Analysis of the energy losses and waiting times for individual ELMs in the Joint European Torus

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Introduction

Edge-localized modes (ELMs) are short, repetitive magnetohydrodynamic instabilities occurring in the edge-region of tokamak plasmas that result in a sudden expulsion of energy and particles from the plasma. On the one hand they contribute towards impurity control but on the other hand large uncontrolled ELMs are expected to cause intolerable heat loads on the plasma-facing components (PFCs) at ITER.

ELM control methods, particularly ELM pacing, relies on the empirically observed inverse dependence between average ELM energy loss ($\bar{W}_{ELM}$) and ELM frequency (f_{ELM}) [1]. However, ELM control is targeted at reducing W_{ELM} of individual ELMs and not the average losses. Therefore, in this work, in contrast to analyzing the relation of the averages, the relation between ELM waiting time (Δt_{ELM}) and ELM energy loss (W_{ELM}) for individual ELMs is investigated in a set of JET plasmas with PFCs made of ITER material combination (Be and W) (hereafter ITER-like wall or ILW). Earlier, Webster *et al*. [2] observed that the inverse dependence between W_{ELM} and f_{ELM} is not obeyed by individual ELMs for Δt_{ELM} greater than 20 ms. However, their analysis was restricted to a set of 2 T, 2 MA ILW plasmas from the JET tokamak. In this work, the analyzed plasmas are selected to cover a wide range of plasma parameters in JET. The aim here is to show that a linearly inverse relation between $\bar{W}_{ELM}$ and $\bar{\Delta} t_{ELM}$ is not ubiquitously obeyed by all ELMs individually.

Database

A database of 32 unseeded and 6 N_2-seeded JET ILW plasmas, with a steady period of H-mode with regular type I ELMs, has been assembled for this study. The dataset has been selected with a view on encompassing a relatively wide range of plasma and engineering parameters. The

*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.

Table 1: *Range of some key global plasma parameters for the 32 unseeded and 6 N_2-seeded JET ILW plasmas analyzed in this work.*

	ILW	ILW $+N_2$		ILW	ILW $+ N_2$
$B_t(T)$	1.3 - 2.7	2.65 - 2.7	$I_p(MA)$	1.3 - 2.5	2.5
$n_e(10^{19}m^{-2})$	1.9 - 7.4	5.4 - 7.4	$P_{input}(MW)$	6.9 - 19	16 - 19
$\Gamma_{D_2}(10^{22}s^{-1})$	0.52 - 4.0	1.3 - 3.7	$\Gamma_{N_2}(10^{22}s^{-1})$	-	0.76 - 2.8
δ_{avg}	0.27 - 0.41	0.27 - 0.39	q_{95}	3.1 - 6.1	3.4
β_N	0.92 -2.0	1.2 - 1.7	-	-	-

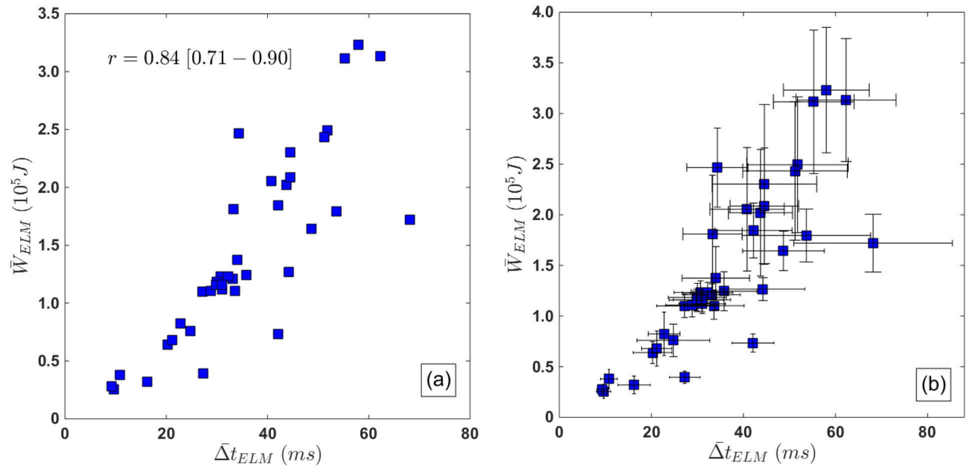

Figure 1: *Scatter graphs between $\bar{\Delta t}_{ELM}$ and $\bar{W}_{ELM}$ (a) without error bars (b) including the error bars specified by a single standard deviation.*

analysis, in this work, has been restricted to time intervals in which the plasma conditions are quasi-stationary with approximately constant gas fueling, input power, edge density and β_N. The range of a number of important engineering parameters in the database is given in table 1.

Analysis of the relation between ELM energy loss and waiting times

In agreement with the findings in [1], it can be noted from figure 1 that there is a strongly positive correlation between $\bar{W}_{ELM}$ and $\bar{\Delta t}_{ELM}$. However, ELM control is targeted at reducing the energy loss of individual ELMs. Thus, basing the control scheme on the relation between the average properties of different plasmas can possibly be an oversimplification. Furthermore, the relation presented in [1] does not take into account the uncertainty on W_{ELM} and Δt_{ELM} whereas it can be observed from figure 1(b) that the standard deviation of $\bar{W}_{ELM}$ and $\bar{\Delta t}_{ELM}$ is substantial and the strongly linear relations depicted by figure 1(a) appears to be dampened by the inclusion of standard deviations in figure 1(b).

It has been shown that the probability distributions of ELM properties contain more compre-

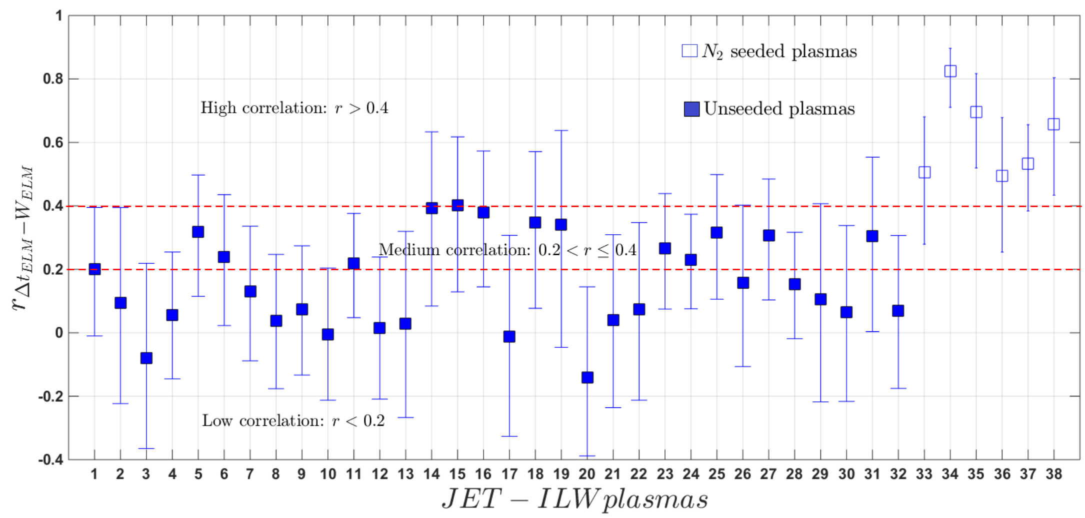

Figure 2: *Estimates of linear correlation between W_{ELM} and Δt_{ELM} for individual ELMs in JET ILW plasmas. 95% confidence intervals are also indicated.*

hensive information as compared to average quantities [3] and indeed a study of the relation between the distributions of W_{ELM} and Δt_{ELM} is likely to yield a more complete picture of the underlying physics. Herein, as a zeroth-order approximation to analyzing the relation between distributions, we quantify the effect of the spread in W_{ELM} and Δt_{ELM} within each plasma by studying the relation between W_{ELM} and Δt_{ELM} for individual ELMs in a discharge.

Estimates of the correlation between W_{ELM} and Δt_{ELM} ($r_{\Delta t_{ELM} - W_{ELM}}$), for individual ELMs from the analyzed plasmas, along with the 95% confidence intervals are presented in figure 2. Despite $\bar{W}_{ELM}$ and $\bar{\Delta} t_{ELM}$ conforming to the expected dependence, the correlation between W_{ELM} and Δt_{ELM} for individual ELMs varies from being moderate for certain unseeded ILW plasmas to being uncorrelated for others. A strongly positive correlation is only observed in N_2-seeded ILW plasmas.

Th observed variation in the correlation can potentially be an outcome of several underlying processes. The size of W_{ELM} is controlled by the pedestal parameters whereas Δt_{ELM} is a consequence of the various timescales involved in the recovery of the pedestal to its pre-ELM state. Any potential modification of the the pedestal recovery time is not likely to influence W_{ELM} which is determined primarily by the pre-ELM pedestal plasma parameters. Further, it is highly plausible that after the pedestal has recovered, an additional increase in Δt_{ELM} will not lead to an additional increase in W_{ELM}. Furthermore, the peeling-ballooning model, which is a leading candidate for explaining ELM onset, fails to explain the phase of saturated gradients without ELMs [5].

Slow transport events

Unseeded JET ILW ELMs are sometimes followed by an extended collapse phase, called the *slow transport event* (STE) [4]. ELMs accompanied by an STE have longer time scales of temperature and density collapse and result in higher total energy loss of the plasma than the losses produced by ELMs alone. Furthermore, we observe from figure 3 that there is a weakly inverse relation between the correlation among W_{ELM} and Δt_{ELM} and the fraction of slow transport events (f_{STE}). The latter is defined as

$$f_{STE} = \frac{N_{(ELM+STE)}}{N_{ELM} + N_{(ELM+STE)}},$$

where $N_{(ELM+STE)}$ is the number of ELMs accompanied by a slow transport event and N_{ELM} is the number of ELMs that are not followed by an STE phase. Figure 3 suggests that the presence of the STEs appears to be at least partly responsible for the observed reduction in the correlation between W_{ELM} and Δt_{ELM} for unseeded plasmas.

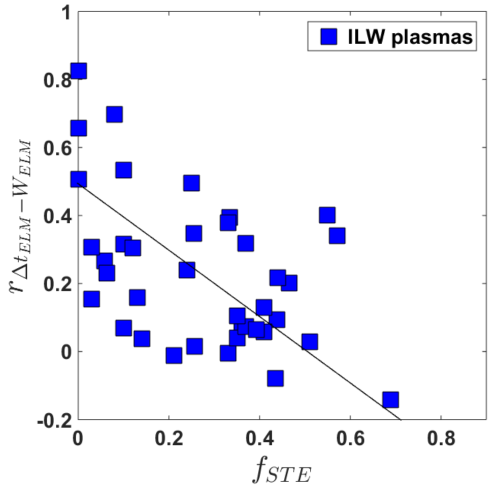

Figure 3: *Variation of linear correlation between W_{ELM} and Δt_{ELM} ($r_{(\Delta t_{ELM})-W_{ELM})}$) for individual ELMs with the fraction of slow transport events (f_{STE})*

Conclusions

It has been seen that an inverse relation between W_{ELM} and f_{ELM} is not always obeyed by all ELMs. W_{ELM} and Δt_{ELM} are stochastic quantities and it is emphasized that analyzing complete probability distributions of W_{ELM} and Δt_{ELM}, will yield a more comprehensive picture for physics studies as well as ELM control.

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