The Statistics of Edge-Localised Plasma Instabilities

A. J. Webster[1], R.O. Dendy[1,2], F. A. Calderon[2], S.C. Chapman[2], E. Delabie[3], D. Dodt[1,4], R. Felton[1], T.N. Todd[1], V. Riccardo[1], B. Alper[1], S. Brezinsek[5], P. Coad[1], J. Likonen[6], M. Rubel[7], and EFDA-JET Contributors*

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK. [1]Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK. [2]Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, UK. [3]FOM Institute DIFFER, Association EURATOM-FOM, Nieuwegein, The Netherlands. [4]Max Planck Institut für Plasmaphysik, EURATOM ASSOCIATION, D-85748 Garching, Germany. [5]IEK-Plasmaphysik, Forschungszentrum Jülich, Association EURATOM-FZJ, Jülich, Germany. [6]VTT, Association Euratom-Tekes, PO Box 1000, FI-02044 VTT, Finland. [7]Alfvén Laboratory, School of Electrical Engineering, Royal Institute of Technology (KTH), Association EURATOM-VR, Stockholm, Sweden.

Edge localised modes (ELMs) [1, 2], are presently common in high performance tokamak plasmas, but must be controlled or avoided in larger future tokamaks. They are quasiperiodic instabilities with a frequency that correlates with the plasma's energy confinement and the heat fluxes from ELMs to material surfaces, and have at least two distinct types that can be distinguished by the response of their frequency to heating[2, 3, 4]. An improved characterisation of these instabilities can place constraints on theoretical models, and has the potential to reduce the experimental time presently required for the classification of ELMs and the development of scenarios. It can also provide new insights into the processes responsible for them.

In [5] a probability density function (pdf) for the "waiting" time intervals between ELMs was rigorously derived, with simple experimentally motivated assumptions leading to a pdf with the specific form of a Weibull distribution. The Weibull distribution arose from a simple model with a power law form [5], a more detailed model when evaluated would lead to a different pdf. To test the Weibull model a tool was developed that can detect ELMs in real-time and for non-steady-state data using the light radiation associated with ELMs. The method uses a single dimensionless threshold to determine whether an ELM has occured, which is set independently of the data and in advance of the analysis. Consequently large data sets can be studied in a quick and easy but rigorous manner. Because the derivation of the Weibull pdf assumed steady-state

---

*See the Appendix of F. Romanelli et al, Proceedings of 24th IAEA Fusion Energy Conference 2012, San Diego, USA.

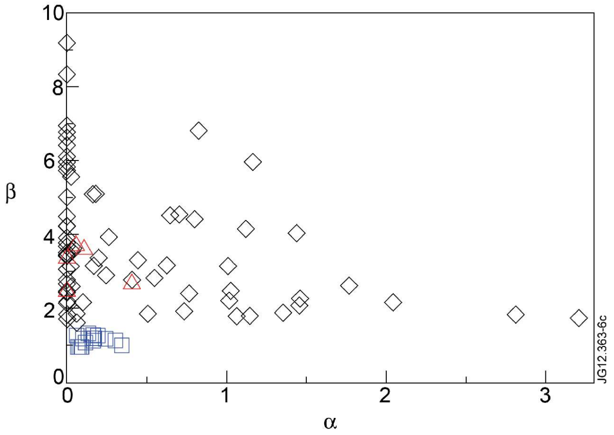

Figure 1: A plot of the dimensionless fitting parameters α and β from maximum-likelihood best fits of the Weibull pdf to JET carbon-wall datasets, with: type I ELM database (black diamonds), type III database (blue squares), and ELMs with a frequency typical of type III ELMs but otherwise similar to type I ELMs and consequently difficult to categorise (red triangles). Type III data is characterised by $\beta \sim 1$, whereas all other data has $\beta \sim 2$ or greater.

data, a database of JET plasmas with between 3 and 6 seconds of steady H-mode was formed. The Weibull pdf has a single maximum, so pdfs with extra maxima that appeared unlikely to be due to noise were explicitly excluded; although the model developed in [5] can be applied more generally. The result was 69 steady-state datasets with type I ELMs and 15 steady-state datasets with type III ELMs, with which to test the model. All of these datasets were from JET plasmas with the Carbon (as opposed to ITER-like) wall.

The Weibull distribution has 3 free parameters that were fitted to each dataset using a maximum likelihood best fit. This has the advantage of giving a unique best fit to a set of data. Goodness of fit was measured with the co-efficient of variation between the measured and theoretical pdfs, and by a likelihood ratio comparison with a Gaussian distribution. As reported in [5], good fits to the data were found.

The quantitative characterisation of ELM waiting times opens a number of possibilties. Ref. [5] explored whether the dimensionless parameters “α” and “β” that were used to fit the data could be used to classify the ELM types. A plot of α and β for type I and type III ELMs is given in figure 1. The type III ELMs are clearly clustered around $\beta \sim 1$ and α between 0.0 and 0.4, whereas the type I ELMs have $\beta \sim 2$ or greater. As noted in [5], for $\beta = 1$, the events are “memoryless”. In other words, for $\beta = 1$, the probability of an ELM in time t to $t + dt$ is independent of the time t, whereas for $\beta = 2$ for example, the probability grows linearly with time. Consequently the type III ELMs appear to be generated by a memoryless process, whereas

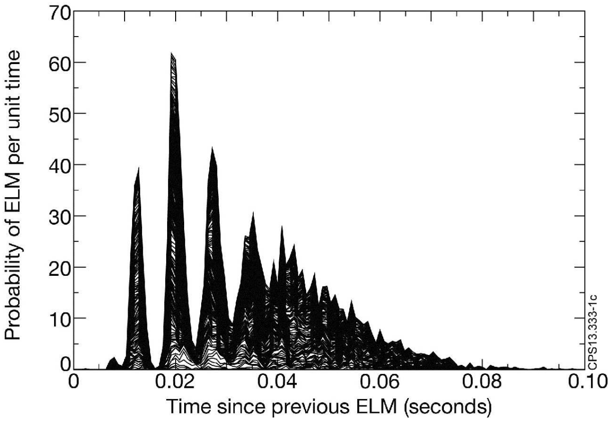

Figure 2: The ELM waiting time pdf resulting from 120 equivalent JET H-mode plasmas, from the last 2 weeks of JET 2012 operation with the ITER-like wall.

the probability of a type I ELM increases with time since the previous ELM, consistent with the build-up of some physical quantity with time that leads to an instability. It is possible that with improved data and fitting methods the classification could be further refined.

Next we consider a set of 120 identical H-mode JET plasmas, that were produced during the last two weeks of JET operation in 2012 with the ITER-like wall. Because the pulses were equivalent, the data was combined to give a dataset with 15,000 ELMs and 8 minutes of steady state JET plasma time. A pdf was formed directly from the experimental data, it is shown in figure 2. The result is entirely unexpected and is not predicted by any plasma physics model. Instead of a smooth single-peaked pdf there are a succession of sharp maxima separated by 7-8 millisecond intervals, corresponding to frequencies of approximately 83, 50, 37, 28, and 24 Hz. The cause of these “resonant” looking maxima is presently unknown.

From a practical perspective, the important question is whether the maxima correspond to resonant frequencies at which ELMs can be more easily triggered, and the zeros to frequencies at which the ELMs are more stable. If the zeros and maxima are related to ELM stability, then future time-dependent ELM control techniques can, and probably will, make use of them to trigger ELMs. A sensitivity of ELM-triggering success to frequency was reported during “vertical-kick” experiments in TCV [6], where the vertical control system was used to rapidly push the plasma up and down with the intention of triggering an ELM. A carefully designed vertical-kick experiment could be used to determine whether the maxima and zeros observed in figure 2 correspond to resonant frequencies or not. It could also test this for the bimodal pdfs observed in [7] that occur for certain levels of gas fuelling.

To summarise, a number of systematic and rigorous studies of the waiting times between

ELMs have been presented. Modelling of the waiting times between ELMs has provided opportunities for classification of ELM types based on ELM statistics alone, complementary to existing experimental approaches. It has also found that type III ELMs are generated by a memoryless process, in contrast to type I ELMs that statistically at least, appear to result from the build-up of a quantity with time, leading to instability. A large dataset of 15,000 ELMs has revealed unexpected structure in the ELM waiting time pdf, possibly indicating resonant frequencies at which ELMs are more easily triggered. Whether this is the case remains to be seen, but suitable vertical-kick experiments could determine this. The cause of these “resonances” is presently unclear. However, whether they are resonant frequencies or not, the results here demand a renewed and deeper understanding of ELMs and the ELMing process.

Acknowledgements: This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] M. Keilhacker, Plasma Phys. Control. Fusion 26, 49 (1984)

[2] H. Zohm, Plasma Phys. Control. Fusion 38, 105 (1996)

[3] A. Loarte *et al.*, Plasma Phys. Control. Fusion 45, 1549 (2003)

[4] K. Kamiya *et al.*, Plasma Phys. Control. Fusion 49, S43 (2007)

[5] A. J. Webster, R. O. Dendy, Physical Review Letters, 110, 155004, (2013).

[6] A.W. Degeling, Y.R. Martin, J.B. Lister, et al. Plasma Phys. Control. Fusion 45, 1637, (2003).

[7] F.A. Calderon, R.O. Dendy, S.C. Chapman, A. J. Webster, B. Alper, R. M. Nicol and JET EFDA Contributors, Phys. Plasmas, 20, 042306, (2013).