MHD perturbation amplitudes required to trigger disruptions

P.C. de Vries[1], G. Pautasso[2], E. Nardon[3], P. Cahyna[4], S. Gerasimov[5], M. Maraschek[2]
M. Lehnen[1], G.T.A. Huijsmans[1], T.C. Hender[5] and JET EFDA contributors*

JET-EFDA Culham Science Centre, OX15 3DB, Abingdon, UK
[1] ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance, France
[2] Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
[3] CEA, IRFM, 13108 St-Paul-Lez-Durance, France
[4] Institute of Plasma Physics AS CR v.v.i., Prague, Czech Republic
[5] CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
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1. Introduction

A disruption of a tokamak discharge is a sudden loss of confinement, or thermal quench, in turn resulting in a quench of the plasma current. The fast release of thermal and magnetic energy could result in very large thermal and electromagnetic loads on the surrounding structures, such plasma facing components or the vessel, especially in large devices such as JET and ITER. Understandably, considerable research efforts are dedicated to develop both timely detectors of these events and mitigating actions.

Magneto-hydrodynamic (MHD) instabilities are often seen as precursors to disruptions. The growth of large, overlapping, magnetic islands is thought to be behind the destruction of the flux surface structure that provides the plasma confinement, triggering the thermal quench [1-4]. The detection of these modes is used to predict disruptions. Usually the analysis of these instabilities focuses on how early and at what level they can first be detected [5]. This paper will investigate a different but related question; is there a specific minimum perturbation level that triggers a thermal quench? This study provides experimental insight in the processes that may trigger tokamak disruptions. The perturbation amplitudes that trigger thermal quenches in JET and ASDEX Upgrade are compared and the results form a strong physics basis to determine protection thresholds to be used at future devices, such as ITER.

2. Scaling of measured mode amplitude

Most disruptions at JET feature a typical locked (i.e. non-rotating) mode precursor [6], although locking or a particular phase of the mode does not seem to be a prerequisite for triggering the disruption itself. At ASDEX Upgrade it is more common to see rotating modes prior to disruptions, although locked modes are also observed. The locked mode amplitude B_{ML} is measured by flux loops located at r_c, that, at JET, are mounted on the low-field-side, on the outside of the vacuum vessel, while at ASDEX Upgrade they are located on the high-field-side, closer to the plasma and inside the vacuum vessel. The amplitude in the plasma, $B_{ML}(r_q)$, will be substantially larger because the perturbation amplitude diminishes with radius. This radial decay is essential to understand the measurements in relation to the thermal quench, because the measured amplitude will depend strongly on the position of the dominant mode, r_q, with respect to r_c. and an approximate correction factor $(r_c/r_q)^{-|m|-1}$ has to be applied to convert the measured data into local amplitudes.

The measured locked mode amplitude for nearly all unintentional and unmitigated JET disruptions from 2011 and 2012 at the start of the thermal quench has been determined. Additionally, a similar analysis has been performed for ASDEX Upgrade disruptions. The database contains 250 JET disruptions and 35 from ASDEX Upgrade, with also information on the plasma current, toroidal magnetic field, q_{95}, li(3), elongation (κ) at the time of the thermal quench. The dependencies of $B_{ML}(r_c)$ with, plasma current and safety factor are shown in figure 1. The measured amplitudes for ASDEX Upgrade are similar to those at JET; although the plasma current is typically lower. This can be explained by its coils being relatively closer to the plasma, or $\rho_c^{ASDEX}<\rho_c^{JET}$. Here ρ_c. is the radial distance of the coils normalised to the minor radius, a

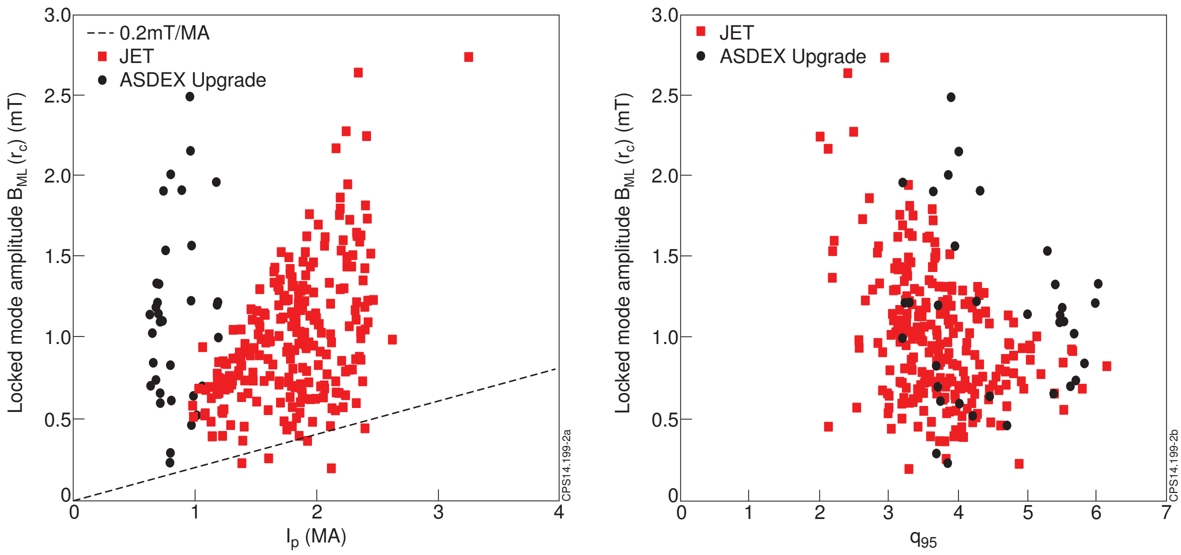

Figure 1: The main dependencies of $B_{LM}(r_c)$ with **a)** plasma current (The dashed line gives the protection threshold used at JET) and **b)** the edge safety factor, q_{95}.

Detailed parameter scalings have been obtained using a regression analysis on the complete database, giving the following result:

$$B_{ML}(r_c) = 7.35\, I_p^{1.10\pm0.06} \cdot q_{95}^{-0.97\pm0.07} \cdot li(3)^{+1.35\pm0.06} \cdot \rho_c^{-3.00\pm0.14} \qquad (1)$$

With $B_{ML}(r_c)$ in mT and where I_p is the plasma current, in MA, q_{95} the edge safety factor, li(3), the internal inductance, and ρ_c. Mode numbers of instabilities, seen prior to disruptions, are not always necessarily m=2, even for entries in this database, but the regression suggests that the average value for the dominant mode is m=2, because $\rho_c^{-3} \sim r^{-m-1}$. Trends with other parameters were not found yet, except that the JET data suggest a possible weak dependency on elongation.

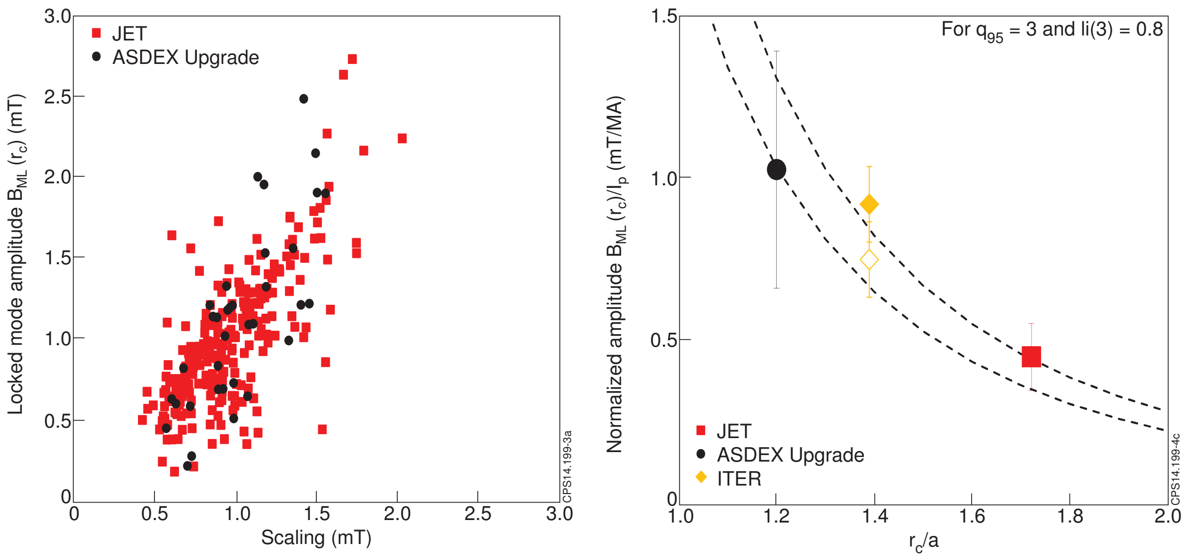

Figure 2: a) Comparison of the experimentally observed locked mode amplitude $B_{ML}(r_c)$ (mT) as measured by the coils/flux loops and the scaling law, for both JET (red squares) and ASDEX Upgrade (black circles) data. **b)** Average JET (red square) and ASDEX Upgrade (black circle) values for subsets that matches the parameters of a typical ITER baseline scenario, using $3.1<q_{95}<3.3$ and $0.7<li(3)<1.0$. These subsets consist of 13 JET and 4 ASDEX Upgrade entries. The error bars are determined by the two times the standard deviation for each subset and the two dashed lines, show the ρ_c^{-3} scaling from both points. The open diamond gives the estimate for ITER based on this trend and the closed diamond is determined with equation 1.

Figure 2a shows that the ASDEX Upgrade data orders well with the general scaling. ITER plans for similar locked mode detection using flux loops on the low-field-side, as at JET, with ρ_c^{ITER}=1.39. For I_p=15MA, q_{95}=3, and li(3)=0.8, for ITER one would find $B_{ML}(r_c)$=14mT, or a more useful normalized locked mode amplitude of $B_{ML}(r_c)/I_p$=0.93±0.12 mT/MA. Of course this level needs to be adjusted for different values of q_{95} and li(3). Another method to estimate the maximum allowable mode lock amplitude for ITER is by selecting JET and ASDEX Upgrade data that match the parameters of a typical ITER baseline scenario, using $3.1<q_{95}<3.3$ and 0.7<li(3)<1.0. These subsets consist of 13 JET and 4 ASDEX Upgrade entries. For a fixed value of q_{95} and li(3) one can plot the average values of both devices against the free parameter, ρ_c., as shown in figure 3b. Based on the trend with ρ_c the ITER value is estimated to be $B_{ML}(r_c)/I_p$=0.75±0.12 mT/MA, which is lower than the previous estimate, though the error bars overlap.

3. Interpretation

The experimental analysis has shown that the thermal quench of most tokamak disruptions is triggered by a well-defined perturbation amplitude. The question is if the observed experimental criterion is consistent with the ideas that either too large a magnetic island or that overlapping islands are the trigger of the thermal quench. To do so, first the amplitude at $\rho_q = r_q/a$ in the plasma is determined, by simply correcting for the radial decay, assuming m=2, using:

$$B_{ML}(r_q) = B_{ML}(r_c) \cdot \left(\frac{\rho_q}{\rho_c}\right)^{-3} \quad \text{with} \quad \rho_{q=2} = 1.69\, q_{95}^{-0.64} \cdot li(3)^{+0.295} \qquad (2)$$

Here ρ_q is assumed $\rho_{q=2}$, the q=2 position, approximated by a scaling with q_{95} and li(3). This converts equation 1 into the following dependency for the amplitude (in mT) in the plasma:

$$B_{ML}(r_q) = 1.52(\pm 0.23) \cdot I_p^{+1.1\pm 0.06} \cdot q_{95}^{+0.95\pm 0.10} \cdot li(3)^{+0.47\pm 0.08} \qquad (3)$$

Note that the dependency on ρ_c disappears. The local perturbation amplitude depends linearly with $I_p \times q_{95} \sim B_T$ and furthermore scales positively with the inductance. The latter indicates that the critical perturbation amplitude scales positively with the magnetic shear, s=q'/q.

This can be compared with the well-known Chirikov criterion [7]. For magnetic islands to overlap, their width should exceed the distance between the two islands such that:

$$\frac{w}{d_{m\to m+1}} = \frac{w}{(m \cdot s)^{-1}} = \sqrt{16 \cdot m \cdot r_q \cdot s \cdot \frac{B_r(r_q)}{B_\theta(r_q)}} > 1 \qquad (4)$$

Here the magnetic island size is given as, $w = 4\sqrt{B_r(r_q) \cdot r_q / B_\theta(r_q) \cdot m \cdot s}$ with $B_\theta(r_q)$ the local poloidal magnetic field. Assuming again q=2 and m=2 this criterion can be rewritten as,

$$\frac{B_r(r_q)}{B_\theta(r_q)} > \frac{1}{16 \cdot m \cdot r_q \cdot s} \;\rightarrow\; \frac{B_r(r_q)}{B_\theta(a)} > \frac{1}{64 \cdot a} \cdot \frac{q_a}{s} \qquad (5)$$

A criterion based on a critical island width w_c can be simply derived as,

$$\frac{B_r(r_q)}{B_\theta(r_q)} > \frac{m \cdot s}{16 \cdot r_q} w_c^2 \;\rightarrow\; \frac{B_r(r_q)}{B_\theta(a)} > \frac{q_a \cdot s}{16 \cdot a} w_c^2 \qquad (6)$$

Both criteria find a linear scaling with plasma current and edge safety factor, but the criterion based on overlapping magnetic islands (equation 5) scales inversely with s, while a scaling similar to that found experimentally is found in equation 6. Equation 6 matches the experimental scaling in equation 3 for a critical island width of $w_c/a \sim 0.30$, similar to previous observations [8]. Similarly, the critical ratio of the local perturbation field to the edge poloidal field is approximately 3%. For ASDEX Upgrade and JET, the perturbation level is of the order of 2 and 3‰ of toroidal magnetic field, respectively while in ITER it is approximately 7-8‰ of B_T. The perturbation levels to reach the criterion given by equation 5 are however, significantly larger than found experimentally.

4. Discussion

Locked mode measurements are standard input to most disruption prediction methods [9,10]. This study tried to understand the measured perturbation amplitudes seen prior to the start of a thermal quench. This physics basis will help determe how to extend disruption prediction techniques to future devices, such as ITER.

It was found experimentally that the thermal quench is triggered at a distinct magnetic perturbation level. This result is rather universal for most JET disruptions and also matched a number of ASDEX Upgrade disruptions that showed locked mode precursors. The scaling was used to determine the maximum allowable locked mode amplitude for ITER. The flux loops at ITER are similar to JET located on the low-field-side of the plasma but relatively closer to the plasma with ρ_c=1.39 for ITER while ρ_c=1.72 for JET. Hence, the expected levels, normalized to the plasma current, for ITER are slightly larger than those at JET, with $B_{ML}(r_c)/I_p$=0.93±0.12 mT/MA for q_{95}=3, and li(3)=0.8. Of course this threshold needs to be adjusted for changes in q_{95} and li(3).

The obtained scaling is an average over the entire database, though individual entries may deviate. Not all modes seen as precursor to disruptions in ASDEX Upgrade and JET are necessarily m=2, although an average mode number of m=2 gave the best fit. Also the precursor mode isn't always locked. In some JET cases the mode amplitude was large enough to trigger a disruption, though it wasn't locked yet. This was however much more common at ASDEX Upgrade, probably due to the smaller relative error fields. A similar analysis could be done for rotating modes. Furthermore, the perturbation may grow very fast, which may complicate detection and the interpretation of the measurement. The JET coils are located behind the vacuum vessel which therefore determines the response of the diagnostic. However, the result also holds for the subset of error field locked modes that grow much slower than the resistive time of the JET vessel (~3ms).

The experimental criterion to trigger a thermal quench, closely matched a theoretical criterion based on a critical magnetic island size. The maximum perturbation is consistent with the presence of a large magnetic island covering nearly a third of the minor radius. It was more difficult to link the start of the thermal quench to a criterion of overlapping islands. This doesn't mean that overlapping islands do not play a role in the process that causes the thermal quench. But, the process is more complex and cannot be described by a concept of slowly growing magnetic islands that suddenly overlap. At critical perturbation amplitude it is more likely that secondary instabilities are driven unstable, resulting in a fast non-linear development of the thermal quench [11,12].

Not all disruptions may have large, locked or rotating, magnetic islands as a precursor and underlying cause. Those that develop at high pressure or high pressure profile peaking developing a fast growth of internal ideal MHD instabilities, are a notable exception [6]. Hence, disruption prediction, solely based on magnetic island width or mode amplitude, may not catch all disruptions and more advanced techniques are needed to increase the prediction success rate.

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