

## ELM occurrence times in relation to the phase evolution of global measurements in JET

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### 1. Introduction

Quantitative characterisation of ELMING processes using measured sequences of ELM occurrence times and inter-ELM time intervals is novel[1-6] and shows unexpected structure. Recently[4-6] we found that the signals from system scale diagnostics, the toroidally integrating full flux loops VLD2 and VLD3 in the divertor region of JET, contain statistically significant information on the occurrence times of intrinsic ELMs seen in the BeII signal. The ELMs occur preferentially when the full flux loop signals are at a specific temporal phase. Here we show, see also [6], that these signal phases contain information on the global build-up to an intrinsic ELM.

### 2. Results

We determine[4,6] each ELM occurrence time from the peak of the Be II signal. After each ELM there is a large amplitude oscillatory response in the VLD2 and 3 signals. There is a class of prompt ELMs[4] that occur within this initial response to the previous ELM. Non-prompt ELMs occur when the system's response to the previous ELM, as measured by VLD2 and 3, has died away. Fig.1 plots standardised raw timeseries for a prompt (left) and non-prompt (right) ELM.

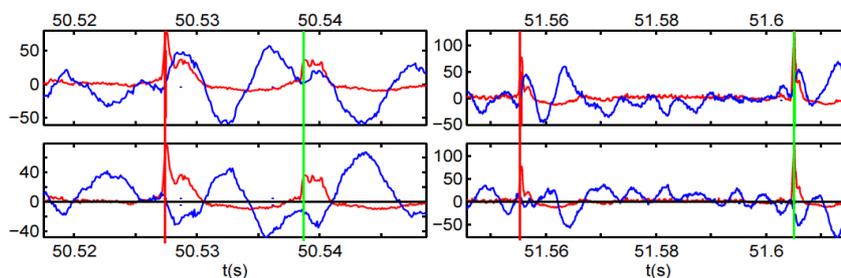


Fig.1: Examples of measured standardised timeseries for pairs of successive ELMs in JET plasma 83773: Be II intensity (red) and full flux loops (blue) VLD3 (upper panels) and VLD2 (lower panels). Left panels show a prompt ELM, and right panels a non-prompt ELM. To facilitate comparison we standardise the signal amplitudes, and the sign convention of the VLD2 and VLD3 signals assigns them opposite polarity. ELM occurrence times are marked by vertical red and green lines.

\*See the Appendix of F Romanelli *et al.*, Proc. 25th IAEA Fusion Energy Conf. 2014, St Petersburg, Russia

Figure 2 shows the VLD3 signal traces for all prompt ELMs in JET plasma 83773 with inter-ELM time interval  $\Delta t < 0.015$  s. For comparison, the VLD3 traces are shifted in time such that  $t = 0$  is the occurrence time of the first ELM, and in amplitude such that the trace is at zero when  $t = 0$ . We mark on these traces the occurrence times of the first (red) and second (green) ELMs. Ordering the data in this manner demonstrates clustering of ELM occurrence times with respect to the phase of the VLD3 signal. These prompt ELMs all arrive after  $\sim 1\frac{1}{2}$  to  $1\frac{3}{4}$  oscillations of the VLD3 response to the previous ELM.

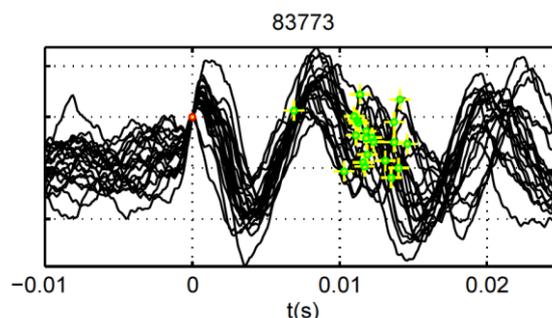


Fig.2: Prompt ELM occurrence times (green circles/yellow crosses) superimposed on corresponding VLD3 traces for ELMs in JET plasma 83773. All ELM pairs and traces are shifted such that  $t = 0$  when the first ELM (yellow-filled red circles) of a pair occurs, and the VLD3 amplitude (normalised as in [6]) is zero at  $t = 0$ .

Figure 3 (left panel) plots the instantaneous amplitude and phase of the VLD3 full flux loop signal versus time for all the ELMs in JET plasma 83773. The instantaneous phase is determined from the measured signal as in [4]: the timeseries  $S(t)$  is decomposed by Hilbert transform into an instantaneous amplitude  $A(t)$  and phase  $\phi(t)$  such that  $S(t) = A(t)\exp[i\phi(t)]$ . We choose the zero time for this plot as in Fig.2. The full flux loop phase difference is taken from the time of the first ELM in the entire sequence. There is clear phase bunching, which we find for *all* non-prompt ELMs during the flat-top H-mode in JET plasmas 83769-83775. ELMs are more likely to occur when the phase of the full flux loop signals is at a specific value. This phase relationship is stable throughout the plasma, that is for all ELMs that occur between 48.5s and 53.8s. We have established that this is not a trivial correlation by testing against randomly shuffled ELM arrival times and VLD2 and 3 timeseries in [4,6].

The upper panels of Fig.3 plot (green circles) the instantaneous amplitude and phase at the time of the second ELM as determined by the peak in the Be II signal. The rise time of the VLD3 response to the ELM is fast enough that it is possible that VLD3 is already responding to the ELM by the time the Be II reaches its peak. The VLD3 phase at the ELM time could then be dominated by its response to the ELM. To test this, we also plot on Fig.3 the amplitudes and phases of the VLD3 signal at times  $dt$  before the second ELM;  $dt$  is increased as we move down the figure. We then see that at  $dt = 0$  (the Be II peak time) the instantaneous amplitude is for some ELMs comparable to the response to the previous ELM. At  $dt = -1ms$  that is, 1ms before the ELM, the VLD3 amplitude is for most ELMs closer to the unperturbed level and for  $dt = -2ms$  the VLD3 amplitude is generally at the unperturbed level. This confirms that the response to the ELM in the VLD3 occurs within 1-2ms just before the ELM time as determined by the peak in the Be II. At this time, the non-prompt VLD3 phases are

bunched, suggesting that there is an indication of the build-up to an ELM in these global, toroidally integrating signals.

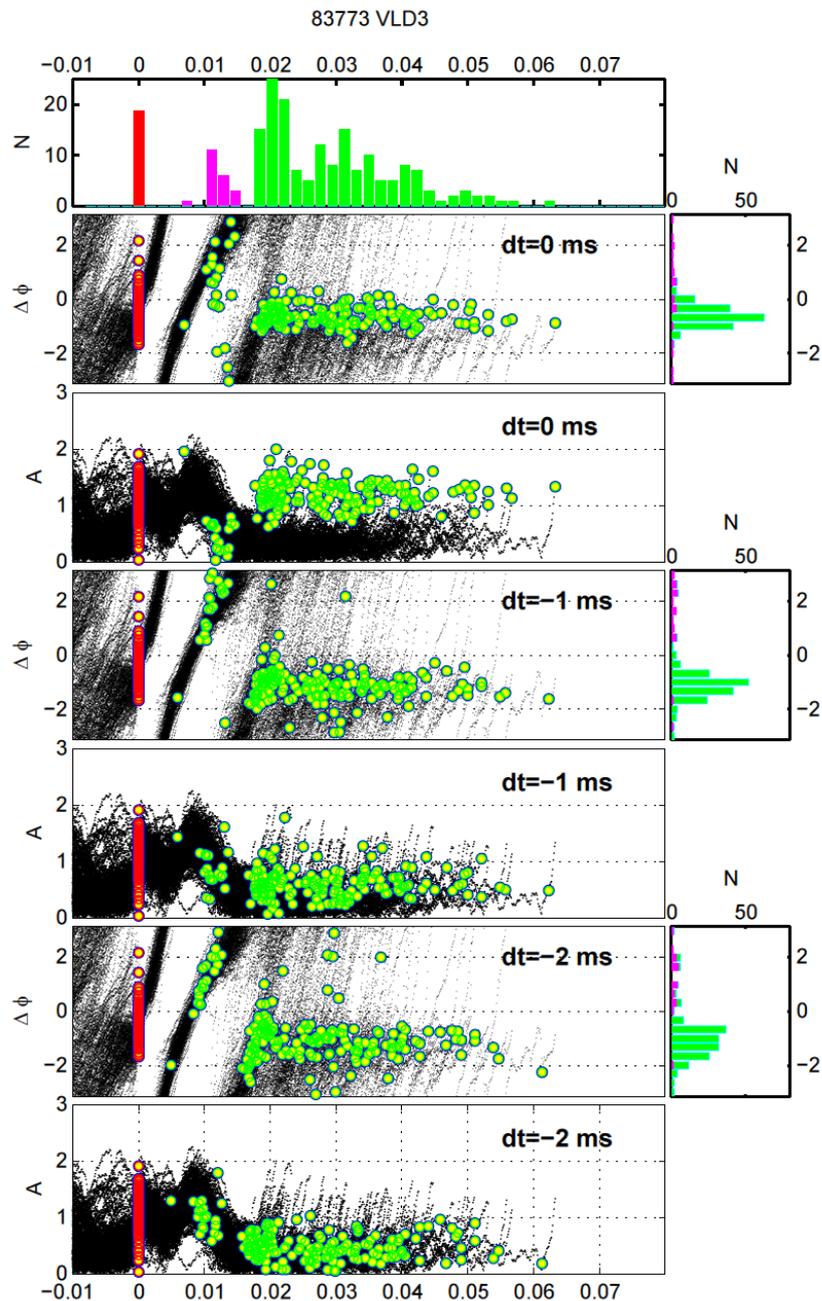


Fig 3: ELM occurrence times and VLD3 instantaneous amplitude and phase in the flat-top of JET plasma 83773. Each set of panels is as follows. Main Panel: VLD3 instantaneous amplitude  $A$  (standardised units) and phase  $\Delta\phi$ , (modulo  $2\pi$ ), plotted as functions of time, up to the occurrence time of the next ELM. The coordinates are time, and phase difference from the occurrence time of the first ELM in the sequence. ELM occurrence times are marked on each VLD3 trace with yellow-filled red circles (first ELM) and green circles (second ELM). Right Panel: histogram of VLD3 phase differences at the time of the second ELMs, for inter-ELM time intervals  $\Delta t < 0.015$  (magenta) and for all ELMs (green). Top Panel: histogram of inter-ELM time intervals for prompt ELMs (magenta) and non-prompt ELMs (green). The instantaneous amplitude and phase are plotted at three times  $dt$  before the second ELM.

The timeseries in Fig.2 also show that prompt ELMs occur at a specific phase in the VLD3 response to the previous ELM. This phase relationship is seen in the panel of Fig.3 with  $dt = 2ms$ . The prompt ELMs occur at a different phase to that of the non-prompt ELMs.

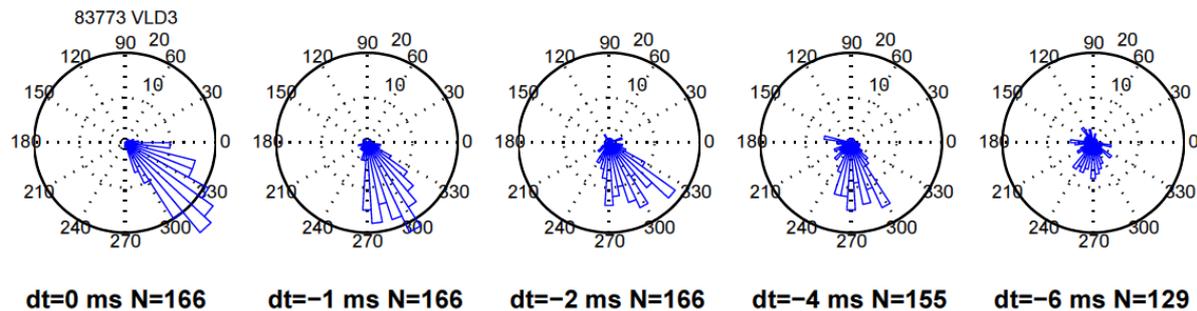


Fig 4: Polar histograms of VLD3 instantaneous phase in the flat-top of JET plasma 83773 at time  $dt$  before the ELM time; from left to right, progressively earlier in time before the ELM. ELMs at  $\Delta t - dt < 0.015s$  are excluded.  $N$  is the number of ELMs remaining in the histogram.

Fig. 4 shows VLD3 phase at times  $dt$  progressively before the ELM time (time of Be II peak). Phase bunching is still seen at  $4ms$  before the ELM. Detailed analysis[6] shows that up to  $\sim 5ms$  before the ELM, there is statistically significant phase bunching. This identifies a global build-up to an ELM as seen in the VLD3 full flux loop signal, which we also find in VLD2.

### 3. Conclusions

Here we show that the phase of the *global* full flux loop signal contains precursor information for non-prompt ELMs: during  $\sim 2-5ms$  before each ELM, it aligns to the same value. Our results suggest a scenario for intrinsic ELMing where the plasma and its interacting environment, including the control system, together self-generate a global plasma perturbation such that the plasma is magnetically ‘self-kicked’. This then leads[5] to an ELM if this global perturbation is sufficient to modify conditions at the plasma edge for instability, as first proposed in [5], and subsequently investigated in [7]. Prompt ELMs[4] occur at a specific phase within the initial full flux loop response to the previous ELM. This suggests an additional testable hypothesis: that compound ELMs may be a pattern of successive prompt ELMs. This is consistent with the observed[2] narrow spread in the time intervals between successive component ELMs in a compound ELM sequence. One would then expect a well-defined phase relationship between high time resolution full flux loop signals and the burst occurrence times within compound ELMs.

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- [1] J Greenhough, S C Chapman, R O Dendy and D J Ward, Plasma Phys. Control. Fusion **45** 747 (2003)
- [2] F A Calderon, R O Dendy, S C Chapman, A J Webster, B Alper *et al.*, Phys. Plasmas **20** 042306 (2013)
- [3] A J Webster, R O Dendy, F A Calderon, S C Chapman *et al.*, Plasma Phys. Cont. Fusion **56** 075017 (2014)
- [4] S C Chapman, R O Dendy, T N Todd, N W Watkins *et al.*, Phys. Plasmas **21** 062302 (2014)
- [5] S C Chapman, R O Dendy *et al.*, 41st EPS Conf. Plasma Phys. (2014) paper P1.101
- [6] S C Chapman, R O Dendy *et al.*, Phys. Plasmas, submitted (2014)
- [7] A J Webster *et al.*, Symp. Fus. Technol. 2014 paper EFDA–JET–CP(14)05/06