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ABSTRACT

A small fraction of plasma disruptions at JET lead to a significant horizontal displacement of the vacuum vessel. This can threaten the integrity of the vessel and, in particular, of various vessel attachments such as the main vertical ports and the neutral injector boxes. These events are referred to as AVDEs (Asymmetric Vertical Disruption Events). In this paper we attempt to identify associations between plasma parameters and large asymmetric vessel displacements, by analysis of data from some hundreds of disruptive JET pulses. As far as the pre-disruption parameters are concerned, the amplitude of vessel sideways displacements shows a trend with the boundary safety factor and the poloidal beta. No link has been identified with the plasma triangularity or elongation. With regard to plasma parameters during the disruption, the data show a trend with the amplitude of the instability mode n=1, and a trend with the plasma current quench rate and the minimum value of the boundary safety factor. A reliable short cut to select disruptions with high asymmetric loads and to estimate the effects on the vessel using disruption data has been proposed. Hardly any practical operational space has been found to be wholly safe from triggering such vessel sideways displacements.

1. INTRODUCTION

In JET the plasma vertical position stability is usually lost during a disruption, as it is in most other elongated tokamak devices [1]. A number of these vertical displacement events (VDEs) show toroidal asymmetry of the plasma, and these events are referred as asymmetric VDEs, or AVDEs. This phenomenon is common to other devices [2-5], and is a source of concern in the design of ITER [6]. What is uncommon is that at JET the asymmetry usually locks and produces net horizontal forces, which threaten the vacuum vessel and its attachments. These forces, due to the elasticity of the vessel system, make the vessel move sideways.

In this paper we attempt to identify associations between plasma parameters and large asymmetric vessel displacements, by analysis of data from some hundreds of pulses at JET. A related objective is to identify regions in the operational parameter space the avoidance of which will minimise the occurrence of vessel sideways displacements.

The paper is organised as follows. In section 2 we describe the phenomenology of AVDEs, and summarise the previous evidence regarding their association with plasma parameters. Section 3 investigates the dependence of the occurrence of AVDEs on plasma parameters prior to the disruption, and section 4 on parameters measured during the disruption. In section 5 scaling identification of laws relating the sideways vessel displacements to plasma parameters is attempted, using the analytical model of a kinked plasma [7] as a guide.

2. PHENOMENOLOGY OF ASYMMETRIC VERTICAL DISPLACEMENT EVENTS (AVDES) AND EXISTING UNDERSTANDING OF THEIR DEPENDENCE ON PLASMA PARAMETERS

During some JET VDEs plasma parameters, such as current and position, are toroidally non-uniform [8]. The asymmetry of the position is characterised by a tilt of the current ring and a small displacement in the direction of the tilt axis, resembling a kink mode (m=1/n=1). If the asymmetry of the plasma locks in a fixed toroidal position, the vessel moves sideways at the end of the disruption. These events are referred to as AVDEs and are rare: less than 10% of VDEs become asymmetric at JET. For a disruption to develop a kink asymmetry the plasma has to move enough from its equilibrium position at almost constant current for the boundary safety factor to decrease to a small value (about 1), so that the m=1/n=1 instability can start. The asymmetry needs to remain locked throughout the current quench to build up a sideways impulse which makes the vessel move sideways as a rigid body in the same direction as the plasma tilt vector. The vessel asymmetric forces are due to the asymmetric fraction of the halo current flowing in close patterns in the wall during the instability. The sideways force can be estimated from magnetic measurements [7], while the vessel displacements are measured at the ports (top and bottom Main Vertical Ports and midplane Main Horizontal Ports, using linear variable resistors) in eight toroidal locations (in each octant of the vessel).

The motion of the vessel is a cause of concern at JET. The vessel is mainly supported at the Main Vertical Ports. The roots of these ports are welded to the vessel. These welds experience significant cyclic stresses during such disruptions, using up what is naturally a limited fatigue life. In-vessel attachments (mostly diagnostics coming through the ports) or out-of-vessel attachments (mainly the two neutral beam injector boxes) are similarly threatened. Indeed, the neutral injector box attachments have already been damaged by these events: for example the AVDE of pulse number 34078 led to the repair of the octant 4 neutral beam injector rotary valve.

The analysis of AVDEs started just after that accident [9]. The first finding of this analysis was a clear distinction observed between upward and downward disruptions during operation with the divertor. Since the divertor coils have been in place (they were installed in JET part way through its life), only upwards VDEs have been found to lead to asymmetric vessel displacements. This is indicated in Fig. 1, where only disruptions during “divertor “campaigns are plotted for clarity. Prior to the installation of the divertor coils AVDEs occurred in association with both

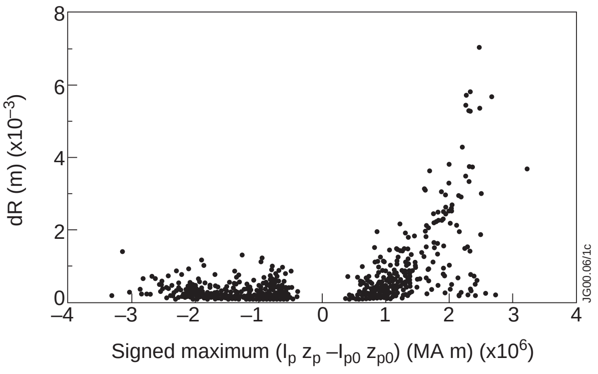

*Fig.1: Vessel sideways displacement (*dR*) plotted versus the maximum of* $\Delta I_p z_p = I_p z_p - I_{p0} z_{p0}$ *(variation of the average vertical current moment during the disruption). Positive values of this quantity correspond to upward disruptions.*

upwards and downwards underlying disruptions. There are two possible explanations of this: induced currents in the divertor structure could quickly compensate and stabilise the asymmetries, or the plasma/wall interaction is less ‘friendly’ in the bottom of the machine so that the plasma current starts to decay well before large net sideways forces at the vessel are generated. No proof of either proposed explanation has been found.

To identify those plasma parameters associated with the AVDEs an earlier analysis [9] focused on the plasma elongation, poloidal beta, upper triangularity and boundary safety factor, prior to the disruption.

Since the plasma displacement at full current is important to start the asymmetry, the plasma elongation, linked to the growth rate of the vertical instability, was believed [9] to be closely associated with the magnitude of the AVDEs. In addition, a link between the plasma upper triangularity (a parameter which quantifies the third harmonic deformation of the plasma shape at the top of its cross section) and AVDEs seemed to appear in the data initially collected [8].

The belief that AVDEs are external kink instabilities (m=1/n=1), which need a resonant surface (provided by a rational safety factor equal to m/n) to be triggered [9], led to the investigation of a correlation between the boundary safety factor and the amplitude of the vessel sideways displacement. This analysis showed a correlation between the boundary safety factor prior to the disruption and the sideways amplitude, and a trend in the minimum safety factor during the disruption.

The first attempts in scaling the sideways vessel displacement [8] were with the square of the plasma current, as the main disruption forces are proportional to this quantity, but even the few data available at the time showed inconsistencies in this method.

3. PRE-DISRUPTION PARAMETERS

The analysis results presented in the following subsections will show that amongst the pre-disruption plasma parameters, the amplitude of the sideways displacement at the end of the plasma instability shows a clear trend with the boundary safety factor and the poloidal beta. Initial links with plasma upper triangulatiry could not be confirmed. Probably the data set used in the first analysis [9] was biased by the fact that high triangularity plasmas were also high poloidal beta plasmas (as the increase of the plasma pressure, roughly proportional to the poloidal beta, has this shaping effect). Indeed high poloidal beta, as it will be shown later, is linked to the amplitude of the vessel sideways displacements. In addition no significant correlation between pre-disruption plasma elongation and amplitude of the sideways displacement has been found.

3.1 Boundary safety factor

The data collected are measurements of the cylindrical approximation of q_{95} (i.e. safety factors computed on the plasma surface where the normalised poloidal flux is 0.95), since the presence of the X-point makes inaccurate the computation of the actual boundary factors.

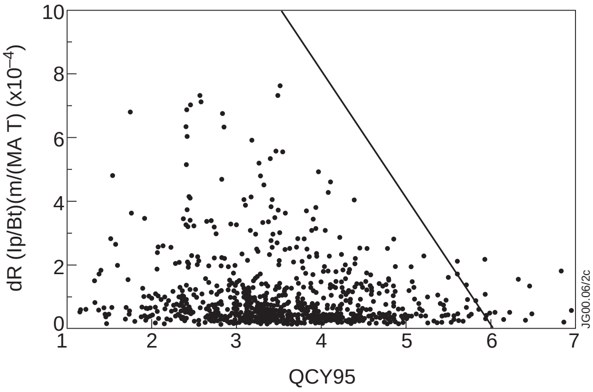

Fig.2: Large sideways vessel displacements occur more when the boundary safety factor (QCY95) before the disruption is small; the few pulses (15 out of about a thousand) with q_{95} *less than 1.5 are due to an incorrect setting of the trigger time for the collection of plasma parameters*

A reduction of the boundary safety factor can occur during VDEs when the plasma cross section shrinks faster than the plasma current falls, due to the plasma being pushed to the wall. For any given plasma current, when the safety factor prior to the disruption is large it seems plausible that the VDEs will produce only small vessel displacements, because there is a large margin in the safety factor before it reaches a small enough value to trigger the first poloidal mode. This trend is shown in Fig. 2, where the normalised (to the product of the plasma current times the toroidal field) sideways displacement is small when the boundary safety factor prior to the disruption is larger than 3.5. In addition, the amplitude of the normalised sideways displacements seems not to depend on the pre-disruption safety factor (when this is in the range 1.5 to 3.5) and among the many disruptions analysed only a few give rise to a large vessel asymmetric motion.

3.2 Poloidal beta

The definition of the poloidal beta, β_p, retrieved in the statistical analysis is the following

$$\beta_p = \frac{\int p\, dS / \int dS}{B_{\vartheta a}^2 / 2\mu_0},$$

where the integrals are surface integrals over the poloidal cross section and $B_{\vartheta a}$ is the poloidal magnetic field at the plasma boundary (taken as $\mu_0 I/l$, if l is the length of the poloidal perimeter of the plasma).

The value of β_p determines the displacement of the plasma when the control of its position is lost: it is usually observed that the larger is the β_p the bigger is the inward jump the plasma will make. When moving away from the equilibrium position the plasma finds a frozen externally imposed poloidal field different from the one at the equilibrium position. Depending on this field the plasma may be pushed upwards or downwards. The first consequence of a large β_p is an immediate strong interaction with the inner wall due to the inward jump. This produces impurities which cause a faster current quench because of the increased resistance [10]. That high poloidal beta plasma do not produce slow disruptions is clear in Fig. 3, where the plasma energy, proportional to $\beta_p I_p^{\,2}$, is plotted versus the plasma current time derivative. The second consequence is a larger push away from the vertical equilibrium position. Of the two effects the predominant is the fast current decay, which prevents the critical boundary safety factor being reached.

A plasma with a small β_p has better chances to survive the energy quench jump, because its inward jump is smaller and unlikely to cause a substantial production of impurities. Consequently the plasma starting the disruption with a small β_p has a higher probability of producing an AVDE and then to cause the vessel sideways motion. This is supported in Fig. 4.

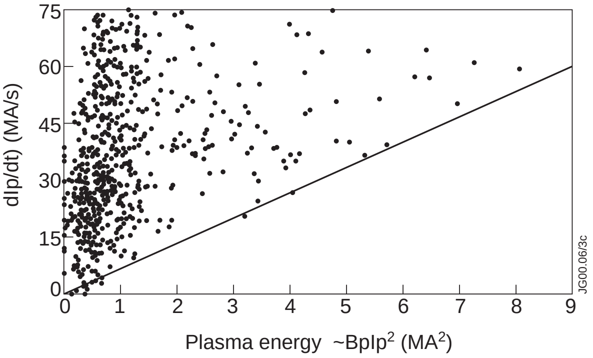

Fig.3: Disruptions starting with high diamagnetic energy have a faster current decay.

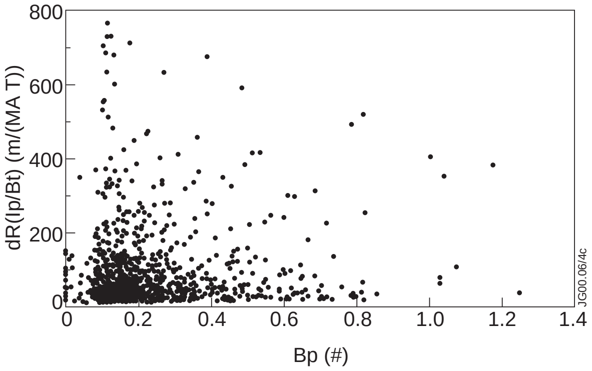

Fig.4: There is a trend between sideways displacements (here normalised to the product of plasma current and toroidal field) and poloidal beta: the smaller is β_p, the larger can be the displacement

4. PARAMETERS DURING THE DISRUPTION

In the following subsections the link between the minimum safety factor at the boundary, the current quench rate and the amplitude of the localised n=1 instability during the disruption and the amplitude of the subsequent vessel sideways displacement will be presented.

4.1 Minimum boundary safety factor

The minimum safety factor during the disruption is not available as processed data, so it has been evaluated, using a cylindrical approximation, as

$$q_c = 5\frac{B_0 a^2}{I_p R_p},$$

where a is the plasma minor radius, B_0 is the vacuum toroidal magnetic field at the magnetic axis, and R_p and I_p are the radial position of the plasma centroid and the plasma current. The plasma minor radius has been taken, from plasma position measurements, as the shortest distance between the plasma centroid and the wall.

In the estimate of this reference minimum boundary safety factor the residual plasma elongation is not accounted for. A circular plasma with minor radius a has a larger safety factor than a plasma with the same current and with the same vertical dimension but smaller horizontal dimension. The q_c value is therefore an overestimate of the actual boundary safety factor. This overestimate is moderate, typically <20% according to a simple analysis, because the reduction of the plasma size during the VDE leads to a substantial reduction of the original elongation. On the other end, the measured current flows partly as halo current outside the confined cross-section area, so the safety factor at a minor radius *a* is larger than the one given by the expression used for q_c. For a typical instantaneous ratio of the poloidal halo current to the total toroidal current of _ the q_c value is underestimated by <25%. Both effects cancel each other to some extent. The adopted expression for the boundary safety factor gives therefore a reasonable reference value.

If the plasma current density prior to the disruption preserve its profile during the event, the elongation has to decrease because of the change in the external quadrupolar field is changing at a slower rate or staying constant. This leads to smaller (by ~20%) value of the boundary safety factor than the one computed, since this is based on the change of the plasma section major axis. If the current profile changes (from a peaked one to a more flat one) the reduction, both on the elongation and on the actual safety factor is diminished (~10%). An opposite effect is due to the presence of the halo current: the plasma centroid position computed from the boundary magnetic field measurements is displaced as it does not discriminate between confined current and halo current producing an overestimate of the actual centre to wall distance, this leads to an underestimate (~20%) of the confined boundary safety factor.

At this stage the asymmetry of the plasma position does not matter: due to all the uncertainties this computation has (i.e. elongation is neglected and toroidal halo current is not discriminated from the confined toroidal current, so that the actual safety factor is between 0.8 and 1.2 times the cylindrical-approximation one), the position asymmetry is simply included in the inaccuracy of the calculation. In addition, the search for the minimum boundary safety factor stops when the plasma current has decreased below a third of its starting value. This simplifies the analysis, by eliminating any spurious extremely small q_{min}, and does not miss plasmas which could become asymmetric when their current is still high.

The analysis of the collected data confirmed that vessel sideways displacements, if not AVDEs, are strongly dependent on the minimum value the safety factor can reach during a VDE. A displacement larger than ~0.4 mm/(MAT) (normalised by the product plasma current times toroidal field) has never been recorded for disruptions whose minimum safety factor at the boundary (q_{min}) has been above 1.2 (Fig. 5), as if a q_{min} of about 1 is needed to trigger the instability.

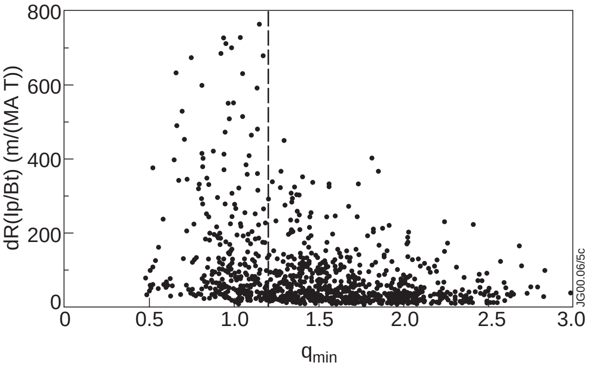

Fig.5: The largest vessel sideways displacements occur when the q_{min} *is smaller than ~1.2*

4.2 Plasma current quench rate

The decay rate of the plasma current is defined as the ratio of the current change to the time during which this change occurs ($\Delta I_p/\Delta t\ 1/I_{p0}$). The interval chosen is the one between the time of the plasma current maximum (the temporary increase of plasma current due to the flattening of the current profile, if present, the starting value, otherwise) and the time when the plasma current has decreased to 40% of that maximum. In other words, the normalised decay rate is 0.6 divided by the time taken for the plasma current to decrease by 60%. A threshold behaviour is even more clear for the normalised initial rate of decay of the plasma current: when the quench rate is more than 30 s^{-1} all normalised sideways displacements are smaller than 0.4 mm/(MA T) (Fig. 6). Figures 5 and 6 together show that large sideways displacements occur only when the plasma current falls sufficiently slowly so that the plasma has time to shrink enough for the minimum safety factor at the boundary to reach an instability-trigger value of about 1. The fact that fast disruptions do not show significant sideways vessel displacements suggests that the use of killer pellets [11-14], or other means of fast plasma termination, could be a way to limit disruption electromechanical loads on the vessel.

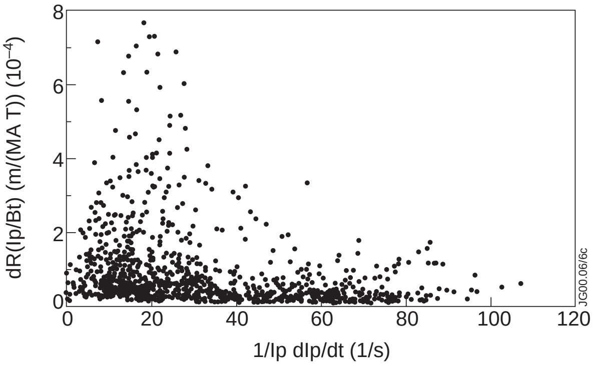

Fig.6: The vessel sideways displacement shows a threshold behaviour with respect to the normalised rate of decay of the plasma current: large displacements are possible only when $\Delta I_p/\Delta t\ 1/I_p < 30\ s^{-1}$, i.e. for slow events.

4.3 Amplitude of the toroidal mode n=1

The amplitude of the toroidal mode n=1 is computed using a combination of poloidal magnetic fields normal to the vessel wall at the midplane (one pair of flux loops per cross section in four toroidal locations, one pair every 90^0). Basically, this quantity is proportional to the amplitude of the asymmetry of the plasma vertical current moment, but it does not carry any information on the toroidal phase angle of the asymmetry and of its possible change of phase angle during the AVDE. The amplitude of the vessel sideways displacement can be therefore small even when the amplitude of the toroidal mode n=1 is high, but if the mode amplitude is small sideways displacements can never be large. This is shown in Fig. 7. Using the same raw magnetic data it is possible to identify the location of the peak of the instability. Information on the amplitude and phase of the toroidal mode n=1 and of the vessel sideways displacement has been collected and analysed only for a selected set of disruptions [10]. In this subset of data a correlation between the two amplitudes and the two phases has been found. This exercise is too complex to check on a large number of pulses.

If the asymmetry locks and the magnitude of the toroidal mode n=1 is taken at the time of the asymmetry, it can give a good estimate of the strength of the asymmetry. Figure 7 indicates that the upper limit of the vessel displacement is roughly proportional to the peak value of the toroidal mode amplitude.

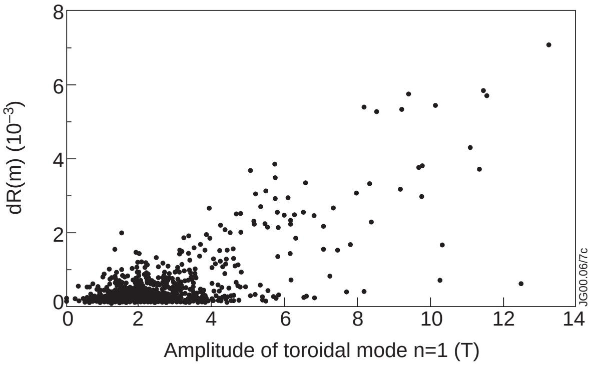

Fig.7: The n=1 mode detector sets an upper envelope to the vessel sideways displacement amplitude: it can be large even when the mode is not locked, hence not contributing to the build up of the sideways force impulse

5. SIDEWAYS DISPLACEMENT SCALINGS

The vessel sideways displacements have an envelope in the product plasma current times toroidal field, as presented in [14] and summarised in section 5.1 below. However, taking advantage of the proportionality with the amplitude of the localised mode n=1 and the thresholds, identified in this work, with the initial plasma current decay rate and the minimum safety factor at the boundary, a fitting of the vessel displacement with measured global plasma parameters can be obtained for a relevant subset of AVDEs. This is discussed in section 5.2.

5.1 The maximum potential sideways force for the longest possible current quench

As shown in [15], the sideways force acting on the vessel during an AVDE is well characterised by

$$F_x = \frac{\pi}{2} \Delta M_z B_T ,$$

where ΔM_z is the asymmetry in the vertical current moment of the plasma. The amplitude of the vessel sideways displacement scales with the time integral of the sideways force [15]. Since in AVDEs the amplitude of the vertical position asymmetry is geometrically constrained and the duration of the current quench is radiatively limited, the maximum sideways displacements scale with the product of the plasma current times the toroidal field. This recipe is well supported by the disruption data collected so far: Fig. 8 shows that there is a reasonable a posteriori scaling of the upper

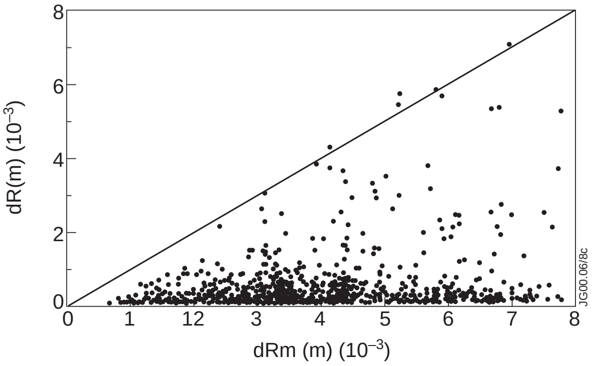

Fig.8: The product plasma current times toroidal field is an upper envelope for the sideways vessel displacement amplitude: only some disruptions satisfy all the requirements to produce the largest possible radial force impulse. The scaling coefficient is obtained by fitting of the largest recorded sideways displacement (pulse 38705, with 7.1 mm for 3.5 MA and 2.8 T).

limit of the sideways displacement with the product of the plasma current and the toroidal field. Even if this is not enough to predict the actual sideways displacement, it provides an upper limit to the sideways displacements (and associated stresses and strains) useful for practical operation.

5.2 The amplitude of the n=1 instability times the toroidal field

Again taking advantage of the model described in [15], a short-cut to scale the vessel sideways displacement with measured parameters can be found by using the peak amplitude of the localised mode n=1. Since at JET usually the asymmetry locks and the duration of AVDEs does not change much from event to event, the peak of the toroidal mode n=1 is an acceptable approximation of the strength of the sideways force. It is slightly less accurate, but far simpler than the time integral of the vertical current moment ($I_p z_p$) asymmetry, which is proportional to the amplitude of the vessel displacement [10]:

$$B_T \int \left[\left(I_p z_p\right)_{\varphi} - \left(I_p z_p\right)_{\varphi+\pi} \right] dt \propto \delta R_{\varphi+\pi/2} \cdot$$

The model used to produce the heuristic line fit in Fig. 9 is based on the observation that only disruptions reaching q_{min} =1.5 or below, with also a current decay rate <30 s^{-1} are able to produce any significant sideways vessel displacement. All others can be discounted. For this restricted set of AVDEs the toroidal field and the mode n=1 peak amplitude have been multiplied and scaled with a common coefficient to fit the event with the maximum sideways displacement (pulse 38705, with 7.1 mm for 3.5 MA and 2.8 T). This is not strictly a prediction because it needs disruption parameters to be known, but fits the data well.

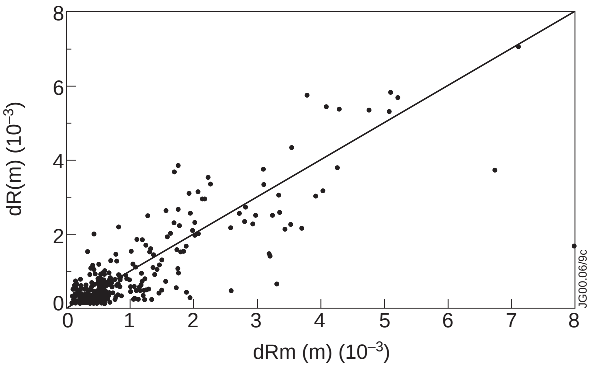

Fig.9: Most of the disruption data, especially for displacements >2 mm, fit the model within a factor of ~2 and only one disruption with large predicted sideways displacement does not, and a separate check revealed that this AVDE did not lock.

6. DISCUSSION AND CONCLUSIONS

The amplitude of vessel sideways displacements at JET shows a trend with two pre-disruption parameters: for high boundary safety factor and for high poloidal beta the displacement is reduced. As far as the disruption parameters are concerned, the phenomenon shows a strong increase of the vessel sideways displacement with the decrease of the minimum boundary safety factor. The boundary safety factor has to be less than 1.5 for an AVDE to become substantial, and this must be accompanied by a plasma current quench rate slower than 30 s^{-1}. The displacement amplitude shows an upper boundary with the amplitude of the instability mode n=1.

These results confirm some of the earlier work on the pre-disruption parameters [8-9, section 2]. No link has been proven with the plasma triangularity or elongation before the disruption [10]. The earlier speculation about the current quench rate [8] has been substantiated by the evidence provided here. The strong link with boundary safety factor has been confirmed and a usable short cut to estimate the effects the plasma asymmetry using the amplitude of the mode n=1 has been proposed.

It has been confirmed that the choice of a high safety factor (i.e. high toroidal field to plasma current ratio) reduces the vessel sideways displacement normalised to the product of plasma current times toroidal field. However the boundary safety factor is intrinsically limited at high current operation. In general, hardly any practical operational space has been found to be wholly safe from vessel sideways displacements caused by disruptions. In fact, high poloidal beta can not be considered a reliable way of avoiding asymmetric disruptions, since this parameter varies during the experiment and depends on the additional heating and on the efficiency of the plasma in exploiting it.

The evidence that only slow-starting disruptions lead to substantial vessel displacements suggests that, for the design of large tokamak devices, one might consider facilities which, after the start of a disruption, could enhance the current quench rate and prevent mode locking. Possible means include impurity pellet and tangential neutral beam injection [11-14]. Such methods can hardly be fail-safe, so the vessel and the supports may have to be designed to cope with significant asymmetric disruption forces in any case.

7. ACKNOWLEDGEMENTS

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