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Time-resonant tokamak plasma edge instabilities?

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Abstract

For a two week period during the Joint European Torus 2012 experimental campaign, the same high confinement plasma was repeated 151 times. The dataset was analysed to produce a probability density function (pdf) for the waiting times between edge-localized plasma instabilities (ELMs). The result was entirely unexpected. Instead of a smooth single peaked pdf, a succession of 4–5 sharp maxima and minima uniformly separated by 7–8 ms intervals was found. Here we explore the causes of this newly observed phenomenon, and conclude that it is either due to a naturally occurring self-organized plasma phenomenon or an interaction between the plasma and a real-time control system. If the maxima are a result of 'resonant' frequencies at which ELMs can be triggered more easily, then future ELM control techniques can, and probably will, use them. Either way, these results demand a deeper understanding of the ELM process.

Keywords: tokamak, plasma, stability, ELMs, statistics

S Online supplementary data available from stacks.iop.org/PPCF/56/075017/mmedia

The economically competitive production of energy in magnetically confined tokamak plasmas requires plasmas with high pressures and high energy confinement times. In present experiments the majority of high performance plasmas have edge localized modes (ELMs) [1], that intermittently eject a small fraction of the confined plasma energy and particles. While ELMs are relatively harmless in present machines, in larger devices such as ITER [2] they will need to be controlled or entirely avoided. The presently accepted model for ELMs involves a build-up of pressure and current at the plasma's edge, that is released by an ELM [3], usually presumed to be triggered by a Magnetohydrodynamic instability [4]. Here we report results that cannot be explained by this picture alone, suggesting that it may be incomplete and that new possibilities for ELM control may exist.

During the 2012 experimental campaign at the Joint European Torus (JET) [5], the consecutive sequence of pulses 83630-83794 repeated the same low triangularity 2T 2 MA plasmas with approximately constant gas fuelling and 11.5 MW neutral beam (NBI) heating for 6 s of steady high confinement H-mode with type I ELMs for 151 good

[10] See the Appendix of F Romanelli *et al* 2012 *Proc. 24th IAEA Fusion Energy Conf. (San Diego, CA, 2012)*.

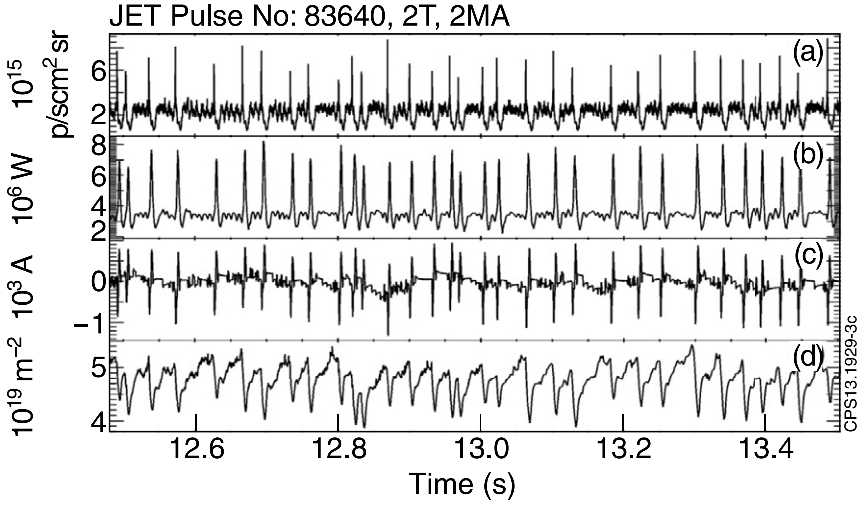

Figure 1. Signals from a typical pulse (83640) in the set 83630-83794. The signals shown are: Be II radiation (*a*), the total radiated power (*b*), the current in the Enhanced Radial Field Amplifier vertical control system (*c*), and the line integrated edge density (*d*). The ELMs are associated with a strongly peaked Be II and radiated power (signals (*a*) and (*b*)), a rapid response of the vertical control system to keep the plasma stable (*c*), and a drop in the edge density (*d*).

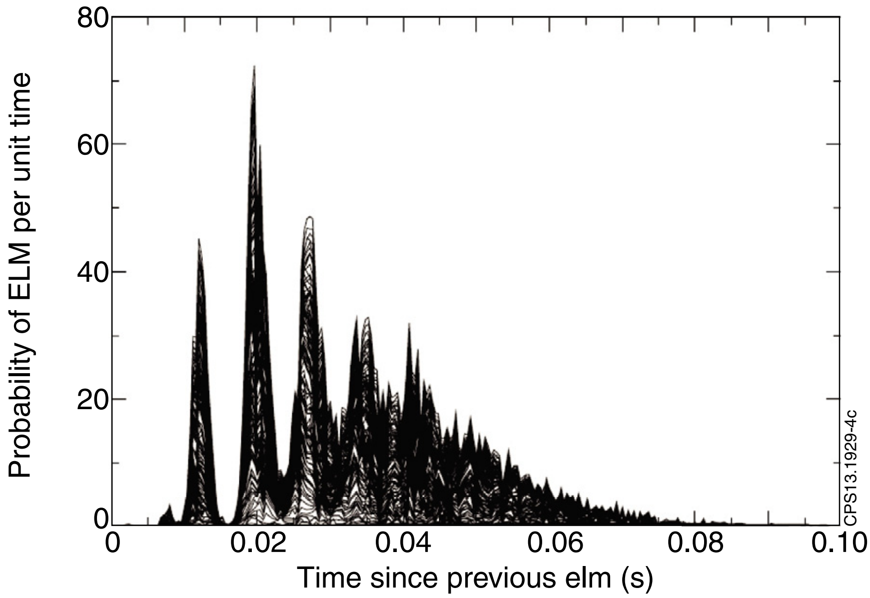

Figure 2. The ELM waiting time pdf inferred from analysing 120 pulses and combining the data to form a single pdf. Each line corresponds to data from an additional pulse.

pulses. The purpose was to investigate material migration, fuel retention, and evolution of wall conditioning during H-mode with the ITER-like wall (ILW). Excluding pulses that have reports of impurity influxes (UFOs), Nitrogen seeding, or any problem preventing them from being steady-state, leaves 120 nearly-identical pulses each with approximately 6 s of steady H-mode plasma, with clear type I ELMs. The berylium II (527 nm) radiation was observed at the inner divertor and recorded in 0.0001 s time intervals. The time series of emissions was analysed, with ELMs inferred from large amplitude signals that exceed the average by at least two standard deviations [6]. An example of the signals studied is in figure 1, and a large sample of typical time traces are provided in the online supplementary material (stacks.iop.org/PPCF/56/075017/mmedia). For each pulse, the number of ELMs with waiting times since the previous ELM between time t and $t + 0.001$ seconds were counted, and used to form a probability density function (pdf) for the waiting times between ELMs in the 9.5–13.5 s interval. Adding together and normalizing the 120 pdfs produces figure 2, which combines the data from nearly 15 000 ELMs and 8 min of steady state JET plasma time.

A previous study [6] reported details of 84 high quality JET datasets for which good agreement was found between the measured ELM waiting times and a simple but rigorous theoretical model. The study was intended to test the theoretical model, which applied to ELM waiting time pdfs with a single maximum. Consequently the study explicitly excluded datasets with more than one maximum. In contrast to the pdfs studied in [6], figure 2 shows a sequence of sharp maxima (and minima) separated by 7–8 ms time intervals, corresponding to frequencies of approximately

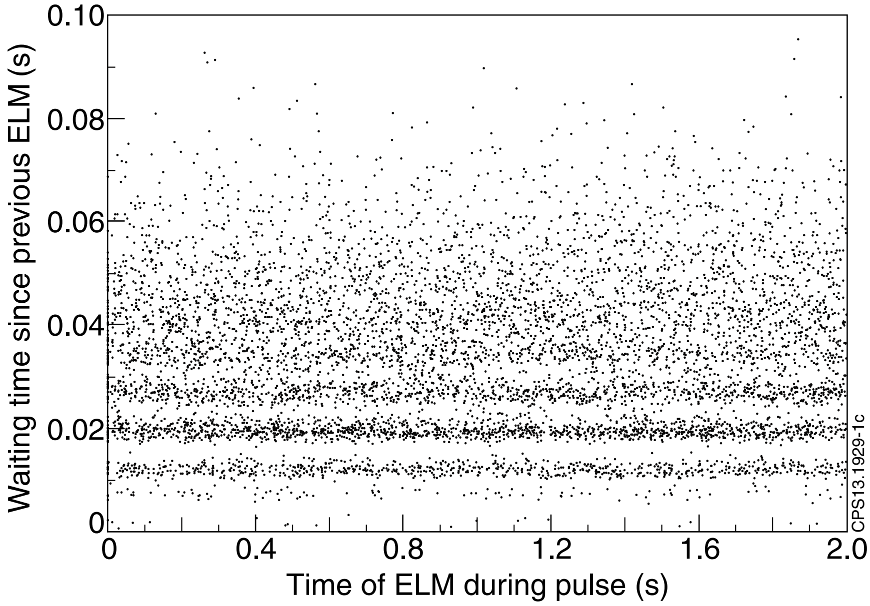

Figure 3. The occurrence time of ELMs (horizontal axis), is plotted against the waiting time since the previous ELM (vertical axis), for the 83630–83794 pulse set described in the main text and analysed between 11.5 and 13.5 s. The ELM occurrence times are offset so that the first ELM is at time zero. If ELMs were being affected by a periodic external system, then we would expect to see clustering of ELMs into vertical stripes, which we do not.

83, 50, 37, 28, and 24 Hz. The pdf's variation between maxima and minima is substantial. Whereas the first peak contains 5–10% of the ELMs, the following minimum indicates that there is approximately zero probability of observing an ELM at 0.016 s after *any* ELM. The structure in the pdf becomes clearer as more data is added, but is clearly visible once data from 5–6 pulses are combined, corresponding to about 500 ELMs. The same results are found with independent ELM analysis algorithms such as those used in [7] and those detailed in the online supplementary material (stacks.iop.org/PPCF/56/075017/mmedia), and the phenomenon is not always present in pulses with different heating and fuelling. Therefore we do not think that a diagnostic or analysis algorithm is incorrectly producing this result, and are confident that the phenomenon is real. Immediate questions are: what is the cause of this phenomenon? And importantly, do the maxima correspond to physical resonances at which ELMs could more easily be triggered?

The rest of this article refers to these observed maxima and minima in the ELM waiting time pdf as 'resonances', although we do not necessarily claim that they are, and explores the possible causes of the phenomenon. The evidence we will present suggests that the cause is either a naturally occurring 'self-organized' [8] plasma phenomena, or a control system that is interacting with the plasma in a plasma-dependent way. We will conclude by proposing a simple experimental test to decide whether there are resonant frequencies at which ELMs are more easily triggered; this question is key to any attempts to pace or trigger ELMs in a time-dependent way.

Figure 3 shows the occurrence times of ELMs (horizontal axis) against the waiting time since the previous ELM (vertical axis), with the occurrence time of ELMs offset so that the first ELM appears at time $t = 0$. The waiting time pdf in figure 2 indicates that the waiting times are clustered around 0.012, 0.020, 0.028, 0.036, and 0.044 s, then more evenly spread for large time delays. This corresponds to the way in which ELM waiting times are clustered in horizontal stripes in figure 3. If the occurrence times of successive ELMs are at least approximately independent (we have found a weak negative correlation between successive waiting times), then after a small number of ELMs we would expect to lose the coherence between ELM times, and we would not expect to see a clustering of ELMs with respect to the horizontal time axis. The lack of vertical stripes in figure 3 is consistent with this. This is a key observation. Remember that we have offset the ELM-times so that the first ELM is at $t = 0$, and that roughly half of those ELMs will have occurred with waiting times in the first four peaks of figure 2, so any pacing with a fixed external frequency(s) would be in phase for the entire duration of at least half of the 120 pulses. Therefore if the ELMs were being triggered by an external influence with a fixed frequency(s), then we would expect to see a clearly visible clustering of ELMs with respect to the horizontal time co-ordinate in figure 3, which we do not. Putting it another way, if a coil current had an oscillation with a 50 Hz frequency for example, that was either directly or indirectly triggering ELMs with that 50 Hz frequency, then we would expect to see vertical clusters with a period of $1/50 = 0.02$ s; which we do not. Because the resonances are only observed relative to consecutive ELMs, we conclude that they are caused either by a naturally occurring self-organized plasma phenomena, or by an interaction with a real-time plasma control system. An alternative argument is to observe that the maxima in figure 2 are separated by 0.008 s, so if ELMs are triggered by an external system then we would expect it to have a period of 0.008 s—which fails to explain why the first ELM is after 0.012 s. Again the conclusion is that the resonances are only observed relative to consecutive ELMs, not with respect to a fixed time co-ordinate. It is well known that the real-time vertical control system can trigger

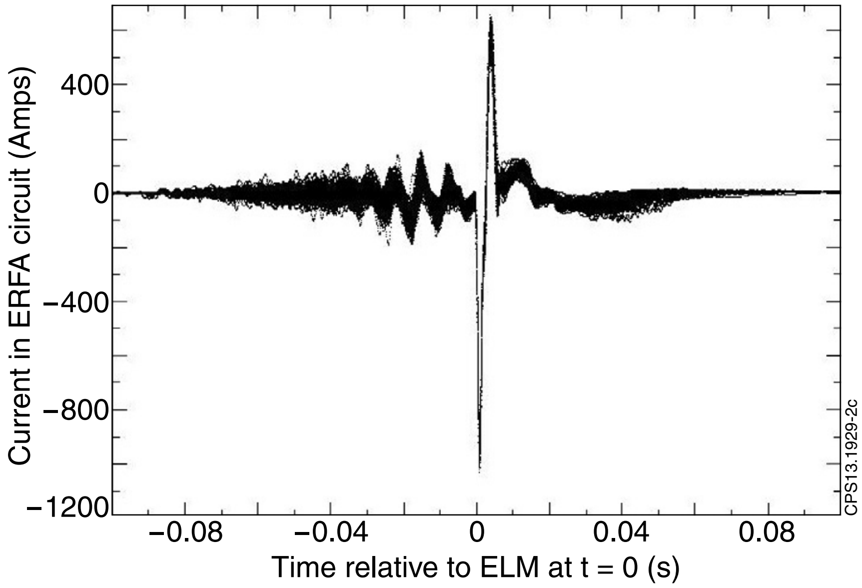

Figure 4. The current (Amps) in the ERFA vertical control system measured between the start of the $(n-1)$th ELM and the start of the $(n+1)$th ELM, with time offset so that the nth ELM appears at $t = 0$, is averaged over all ELMs in a pulse, and then all pulses from the 120 pulse dataset are simultaneously plotted over each other.

ELMs [9], so it is an obvious potential cause of the resonances. This possibility is considered next.

Consider the current flowing in the vertical control system's coils (the Enhanced Radial Field Amplifier system [10]), measured from the time of the $(n-1)$th ELM to the time of the $(n+1)$th ELM, with the time offset so that time $t = 0$ corresponds to the time of the nth ELM. If we combine and average these over a single pulse, then superimpose the resulting plots from the 120 pulses in our data set, the result is figure 4. There are a number of striking features. First there is a distinctive large-amplitude response of the system immediately following an ELM, roughly between $t = 0$ and $t = 0.008$ s, that is the same in different plasmas. This response is however known to be dependent on the vertical control system settings. When JET's carbon plasma facing materials were replaced with the new ILW, the vertical control system was modified and optimized for use with the new wall [11]. We have noticed that the large amplitude response that immediately follows an ELM is very different for the carbon-wall plasmas, with a large-amplitude signal that damps towards zero much less rapidly than in the present system. We have not yet found evidence of resonances in carbon-wall data. Returning to figure 4, as t increases positively the signals average to zero. This indicates that the response of the system to different ELMs is out of phase, and differs between ELMs. For negative t there is the appearance of an oscillation in the signal. This is a necessary consequence of the pdf shown in figure 2, that ensures that the large amplitude signal that immediately follows the $(n-1)$th ELM is observed predominately at intervals of 0.012, 0.020, 0.028, 0.036, and 0.044 s prior to the nth ELM. Because figure 4 plots from the start of the $(n-1)$th ELM to the *start* of the $(n+1)$th ELM, the large amplitude signal that *follows* the start of the $(n+1)$th ELM is not plotted, and consequently similar oscillations are not produced for positive t. Oscillations are not observed for ELMs with waiting times in excess of 0.044 s, consistent with the pdf in figure 2. These remarks do not rule out a coupling to the vertical control system, but we have not been able to demonstrate one yet. The co-incidence of the 0.008 s oscillation period of the current in the vertical control system's coils, and the 0.008 s period between maxima and minima in figure 2 is particularly striking. The possibility of a coupling between the vertical control system and the ELMing plasma is being explored with more sophisticated techniques.

A further search of plasmas with the ITER like wall has found that the resonances are sensitive to heating. The plasma parameters of the JET H-mode pulses 83393, 83429, and 83593, are equivalent to pulses 83630–83794, but have only 5–6 MW of NBI heating. For these pulses no evidence of resonances has been found. For pulse 83155 the heating was increased from the approximately 11.5 MW of NBI heating in pulses 83630–83794 to 17 MW, while the fuelling rate was reduced from approximately 1.15×10^{22} to 0.9×10^{22} particles per second. Here again there is no evidence for resonances similar to those in figure 2. The sensitivity of the waiting time resonances to the plasma heating (and possibly also to fuelling), indicates that they are either caused by a plasma phenomenon, or by an interaction between the plasma and a control system in real time, and in a way that is sensitive to the plasma's rate of heating. Because a clear observation of resonances requires more ELMs than are usually present in the steady phase of typical JET H-mode plasmas, and even more for higher frequency resonances, it is presently uncertain how common the 'resonance' phenomenon is.

The time interval of 0.008 s between the observed resonances in figure 2 could be explained if the plasma was rotating with a frequency of order 125 Hz and interacting with some toroidal asymmetry, sometimes triggering ELMs and sometimes not. The rotation rate as measured by the charge exchange diagnostic in pulses 83630–83794, is greatest in the plasma's core, reduces to approximately 1 kHz at the top of the pedestal, then reduces further towards the separatrix. Unfortunately the uncertainty in the flow measurement increases with proximity to the separatrix, where the flow rate is likely to be lowest. Therefore all we can say with certainty at present is that we do not know whether the plasma flow in the region between the top of the pedestal and the separatrix could be responsible for the resonances, or not. Interestingly a time interval of 0.008 s was found in [12] to equal an estimate for the resistive diffusion time of the plasma pedestal. Whether this is coincidental or important, remains to be determined, but it does suggest that transport processes to restore the equilibrium could be involved.

From a practical perspective, an important question is: are there resonant frequencies at which ELMs can be triggered more easily? Fortunately this can be answered relatively easily without understanding the cause of the phenomenon, by exploring whether ELMs in equivalent plasmas can be triggered more (or less) easily with vertical kicks [9] at frequencies of the maxima (or minima) of the pdf in figure 2. A sensitivity of kick-triggering success to kick frequency was found in TCV [13], with similar ranges of kick frequencies remaining successful (or not), in different plasmas. It was suggested that the preferred frequencies might be an intrinsic property of the plasma when it is regarded as a driven dynamical system ([13], page 1645). A similar cause was suggested for the formation of a bimodal ELM waiting time pdf as gas fuelling is systematically increased [14]. Whether this is the correct physical interpretation remains to be seen, but a carefully designed experiment in conjunction with the results presented here should conclusively determine whether the likelihood of triggering an ELM is correlated with the resonances in figure 2. Such experiments can provide insights and improve our basic understanding of ELMs, possibly leading to an entirely new explanation for the results presented here, but no-doubt leading both directly and indirectly to improved methods for plasma control.

The primary experimental results presented in this paper are unanticipated by theory and, to our knowledge, are not foreshadowed by previous ELM experiments. A comprehensive understanding of ELM dynamics is still missing, and it is hoped that the present results will contribute to its construction. Theory suggests that linear instabilities may initiate ELMs after the plasma current or pressure has passed some threshold value; for a recent review see [4]. We note that thresholded instability can give rise to many different kinds of event time series, spanning the dripping faucet [15] and sandpile avalanching [16, 17]. The theoretical considerations that are candidates for inclusion in such a model span most of tokamak edge pedestal modelling, and include local turbulence, transport, and stability, together with the magnetohydrodynamic character of ELMs and the plasma boundary. We refer to [4, 18, 19], and citations therein, for further discussion of the issues involved and examples.

To conclude, we have found clear examples of plasmas in which the waiting times between ELMs have preferred frequencies at which ELMs are more commonly observed. This was totally unexpected, and was not predicted by present models for ELMs. The phenomenon has been found to depend on the rate of heating, and the 'resonances' are observed relative to other ELMs, but not in absolute time. These observations suggest that they are either caused by naturally occurring self-organized plasma phenomenon or triggered by a real-time interaction between the plasma and a control system. We have no clear evidence that they are related to the plasma's rotation, or to an interaction with the vertical control system, but it is presently not possible to conclusively rule out these possibilities. The phenomenon has not yet been observed in carbon-wall JET plasmas, but this could be because an experiment was not performed with a series of sufficiently long and steady plasmas, with appropriate physical conditions for resonances to be observed. From a practical perspective, an important question is whether there are frequencies at which ELMs can be more (or less) easily triggered. Fortunately this latter question can be answered by using 'vertical kicks' to explore if ELMs are triggered more (or less) easily at resonant (non-resonant) frequencies. Because of the relative simplicity but importance of this experiment for our basic understanding of ELMs and ELM control, this is an experiment we recommend. New developments are required to successfully understand and model this newly observed phenomenon. This is likely to include successful modeling of the processes by which the post-ELM plasma edge reforms prior to successive ELMs, and the inclusion of any relevant interactions between the plasma and real-time control systems. Either way, the results here seem to require new lines of research, and a fresh picture of ELMs and the ELMing process.

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