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ABSTRACT.

A characteristic feature of ELMy H-mode regimes with so-called mixed type-I/II edge localized modes is a change in the magnetic fluctuation spectrum measured with pick-up coils near the plasma boundary. The power losses in-between ELMs can be attributed to so-called washboard modes, i.e. bands of small-scale MHD modes rotating in the electron diamagnetic drift direction, which become more pronounced in these plasmas. The washboard modes can cause a saturation of the edge temperature, but they are not strong enough to stop the evolution of the edge density. The onset of the ELM precursor modes suppresses the washboard bands and allows the pedestal pressure to build-up faster, which leads eventually to the ELM crash.

1. INTRODUCTION.

The good energy confinement in type-I ELMy H-mode discharges is achieved by a transport barrier located at the plasma edge. This transport barrier causes a steepening of the plasma profiles. The increased pressure gradient at the edge leads eventually to the destabilization of the ELM collapse. The energy and particle losses during the short ELM bursts cause high transient heat loads on plasma facing components and the extrapolation to ITER yields that the lifetime of the divertor may be severely limited. Plasma scenarios with more benign ELM behaviour are therefore required. A possible solution recently found on ASDEX Upgrade in quasi double-null plasma shape discharges at high density, is the so-called type-II ELM regime, where the bursts are replaced by continuous MHD activity located at the plasma edge [1].

Various experiments aimed to reduce the ELM induced power loads were performed at JET . Impurity seeding results in a reduction of the ELM energy loss, partly due to a reduced energy content in the pedestal, but probably also because a fraction of the ELM energy is dissipated via radiation [2]. Other experiments aimed to establish a type-II ELM regime in ITER-like or near double-null configurations with high triangularity and high density. Up to now, no pure type-II regime could be identified, although mixed type-I/II behaviour, where the ELM frequency is reduced, has been commonly found [3, 4]. In the following the typical differences in the MHD behaviour of these discharges are described.

2. EXPERIMENTAL OBSERVATIONS IN MIXED TYPE-I/II REGIMES.

Figure 1 shows an example for the typical MHD observations in type-I ELMy H-modes at high triangularity. The Pulse No's 57897 and 57889 have a toroidal magnetic field of 2.7T, a plasma current of 2.5MA, and are heated by 13.5MW NBI and 3MW ICRF. The main difference between both discharges is the applied gas fuelling (6.8×10^{21} D/s for 57897, 6.2×10^{22} D/s for 57889) and therefore the achieved electron density ($\bar{n}_e = 7.5\times10^{19}$ m^{-3} for 57897, $\bar{n}_e = 10.5\times10^{19}$ m^{-3} for 57889). As can be seen in figure 1 the ELM frequency in the high fuelling case has dropped by more than a factor 2 down to approximately 10Hz. The radiated power stays the same (about 9MW) in both cases. Despite the lower ELM frequency in the high fuelling case, the stored energy is more or less the same, and the power loss per ELM is not found to increase [3]. This indicates that some additional loss mechanism has to be present.

The comparison of the spectra in figure 1 shows that the high fuelling Pulse No: 57889 has an increased level of magnetic fluctuations in the range between 10 - 30kHz. This is quantitatively seen when the Fourier spectra are time averaged between two ELMs (vertical lines in the spectrograms). Figure 2 compares the time averaged Fourier spectra (normalized to frequency in order to compensate ω the dependence of the pick-up coil) of both discharges. The behaviour is quite different: Pulse No: 57897 has lower amplitudes at low frequency, but falls off less than Pulse No: 57889 at higher frequency.

The enhancement of magnetic fluctuation amplitudes in the frequency range between 10 - 30kHz amounts to a factor of 3 in this example (NB: The low frequency lines in the spectra are due to core MHD like sawtooth precursor modes or neoclassical tearing modes and do not contribute to the edge power loss.). A corresponding increase of low frequency fluctuations could also be identified on a fast sampled (100kHz) interferometer channel intersecting the plasma in the vertical direction a few cm inside the separatrix.

The toroidal mode number spectrum of a similar high triangularity type-I ELMy H-mode with low fuelling is shown in figure 3. The constant lines at 12kHz and 44 kHz are due to a sawtooth precursor mode (1/1) and a 5/4 tearing mode. A regular phenomenon observed in H-modes on JET are the broad bands of mode activity with negative toroidal mode numbers (blue). These modes were already identified in 1999 and called washboard (WB) modes [5]. The modes with higher positive mode numbers shortly before the ELMs are ELM precursor modes located in the steep gradient zone at the plasma edge [6].

3. FEATURES OF WASHBOARD MODES.

Washboard modes have the following properties: (i) they rotate in the direction of the electron diamagnetic drift, (ii) the mode amplitude (displacement of the flux sur-faces) is quite small in the sub-millimetre range [5], (iii) the range of toroidal mode numbers is -1 to -8, (iv) they don't have an island structure, and (v) their frequency follows the evolution of the edge temperature. The latter is clearly visible in the example in figure 4 where the mode number spectrum shows the WB bands (blue colors) which follow in frequency the evolution of T_e (middle) although the edge density (right) constantly increases.

The detailed comparison of many discharges in the type-I/II ELM regime yielded that the enhancement of the magnetic fluctuation spectrum in the low frequency range is due to stronger WB modes. The appearance of WB modes with larger amplitudes leads to a slower evolution of the pedestal pressure, resulting in longer ELM periods. Figure 4 shows that the edge temperature stays nearly constant (as does the WB frequency) until it starts to increase at 16.87s. This is at the same time when the ELM precursor mode appears.

The complex interaction between WB modes and ELM precursors is shown in figure 5. Here it is visible that the WB modes (negative mode numbers, blue) show the opposite behaviour than the ELM precursor (n = 4, yellow). The precursor mode has a strong modulation in amplitude, i.e. it appears and vanishes several times. This observation suggests that ELM precursor modes tend to weaken or even inhibit WB modes.

DISCUSSION AND CONCLUSION

Washboard mode are a likely candidate to explain the enhancement in magnetic fluctuations during ELM-free periods in the mixed type-I/II regime on JET. Although they enhance edge transport, their usual strength is too small to saturate the edge profiles. Slowing the build up of the edge pressure can explain the reduced ELM frequency.

The nature of washboard modes is still unclear. Resistive ballooning modes and Kelvin-Helmholtz instabilities are possible explanations [7].

WB modes, i.e. modes rotating in the electron diamagnetic drift direction, have recently also been seen on ASDEX Upgrade [8]. The nature of the edge harmonic oscillation observed on D-IIID [9] and recently also in ASDEX Upgrade [10], which occurs at low n_{ped}, high T_{ped}, and counter neutral beam injection, is clearly different to the present observation.

Future work should aim at a better understanding of WB modes and similar MHD activity at the plasma edge, which acts as an additional energy loss mechanism. The tailoring of the plasma edge in order to enforce such kind of mode activity could aid in the development of an ITER operating scenario with acceptable divertor heat loads.

ACKNOWLEDGEMENTS

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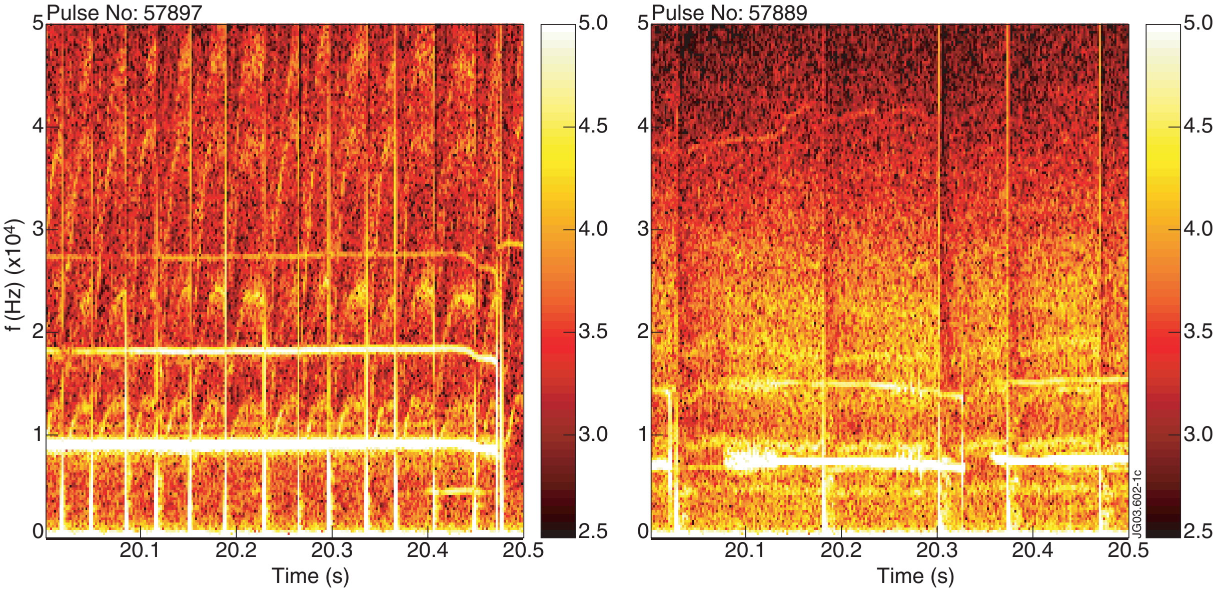
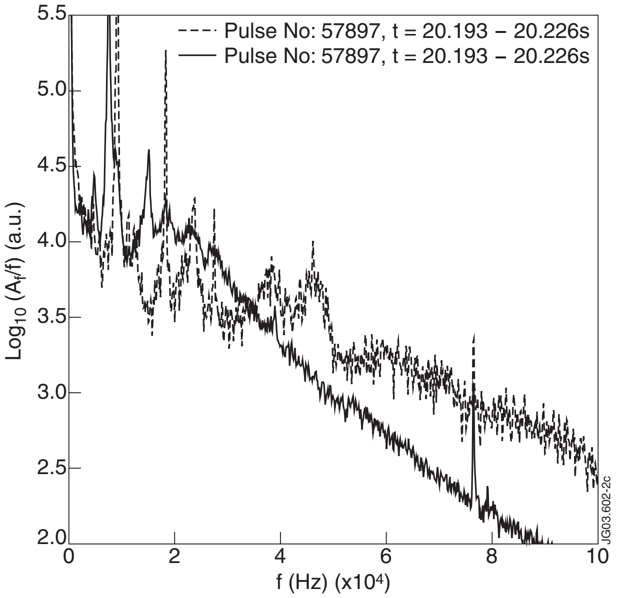


Figure 1: Comparison of two spectrograms calculated from the signals of a magnetic pick-up coil located at the low-field side of the torus. The spectrograms are normalized to frequency. (a) reference type-I ELMy H-mode, (b) the same scenario with increased gas puffing.



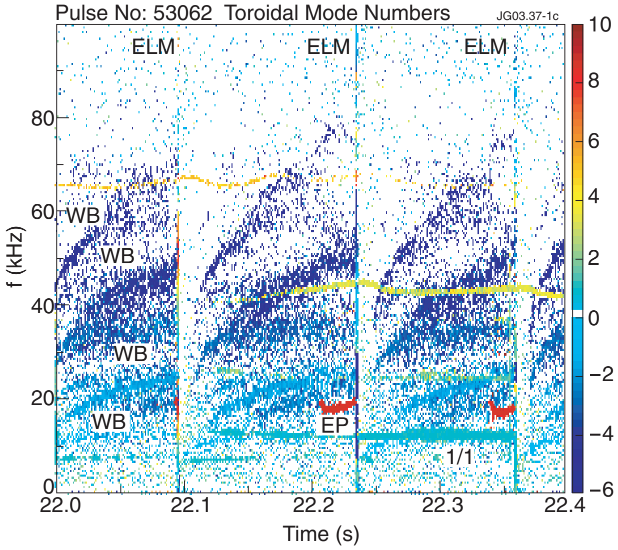


Figure 2: Time averaged magnetic fluctuation spectra between ELM crashes (same discharges as shown in figure 1).

Figure 3: Spectrum of the toroidal mode numbers. The broad bands of turbulence have negative mode numbers.

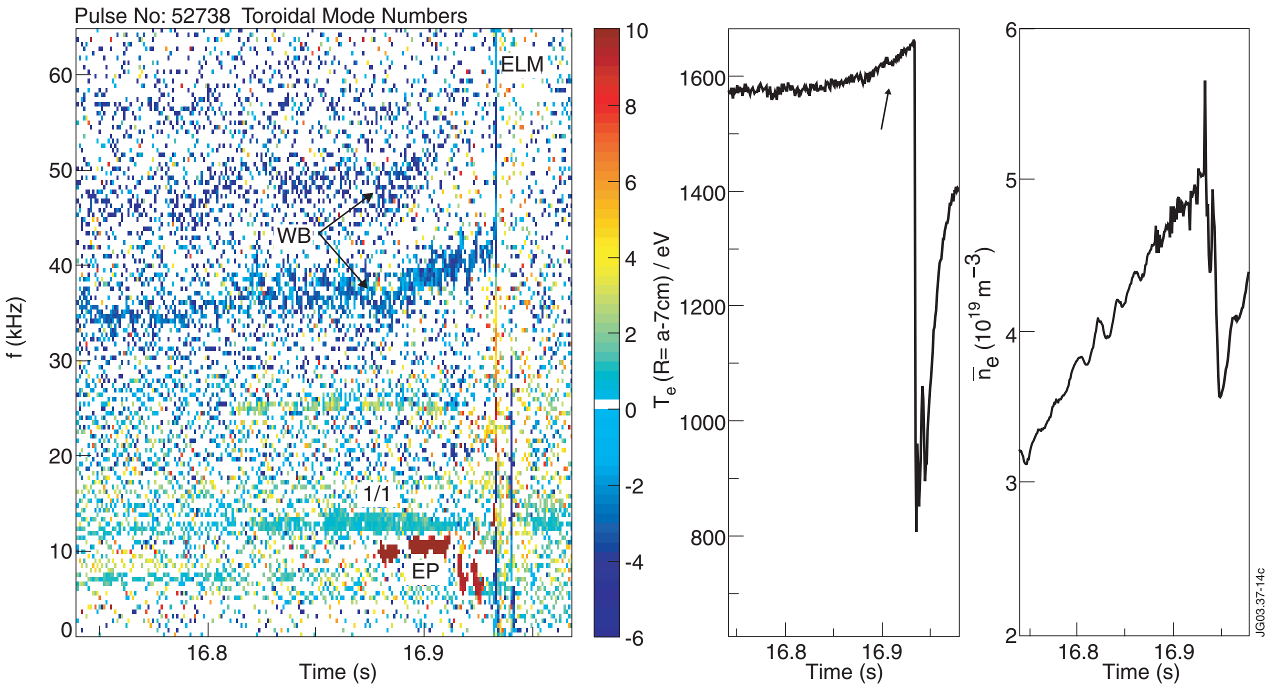


Figure 4: Toroidal mode numbers (left), electron temperature (middle) and electron density (right) near the top of the edge pedestal.

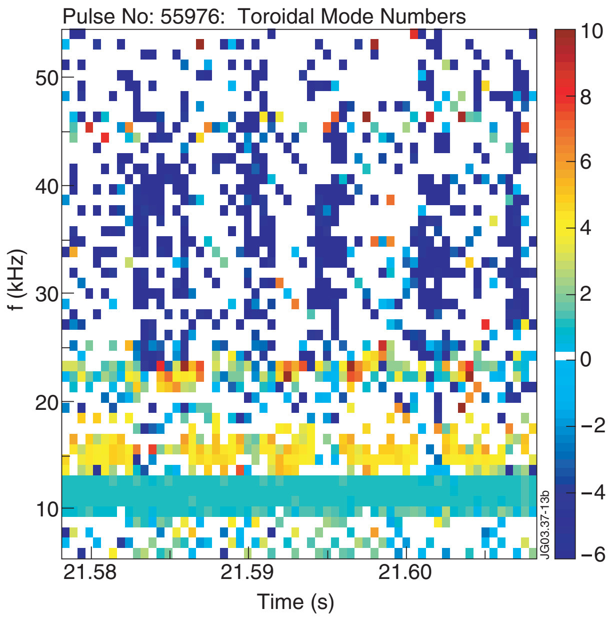


Figure 5: Interplay between washboard modes and ELM precursor modes