

## Variability and risk of edge-localized modes at JET using machine learning

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Edge-localized modes (ELMs) are quasi-periodic edge instabilities in tokamaks, accompanied by expulsion of heat and particles from the plasma. Large ELMs can heighten the risk of damage to the plasma-facing components (PFCs). However, under certain conditions, ELMs can exhibit strongly stochastic behavior, showing a mix of relatively small and larger bursts. This complicates the predictability of the effects of ELMs on plasma operation and plasma-wall interaction. It is therefore of key interest to understand the conditions governing the degree of ELM stochasticity.

In this work, we investigate probability distributions of ELM timing and ELM size at JET, as well as the dependence of the distributions on some of the main operational characteristics. This allows us to exploit information about ELM variability under stationary plasma conditions. More than 1000 JET discharges were analyzed, dating back to 2012 after the installation of the ITER-like wall. Advanced machine learning techniques were developed in order to robustly detect the ELMs under a broad variety of plasma conditions, based on a training set of 16000 manually marked ELMs. The inter-ELM time was determined for all ELM events in the database, as well as an estimate of the drop in the plasma stored energy as a measure of ELM size. Focusing on time windows with stationary plasma conditions, the inter-ELM time can be modeled adequately by a Weibull distribution, while the log-normal distribution is an appropriate model for the ELM size. We use regression analysis to quantify the dependence on machine operational parameters of various characteristics of the distributions, going beyond the analysis of averaged ELM properties by studying the variance, percentiles and tail heaviness. In particular, the tail heaviness of the ELM size distribution is an indicator of unaccounted risk, as the released energy may exceed wall tolerances defined on the basis of average ELM behavior. We highlight the influence of plasma current, triangularity and gas fueling rate on distributional properties. A more qualitative view is offered by a set of fuzzy logic rules, indicating areas of the operational space with the highest risk of tail ELMs. Another indicator of risk is the energy released by several consecutive ELMs. We show that the cumulative energy loss due to multiple ELMs is largely affected by heating power and plasma current.

Overall, this study provides both qualitative and quantitative insight into the occurrence of rare, but potentially impactful ELMs. The code for ELM detection, which can be easily adapted to other types of events, will be published as open source.

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