

## Inter-ELM Fluctuations and Flows and their evolution when approaching the density limit in the ASDEX Upgrade tokamak

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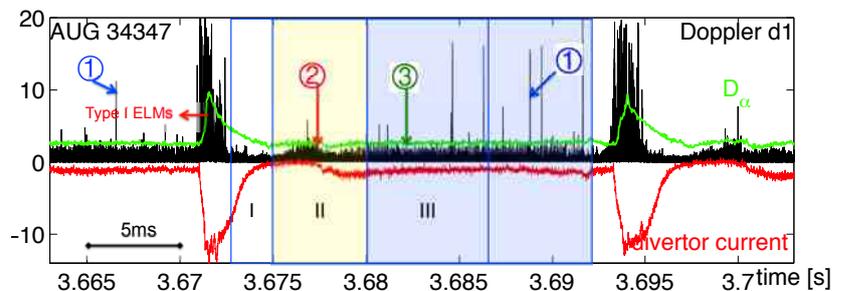
High performance regimes (H-mode) are reached through the spontaneous formation of a transport barrier resulting from the shear-flow suppression of turbulence. The steep edge density and temperature gradients allow for large pedestal top temperature and density, thought to be necessary for ITER to achieve its fusion power targets. However these steep gradients drive instabilities such as edge localized modes (ELMs), which appear as repetitive collapses of the edge pressure profile that may release unacceptable heat loads on the machine walls. Between ELMs, temperature and density profiles build up again on different time scales [1,2,3], raising the question of which transport mechanisms determine the profile evolution until the next ELM [4].

Intermittent density fluctuations persist in the inter-ELM phase, although the overall fluctuation level is strongly reduced as expected in the pedestal region. They appear in Doppler back-scattering signals as bursts at different level and with different time dynamics. In this paper their properties are related to the different phases of the ELM cycle that were identified in ASDEX Upgrade in [2,3] in the recovery of density and temperature profiles, and their associated magnetic fluctuations.

### Typical ELM cycle phases

Figure 1: type I ELM cycle in ASDEX Upgrade: outer divertor shunt current (red), outer  $D_\alpha$  signal (green) density fluctuation level from Doppler back-scattering amplitude (black), arbitrary units.

AUG #34347 ( $B=2.4T$ ,  $I_p=0.8MA$ ,  $P_{tot}\sim 4MW$ ) ELM frequency 50Hz.



The strong density fluctuation

level accompanying the ELM crash is sharply reduced close to noise level typically during 1.0-1.5ms after the ELM. This quiet phase is also observed in magnetic signals, and corresponds to a fast recovery phase of the density profile [2,3,5], identified as Phase I of the ELM cycle. The density fluctuations rise again in Phase II, lasting around 5ms, on the same time scale of the second bump observed in the  $D_\alpha$  signal, identified as a high recycling regime [6], during which the divertor shunt current stays close to 0. During this phase, density fluctuations evolve from broadband continuous small fluctuations to strongly intermittent bursts, often grouped in regular trains (② in Fig.1 and Fig. 3) at high repetition rate (50-100kHz); the increase of magnetic fluctuations characteristic of phase II occur in the same frequency range. The density fluctuations activity slows down when the divertor current rises again and the density profile stays clamped (Phase III). Fluctuation bursts grouped in a regular long sequence at slower repetition rate (10-20kHz) are generally observed in this phase (③ in Fig. 1 and 5); the sequence can be interrupted by strong bursts (① in Fig.1) later seen in the SOL in radiation signals (Fig. 5) and divertor Langmuir probes.

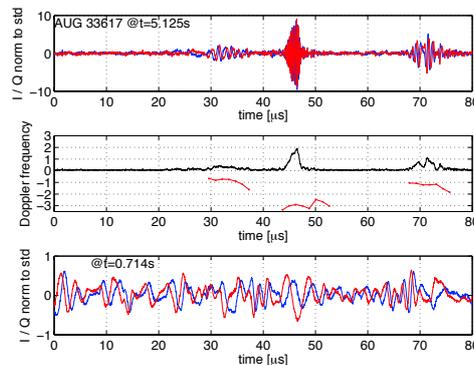
This phase, during which the temperature profile recovers and clamps, can last from 2-3 to 10 ms. There is no evidence here of a specific activity which could explain the scatter in this phase duration, even the occurrence of strong bursts.

More detailed properties of density fluctuations occurring in the different phases are given below.

### Strong rare bursts

Fig. 2 shows singular events typical in inter ELM Doppler backscattering signals like the ones labelled ① in Fig. 1. The upper panel shows a detailed time series (80 $\mu$ s) of the real and imaginary parts of the Doppler complex signal (referred to as I and Q signals) oscillating at the Doppler frequency  $k v_{\text{perp}} = 2\pi f_D$ , where bursts are temporally well resolved. Conversely to typical L mode signals (lower panel, Fig. 2), they appear as ‘individual’ structures passing through the probing beam, with a lifetime of the order of 10  $\mu$ s, larger than typical L mode fluctuation correlation time (1-2  $\mu$ s). Each burst appears as a coherent or ‘‘filament like’’ structure in the sense that the amplitude rises and drops sharply from the noise level, and the Doppler frequency stays roughly constant during the burst. The Kurtosis of the Probability Distribution Function of the IQ signals reaches very high values (5-15) characteristics of wide distribution tails showing a degree of intermittency. The observed velocity can differ considerably from one burst to the next. The dispersion among bursts gives an overall broad Doppler spectrum, typical of H mode. Fluctuation perpendicular velocities are typical of ExB velocities in the H mode Er well:  $v_{\text{perp}} \sim 4-15$  km/s hence  $E_r \sim 9-30$  kV/m, the largest burst having also here the highest velocity.

Figure 2: Doppler back-scattering detailed time series: (upper panel) Inter ELM I and Q signals (red and blue); (2d panel), corresponding amplitude (black) and Doppler frequency (red); (lower panel) L mode I and Q signals.

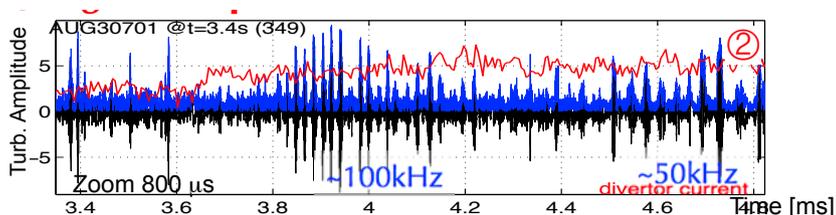


Strong singular bursts can occur anytime after phase I, though mostly observed in phase III close to the ELM onset. Associated radiation bursts are often observed later in the SOL and divertor (see Fig 6); it indicates that the particle flux to the divertor can also be highly intermittent with strong events between ELMs.

### Regular amplitude oscillations, Phase II

After the increase of broadband density fluctuations, bunches of strong bursts develop at the end of phase II, from 3-4 events (at low plasma density) up to dozens (at high density) grouped in regular trains; the time delay between the bursts is typically around 10 to 20  $\mu$ s, as shown in Fig. 3 (3.8 to 4.2 ms) and slows down afterwards. These fluctuations could drive an additional transport responsible for the clamping of the density profile. The apparent amplitude oscillation is then in the frequency range 50-120 kHz, which is also the typical frequency range of modes detected by normal reflectometry and magnetics in this phase [2].

Figure 3: Typical end of Phase II (800  $\mu$ s sequence), when the divertor current (red) starts to rise. Doppler IQ signals (black) and amplitude (blue) at  $\rho \sim 0.985$ . Discharge AUG#30701 ( $B = -2.5$  T,  $I_p = 1$  MA,  $P_{\text{tot}} \sim 5$  MW) from [2,3].



Combined fluctuation measurements should help to determine whether this amplitude modulation results from a change in probing conditions due to a mode affecting the pedestal or is intrinsic to the fluctuation dynamics. In this respect, some similarity with I-mode strongly intermittent fluctuations should be noted here: single high intensity bursts, sometimes grouped in bunches of 3-4 events, have typical repetition times in the same 10  $\mu$ s range [7]. This dynamics could be a signature of the generation of solitary structures, by modulational instabilities [8] or by non linear interactions with quasi-coherent modes [9].

Trains of bursts are observed mainly in the pedestal ( $E_r$  well). They are not observed in the SOL.

Simultaneous measurements using 2 or more Doppler channels at different probing frequencies allow one to identify a time delay indicating an outward propagation.

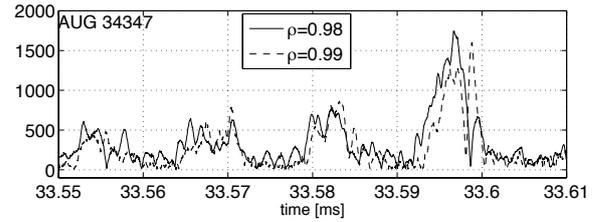


Figure 4: Doppler amplitude time sequence measured at 2 different locations.

### Regular amplitude oscillations, Phase III

Longer time sequences of regular trains of bursts of density fluctuations are observed in phase III, with a slower repetition rate down to 10-20 kHz. These frequencies appear also in the magnetics in this phase [2], but higher frequencies (200-250 kHz) dominate in this phase when the temperature gradient saturates. The latter correspond, with typical associated  $(m,n)$ , to fluctuations flowing at the  $ExB$  velocity, for typical  $E_r$  well values.

Figure 5: regular bursts of fluctuations (Doppler amplitude, black) terminating with the occurrence of two strong events, visible in bolometry signals (AXUV diodes viewing the outer SOL down to the divertor) with a delay of  $\sim 50 \mu s$ , and in divertor current.

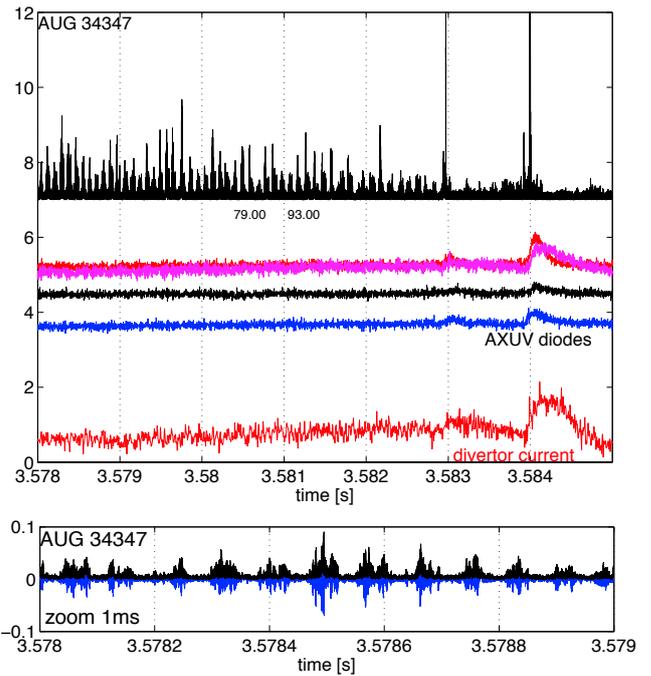


Figure 6: zoom in the bursts time sequence. Burst duration is also larger than in phase II  $\sim 30-50 \mu s$ .

So these high magnetic fluctuations should be compared to the Doppler frequencies and are consistent with them, since higher wave numbers are detected by DBS (x3 -10). The role played by these fluctuations (the amplitude modulation) in temperature profile saturation and pre ELM behaviour is however less clear than in the magnetics [2,3].

### Strong intermittent bursts dominate when the ELM regime changes close to the density limit

When the density is increased, typically when the H-mode confinement degrades and the ELM regime changes from a pure type I ELM to mixed type I and type III (or small ELMs), the overall fluctuation level increases, keeps a strongly intermittent character in the confined plasma while the SOL becomes L-mode like. The detailed changes in ELM regime and confinement when approaching the density limit is described in [9].

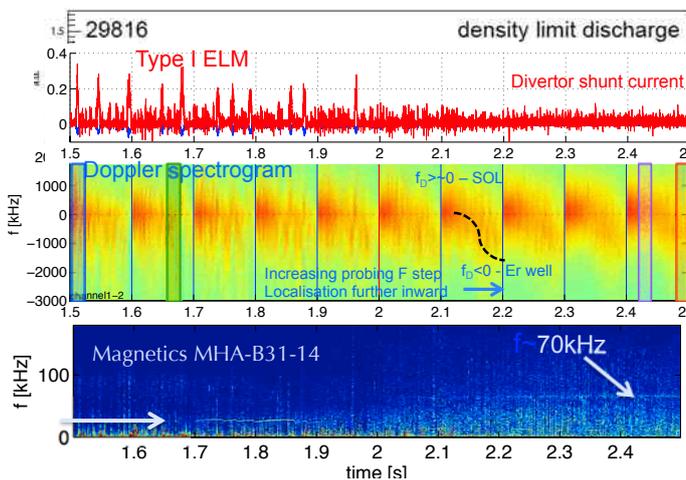


Figure 7: Transition from type I ELM H mode to small ELMs and degraded H mode, AUG discharge #29816 ( $-2.5T$ ,  $I_p=0.8MA$ ,  $P=7.5MW$ , density up to  $10 \cdot 10^{19} m^{-3}$ )[7]. Divertor current (upper panel, red) and Doppler spectrogram (middle), spectrogram of the magnetic fluctuations ( $dBr/dt$ ) in the midplane (lower panel).

The plasma edge is probed at ten radial positions in 10 ms steps. The Doppler spectrum maximum (highest intensities in red) evolves from slightly positive values in

the SOL to strongly negative values in the pedestal (Er well) during each 100 ms sequence (between blue line separators). Note that due to the density ramp, the radial coverage shifts from [pedestal top-near SOL] to [pedestal – far SOL]. 4 steps marked by shaded boxes correspond to SOL and pedestal locations, during type I then small ELMs.

In the pedestal ( $\rho \sim 0.99$ ), during the type I ELM phase, the same inter ELM phases as described above are observed though shortened (phase III) due to the higher ELM frequency (Fig. 8, left).

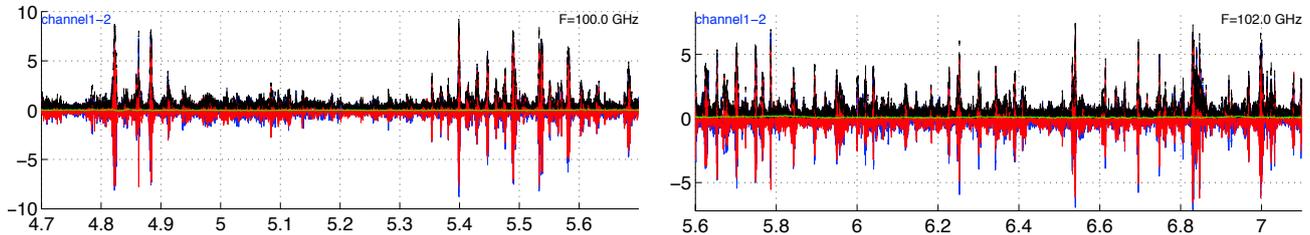


Figure 8: Doppler signals during the type I ELM phase (left) and small ELMs phase (right) ( $r \sim 0.99$ )

In the Small ELM phase, the sequence of repetitive bursts ( $\Delta t \sim 14 \mu s$  in this example) are more frequent (Fig.8 right), though less regular as density increases. The associated frequencies around 50-100kHz are also seen in magnetics signals (Fig. 8 lower panel). The PDF of the signals is still strongly distorted (Kurtosis values around ten compared to above 15 in type I ELM phase). The overall fluctuation level increases with respect to the type I ELM phase. The effect of this increase on transport and pedestal erosion remains to be quantified. Also the resulting increase of the outward density flux across the separatrix needs to be evaluated, as a possible link to the formation of a shoulder in the density profile in the near SOL. The typical fast trains regime dominate the dynamics as the inter ELM phase is shorter and even difficult to define when approaching the breakdown of the H mode.

In the SOL, broadband fluctuations are observed during the type I ELM phase. The PDF of the Doppler signals indicates a moderate level of intermittency ( $K \sim 1-2$ ), which is observed typically in the SOL by Langmuir Probes, but no regular bursts are observed. In the small ELMs phase, density fluctuations increase and become less intermittent (L mode like), with a PDF close to a Gaussian. This overall increase could be either an effect of the higher flux crossing the separatrix (see above) or intrinsic to the development of instabilities, linked to the shoulder formation.

In conclusion, strong intermittent density fluctuation bursts are observed between the ELMs: mostly rare events at low plasma density, they group in regular structures at a repetition rate of 10-100kHz. The fast repetition rate occurs mainly at the end of the phase of slow density profile recovery, associated with a second bump in  $D\alpha$  signals identified as high recycling divertor regime. The bursts repetition slows down (10kHz) when the density profile is clamped (divertor re-attached). Longer fast sequences of intermittent bursts and increased intensity dominate at high plasma density, while SOL fluctuations lose their intermittent behaviour (small ELMs regime).

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