Statistical Analysis of Disruptions in JET

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1. Introduction

A disruption is a termination of a Tokamak discharge after a sudden loss of stability or confinement. Because of the fast time scale in which the plasma thermal and electromagnetic energy are dissipated, these events lead to large thermal loads on in-vessel components and strong electro-magnetic forces on surrounding conductors. Especially in larger tokamaks, like JET, disruptions have been able to cause considerable damage and in order to preserve the integrity of the device it is therefore important to prevent or mitigate such events [1]. Hence it is important to limit the number of disruptions during the operational life-time of the device. For ITER operations at high current the disruption rate should be 1% or less.

It is therefore useful to study what the rate of disruptions in present day, large, Tokamaks, like JET is. Here the disruption rate is defined as the fraction of discharges that disrupt. Previously disruption rates of various devices have been reported to be in the order of 20-40% [2], significantly higher than those aimed for ITER operations. Another, even more useful, parameter that can be determined is the disruptivity of specific plasmas, i.e. the likelihood that plasmas in a specific state will disrupt.

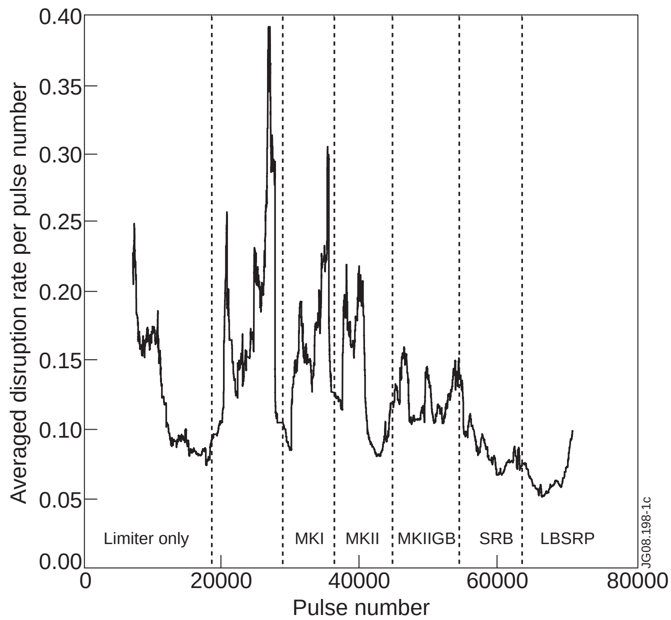
At JET a dedicated database has been maintained, recording each disruption during the operational life. Using this database a statistical analysis of the occurrence of disruptions at JET has been carried out to obtain the overall disruption rate of JET [3]. Furthermore, trends in the disruption rate can be determined. These results will be presented in the first section of this paper. In section 3 the disruptivity as function of various plasma parameters will be presented. Here we focussed mainly on the three main operational boundaries of Tokamak operations, i.e. the low-q limit [4], the density or Greenwald limit [4,5] and the β or Troyon limit [6]. In section 5 the statistics of the JET disruption prevention system are presented followed by a concluding section.

2. Analysis of the disruption rate

In order to get a general idea of the average frequency of disruptions over the entire period of JET operation, the disruption rate can be approximated as the number of disruptions as recorded in the database divided by the number of JET pulses carried out over a specific period. Figure 1 shows this number, i.e. the disruption rate per pulse number, using a sliding average over 2000 pulse numbers. One should note that this calculation is not entirely accurate because also pulses without plasma, e.g. dry-runs or ones with non-sustained breakdowns, are counted. Hence, the actual disruption rate of plasma discharges is therefore slightly larger but a similar trend as in figure 1 was found [3]

The disruption rate, the frequency at which disruptions take place, in JET was found to have dropped over the years. Recent campaigns show a yearly averaged disruption rate of only 6% while from 1991 to 1995 this was often higher than 20-30%. These values are close to those reported in ref. [2]. In figure 1, average disruption rate of 40% around #26800 (in 1991) suggests that about 800 of the 2000 pulses in this interval disrupted. The question is if the variations found in figure 1 can be explained. Prior to #46000 (=1998) there are 3 periods with notably lower disruption rates; 1987-1988 (#12300-#18300), early 1994 (#27900-#30900) and in 1997 (around #42900). These periods can be identified as a long sustained campaign of limiter operations, an extended commissioning period after the installation of the Mark I (pumped) divertor and the main Deuterium-Tritium (DT) campaign, respectively. All these periods are characterised by careful operations using well-tested or standard scenarios. These contrast with a phase of high disruption rate that start after approximately pulse number 20000. This coincides with the first X-point operations at JET.

Figure 1: The moving average of the disruption rate over 2000 pulse numbers as a function of pulse number. The first vertical dashed line from the left indicates the start of X-point operations (just before pulse 20000). The others the various phases of the JET divertor, Mark I, II Gas Box (GB) divertor, with septum replacement plate (SRP) and a Load Bearing SRP (LBSRP)



The early attempts were prone to vertical displacement events (VDEs) resulting in a large number of disruptions. A similar period with a high number of disruptions is found during the times leading up to the DT campaign when many of the high power and high current scenarios for these experiments were being developed. Less well explained is the much lower disruption rates observed in the recent campaigns, where after 2001 (#54345) the disruption rate drops significantly below 10%.

3. Disruptivity of JET discharges

The downward trend in disruptions seen in figure 1 may be connected to a better understanding of Tokamak physics and the operational boundaries of Tokamak operations. However, one should be aware that within the disruption rate, all disruptions are counted, even those due to technical problems. The disruptivity is a measure for the likelihood that a disruption takes place when the plasma is in a specific state and could be linked to, for example, the operational boundaries of Tokamaks. Although often confused, disruptivity and the disruption rates are two different quantities and are definitely not directly related to each other. Studying disruptivities is complicated by the highly non-linear nature of plasma stability, such that the disruptivity may depend on a complex set of multiple parameters. It may therefore be difficult to link disruptivity to a plasma state described by only 1 or 2 plasma parameter(s). Nevertheless, the insight of where in the operational space disruptions take place may reveal indications of the main causes of JET disruptions.

Sufficient statistics are required in order to determine the disruptivity accurately; hence one has to average over a long period of operations. The following studies have been carried out over the recent operational period from 2000 to 2007. For each discharge the plasma state is sampled each 250ms (i.e. 4Hz) when the plasma current is above 1MA. This gives the total number of times (within a 250ms interval) that the plasma is in a specific state, i.e. has a specific plasma current or density. The frequency of 4Hz was chosen to be the same as the JET Thompson scattering diagnostic which provided part of the data. In total more than 15000 plasma discharges were sampled, resulting in 1.4 million sample points for each requested parameter. The disruptivity is defined as the number of disruptions when one plasma is in a specific state (i.e. occurs within the same time frame in which the plasma is within a particular parameter range) divided by the total number of time frames in which the plasma is in this same parameter range, normalised to the sampling time. The inverse disruptivity is statistically the average time that the plasma can be within this parameter range before a disruption. The higher the disruptivity, the sooner one may expect a disruption.

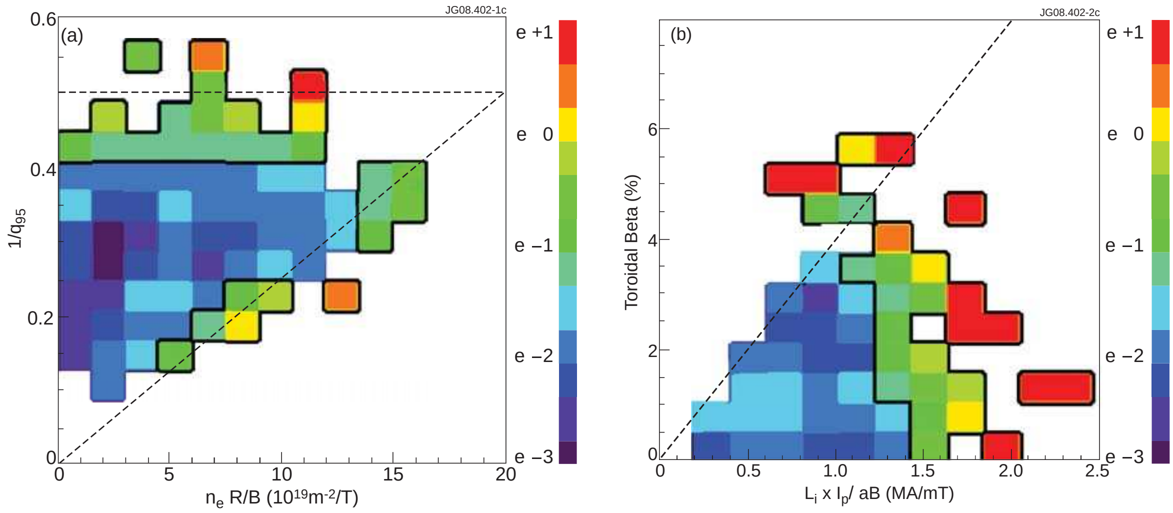


Figure 2: a) so-called Hugill-diagram [4], with the disruptivity. The dashed lines show the so-called Greenwald-limit and the *q*=2 limit, respectively. **b)** A diagram showing the disruptivity in the operational space toroidal β versus $li \cdot I_p /aB_T$. The dashed line shows $\beta_N = 4 \cdot li$. Note that in both graphs, the contour levels are spaced logarithmically. The area where the disruptivity exceeds an arbitrary level of *0.01* is given by the black thick line.

The results of such a calculation have been plotted in figure 2. Firstly the disruptivity has been determined as function of the low-*q* (*q* is the safety factor) and Murakami parameter, i.e. density n_e normalised to the magnetic field *B* and the plasma major radius *R*. Those zones of high disruptivity are found near the two well know operational boundaries, the Greenwald limit and the one at *q=2*. Clearly the disruptivity is higher near these boundaries and when operating near them the likelihood of a disruption is higher. Secondly, tokamaks usually struggle to operate above levels of $\beta_N = \beta_T \cdot aB_T / I_p \sim 4 \cdot li$, where β_N is called the normalised β. This operational boundary is related to the so-called β-limit in Tokamaks [6]. The disruptivity has been calculated in the operational space of the toroidal β versus $li \cdot I_p /aB_T$., shown in figure 2b. Here the picture is less clear and at the β-limit no clear area of elevated disruptivity is seen. The disruptivity is higher on the right-hand-side, which is however simply linked to the low-*q* limit. One may argue that most high-power scenarios operate with $li \cdot I_p/aB_T \sim 0.8\text{-}0.9$ for which indeed higher disruptivity is found at highβ. Nevertheless, the β-limit does not appear as clear as the other to operational boundaries. One possible explanation may be that not always sufficient power is available at JET to reach this boundary.

It was found that the disruptivity near the operational boundaries did not vary much over the time [1]. However, the disruptivity in the area far from the boundaries decreased. This is consistent because the largest fraction of disruptions happen in this parameter space such that these are a dominant contributor to the disruption rate. It may also suggest that the drop in disruption rate, seen in figure 1, is due to a reduction in disruptions in plasmas that are operated far from the operational boundaries.

4. Precursors and mitigation of disruptions

At JET a straightforward protection system is in place that terminates the plasma discharge in case of control problems or when plasma instabilities are detected. Hence, some disruptions may be prevented or their effects can be mitigated. Figure 3a shows the warning times generated by this system. For 43.1% of all disruptions a warning trigger was given due to the presence of a mode lock while only 2.3% was stopped due to a rotating MHD mode. 17.8% was due to technical problems, for example the shape control. 37.4% of all disruptions and 49% of all unintentional disruptions (some are done on purpose) can be detected with a warning time of 200ms or more. The main mitigating actions by the system are the reduction of the plasma and shaping currents. These actions have a characteristic time at JET of approximately 200 and 30ms, respectively. The effectiveness of the system is illustrated by figure 3b, which shows that the averaged forces on the vessel after a

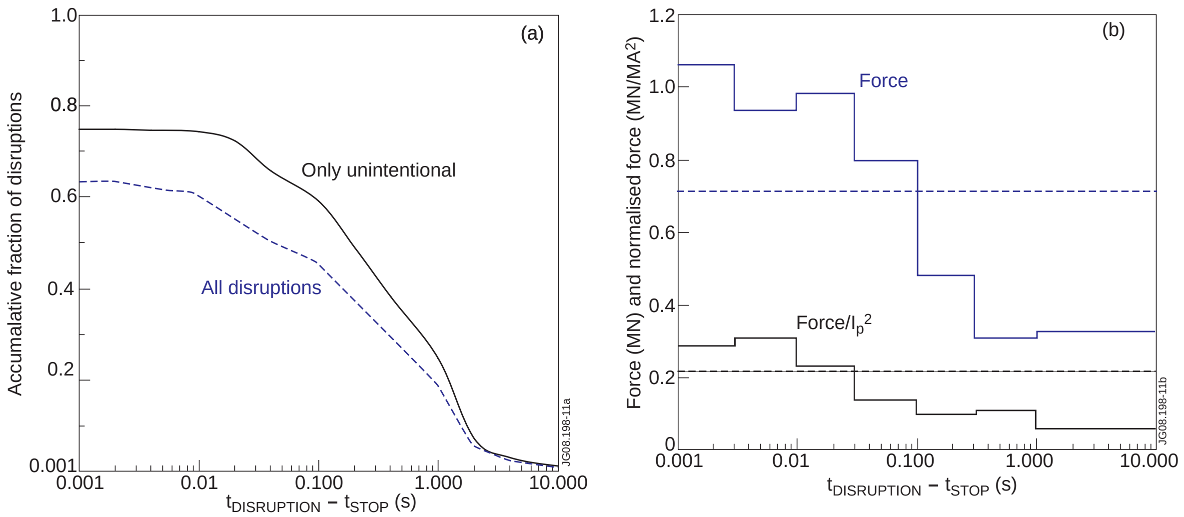


Figure 3: a) The accumulated fraction of all JET disruptions between 2000 and 2007 (blue dashed) and only unintentional ones, as function of the warning time, i.e. the time between a possible pulse termination trigger and the disruption. **b)** The averaged vessel force (blue) and normalised force for disruptions (black) versus the warning time. The dashed lines gives the force averaged over all disruptions (= 0.71MN) and the average normalised force (=0.218MN/MA^2).

disruption [3] decrease as a function of the warning time. One should note that the forces shown here are averaged. Significantly larger forces than the maximum shown in figure 3b have been measured at JET (up to 4.5MN). A similar trend is found for the normalised disruption force, i.e. normalised to the square of the plasma current. This also suggests that the force mitigation is not only due to the reduction in plasma current, but also due to the change in plasma configuration and hence the vertical growth rate of the VDE.

5. Conclusions

The disruption rate (the percentage of discharges that disrupt) in JET was found to have dropped over the years, especially after the time when first X-point operation was attempted at JET, characterised by a very high disruption rate. Beside the disruption rate, the so-called disruptivity, or the likelihood of a disruption depending on the plasma parameters, has been determined. The disruptivity of plasmas was found to be significantly higher close to the three main operational boundaries for tokamaks; the low-q, high density and β-limit. One should be careful to project the values of disruptivity to for example ITER, because it is not certain if the time scales involved are the same. The disruptivity near the boundaries did not change in time significantly. The largest reduction of disruptivity was found far from the operational boundaries, leading to the conclusion that the improved disruption rate is due to a better technical capability of operating JET, instead of safer operations near to the physics limits. The statistics showed that a simple protection system was able to mitigate the forces of a large fraction of disruptions.

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