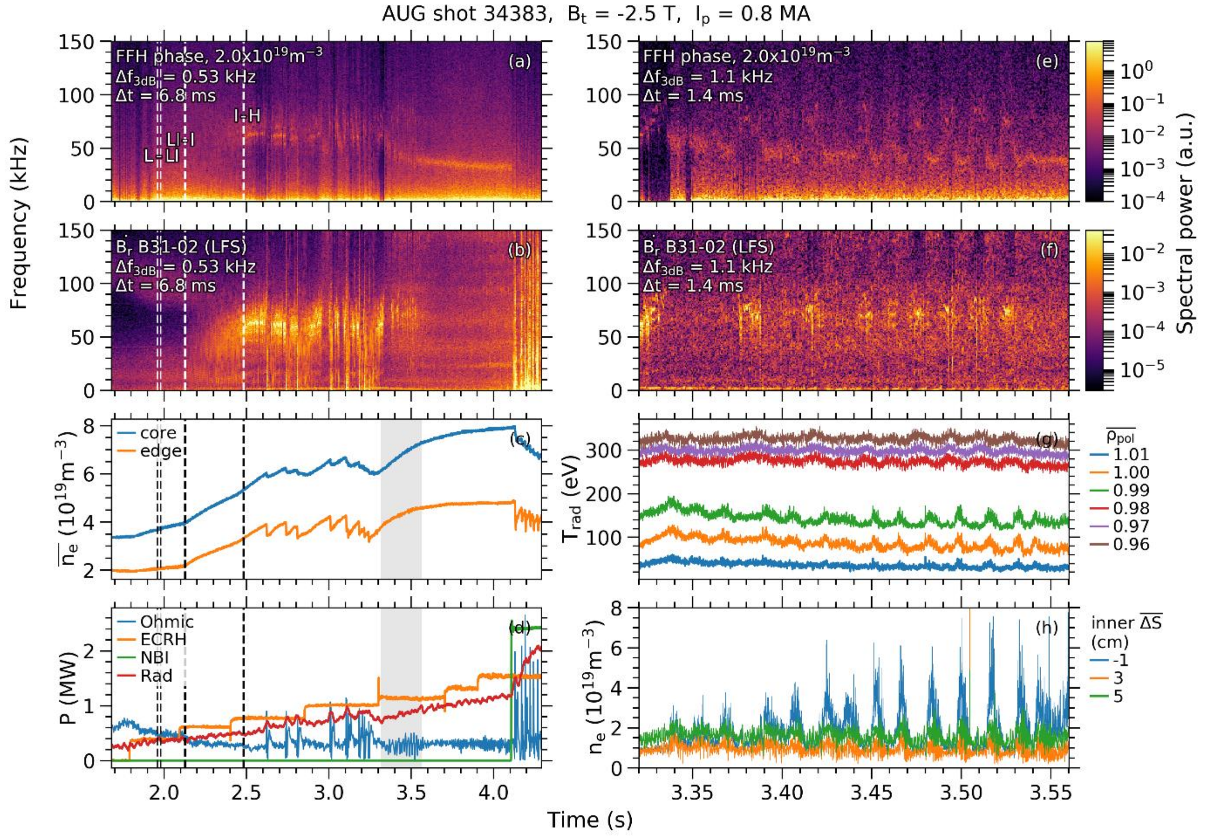

Figure 1: Time evolution of different quantities in the medium density shot: (a), (e) spectra of reflectometry phase caused by density fluctuations; (b), (f) spectra of radial magnetic field coil; (c) line-averaged electron density; (d) heating and radiated power; (g) ECE radiation temperature; (h) electron density measured by Langmuir probes in the divertor. The vertical dashed lines indicate the time instants of L-I-H transitions.

region [8]. However in the low density shot similar modes are observed on both sides of the plasma as there is no HFSHD, due to the lower gas puff rate. On the HFS they are visible in the confined region but not in the SOL. The modes have an up-chirping frequency in time, reaching up to 140 kHz, and their properties have also been measured by PCR: perpendicular wavenumber $k_\perp = 0.15\text{-}0.3\ \text{cm}^{-1} \sim 0.03\ \rho_s^{-1}$, velocity in the lab frame $v_\perp = 20\text{-}24$ km/s and toroidal mode numbers n = 5-10, which is consistent with the magnetic measurements in that shot. The modes are also visible in a couple of edge ECE channels, but the data should be interpreted with care as the plasma is optically thin outside the confined region. After the short ELM-free H-mode phase in the medium density shot there is a period of very low frequency ELMs until 3.3 s, since the heating power continues to be just slightly above the L-H power threshold as the density increases, but there is no impurity (tungsten) accumulation. The coherent modes are still present in this ELMy phase though they disappear and reappear with each ELM.

After the ELMy phase the plasma enters a very long ELM-free phase which lasts from 3.3 to 4.1 s and appears to approach stationarity (see figure 1(c)), being interrupted by NBI. There is no impurity accumulation in this phase either, despite the absence of ELMs. The coherent modes are not present, but a different instability is visible in the reflectometry spectrogram of figure 1(b), this time with a broad peak and down-chirping frequency from 60 to 35 kHz, which we refer to as a quasi-coherent mode (QCM). This QCM is not visible in any magnetic signal, which could mean that it is an electrostatic instability or that its different spatial structure and amplitude render it undetectable by the coils. The mode is visible by LFS reflectometry in the steep gradient region of the pedestal ($\rho_{pol} > 0.98$), near the separatrix and weakly visible in the SOL. It is possible that it also exists at smaller ρ_{pol} but no reflectometer channels probed inner layers during this part of the shot. On the HFS the QCM is not detected, possibly due to the presence of the HFSHD. The mode is clearly visible in four edge ECE channels, but not all of them measure an optically thick layer of the plasma, allowing only to estimate that the temperature fluctuation is at least in the confined region around $\rho_{pol} = 0.98$. The QCM is also present in the high density shot, appearing after the transition from I-phase to ELM-free H-mode, but the coherent modes with magnetic signature do not appear in this shot. Since the high density QCM is not detected by the coils its spatial structure has to be measured by other diagnostics. According to the PCR it has $k_\perp = 0.6\text{-}0.7\ \text{cm}^{-1} \sim 0.06\ \rho_s^{-1}$, $v_\perp = 5.5\text{-}6.4$ km/s in the electron diamagnetic direction and n = 20-23. The high density quasi-coherent mode is therefore smaller and slower (in the lab frame) than the low density coherent modes.

Mode alternation and effect on the pedestal and divertor

As explained in the previous section the medium density shot has first an ELMy period with edge coherent modes and then an ELM-free phase with a quasi-coherent mode. In between, from ~3.33 to 3.55 s, there is a period of alternation between the two modes which is shown in figure 1(e)-(h). The peak in the reflectometry spectrogram of figure 1(e) jumps back and forth between low and high frequency, while only the high frequency peak appears intermittently in the magnetic spectrogram of figure 1(f). This alternation is correlated with changes in several edge and divertor parameters. Figure 1(g) shows the ECE radiation temperature measured by edge channels which display an oscillation synchronized with the mode alternation. When the QCM appears, the temperature decreases in ECE channels within the confined region, the edge line-integrated density decreases (not shown) and the density measured by divertor Langmuir probes increases, as shown in figure 1(h). A rise in the temperature and current to the divertor is also observed. Low frequency divertor B_θ and SOL ECE oscillations are concomitant with these effects. The changes in the divertor happen after the changes in the pedestal, which allows the inference of a causality effect: the QCM and/or the low frequency fluctuations cause an increase of particle and energy transport in the pedestal region, expelling plasma to the divertor. This may explain the absence of impurity accumulation and ELMs, as the increased transport could prevent the edge gradients from reaching the peeling-ballooning instability boundary. If so, these observations may open the door to a new ELM-free regime at AUG which will be the subject of future experiments.

Conclusions

Edge instabilities with frequencies ranging from 35 to 140 kHz and a complex time evolution after the L-I-H transition have been observed. Their type and behaviour is different for the low and high density branches of the L-H power threshold. At medium density both types of modes are observed: first the coherent and then the quasi-coherent one. There is a period of alternation between the two which is correlated with changes in edge and divertor parameters, suggesting that the QCM causes increased transport losses. These instabilities may play an important role in the H-mode pedestal structure, stability and confinement.

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References

[1] A. Medvedeva et al., PPCF 59, 125014 (2017)
[2] S. da Graça et al, EPS Plasma Physics (2013)
[3] H.Q. Wang et al, PRL 112, 185004 (2014)
[4] A. Diallo et al, NF 55, 053003 (2015)
[5] A. Silva et al., RoSI 67, 4138 (1996)
[6] L. Cupido et al, RoSI 77, 10E915 (2006)
[7] D. Prisiazhniuk et al, PPCF 60, 075003 (2018)
[8] L. Guimarais et al, NF 58, 26005 (2018)