

Disruption causes during first operations with the JET ITER-like wall

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1. Introduction

Disruptions are a key issue for large Tokamaks such as ITER because of the fast release of high thermal and magnetic energies, resulting in extreme electromagnetic forces and heat loads. In order to preserve the integrity of the device, the number of disruptions has to be limited. JET has shown to be able to operate previously with a low disruption rate of 3.4% [1].

The tolerable heat loads on the ITER-like wall (ILW) are more restricted because of the potential for melting. This is exacerbated by the fact that with the ILW significantly less energy is radiated during the disruption and thus more energy is conducted to the PFCs [2,3]. The lower radiation and therefore higher temperatures also slowed-down the current decay, yielding larger vessel forces [2,3]. These results highlight the significance of disruption avoidance and mitigation. At higher plasma currents ($I_p \geq 2.5$ MA) Massive gas injection (MGI) had to be applied to safely operate with the ILW [3,4].

The start of operations with the ILW at JET showed a marked rise in the average disruption rate to 10%, while in the latter part of the campaign, with standard high-power H-mode operation, 17% of the pulses disrupted. Here, disruptions are defined as those having a current quench faster than $dI_p/dt > 5$ MA/s. Effective disruption avoidance and mitigation schemes can only be devised when knowledge of the root cause and the subsequent series of events that leads to a disruption, are at hand. Therefore, the cause of each disruption, during the first period of operations with the ILW, has been analysed. The results will be summarised and compared with carbon wall disruptions. Thereafter a description of the dominant disruption cause in 2011-2012 (i.e. those due to high-Z impurities and too high core radiation) will be given.

2. Survey of disruption causes with the ITER-like wall

For each of the 275 unintentional disruptions, that occurred during ILW operations in 2011-2012, the sequence of events that led to the disruption has been determined, identical to the survey done for carbon wall operations [1]. Figure 1 shows a statistical summary of these results.

There are a number of obvious differences with the picture obtained for carbon wall operation (figure 4 in ref. [1]), although this concerned data from a much longer operational period. For example no disruptions due to too strong internal transport barriers (ITB) took place, for the simple reason that ITB scenarios were not performed yet with the ILW. The absence of any disruptions due to vertical stability (VS) control issues might be attributable to the VS control upgrade prior to the installation of the ILW [5]. Moreover, advancement in the design of emergency termination scenarios might have improved the control over the plasma during such events and avoided disruptions, shown by the absence of a return-path ML → STOP (indicated by the dashed line in figure 1) which was a frequent occurrence during carbon wall operations [1]. Previously, density control could be compromised by increased recycling when errors in the position or shape control brought the plasma too close to the carbon wall, following the path SC → WAL → RCY. With the

ILW only few such cases were found. The occurrence of other disruption classes, such as for example neo-classical tearing modes (NTMs) was found to be unchanged.

Besides these positive differences, some paths have worsened in 2011-2012. Firstly, it was found that more often disruptions due to error field locked modes took place. The new wall is rather uncompromising with respect to any failure of density control. In such cases the density would drop quickly to very low levels (NC→LON→ML), while with the carbon wall, recycling often would have maintained a high enough density to avoid these modes. Secondly, disruptions occurred due to strong radiation peaking, something that was uncommon (but not absent) with the carbon wall. In total 131 cases were identified making it the dominant disruption case during 2011-2012. If these would have been avoided the disruption rate would have been a respectable 5%.

Of these 131 cases 52% happened during the exit from H-mode (after the switch-off of the auxiliary heating), although often radiation peaking already developed during the main heating phase. It should be said that this analysis does not present a clear root cause for this disruption class. That is, the reasons for the strong core impurity radiation are not always clear. Often the radiation peaking is a slow process, associated to high Z impurity transport yielding impurity accumulation in the core. Although in 30% of the cases the radiation increase is much faster than transport time-scales and might be associated by a sudden in-flux of impurity material, either from an enhanced divertor source or via so-called transient impurity events [6].

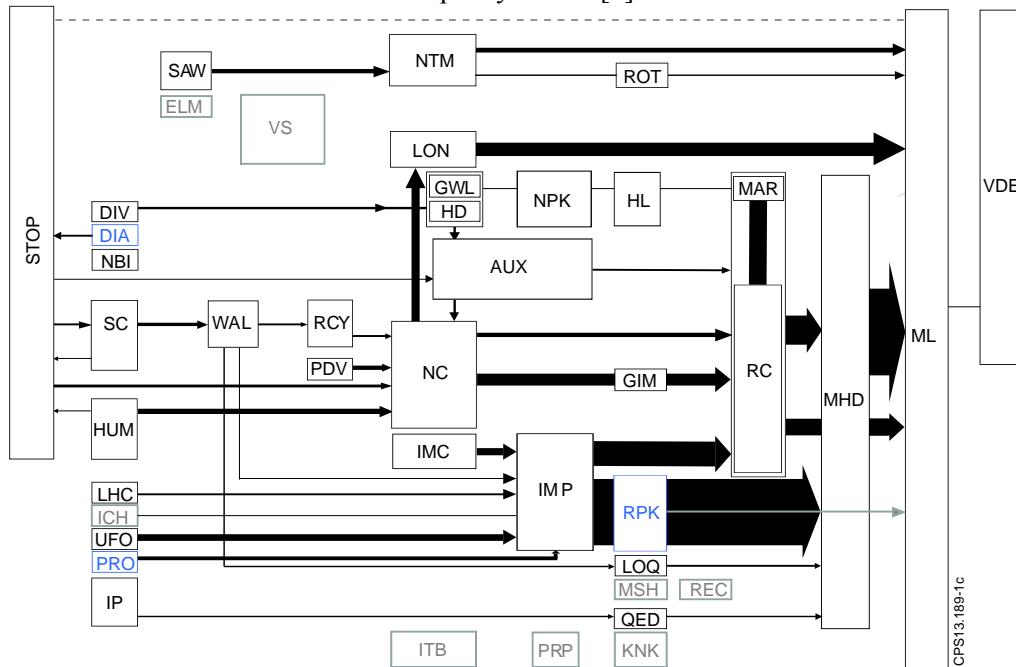


Figure 1: A schematic overview, showing the statistics of the sequence-of-events up to the (first) thermal quench for 275 unintentional disruptions at JET during the period 2011 to 2012. The width of each arrow indicates the number of cases found in the database. For comparison with the carbon wall operations, the MHD→ML arrow width is kept the same as that used in figure 4 in ref. [1]. The details on the meaning of each node can be found in ref. [1]. Those nodes in grey were absent in 2011-2012, while those in blue are new (RPK: radiation peaking, PRO: reciprocating probe, DIA: diagnostic errors)

3. Disruptions due to high core radiation

This section describes the plasma destabilization due to radiation peaking that resulted in disruptions of nearly ~15% of all H-mode pulses during 2011-2012. In figure 2, a typical example is shown of a discharge that accumulates high Z impurities and develops a strongly peaked radiation profile. In this specific case the radiation increases rapidly after about $t \sim 10.5$ s, associated with a sudden increase of the divertor impurity source. Although the total radiation never exceeds the total input power, locally in the core it affects the power balance and within ~500ms the temperature profile becomes hollow while the density profile strongly peaks. Thereafter these profiles stabilise.

On a much slower (resistive) time scale, the hollow temperature profile, starts to affect the current density, indicated by the slow reduction in internal inductance. CRONOS predictive

calculations provide information on the q -profile modification, showing the slow development of a hollow q -profile with a central q reaching $q_0 > 2$ at $t \sim 12.7$ s. This is corroborated by the frequencies of various MHD instabilities spinning up (figure 3), suggesting rational q -surfaces moving inward. These core instabilities and the value of q_0 are not the reason for the disruption and in other examples a much smaller increase of q_0 is found. These disruptions are always initiated by a low frequency, here $f \sim 2.5$ kHz, $n=1$ instability (figure 3) in the outer part of the plasma [7]. In figure 2 this mode shows a sudden growth from $t=12.8$ s, it locks, growing further, yielding a first thermal quench at $t=13.16$ s. It is thought, but not proven, that this mode is driven unstable by the broadening of the q -profile, due to current being expelled from the cold core. It suggests a relation to similar instabilities found during too fast current ramp-ups or in advanced tokamak scenarios when the edge q is close to a rational value [1]. Hence, a fast reduction of the plasma current may have a stabilizing effect on these plasmas

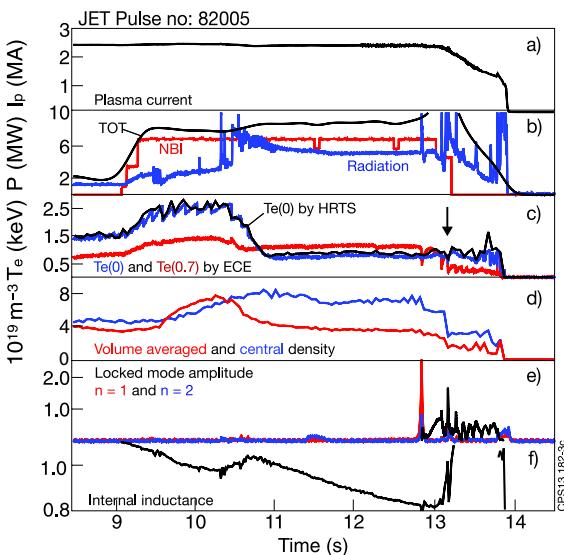


Figure 2: A summary of events of a characteristic disruption due to high-Z impurity accumulation and a peaked radiation profile. In c) the (first) thermal quench is marked by an arrow.

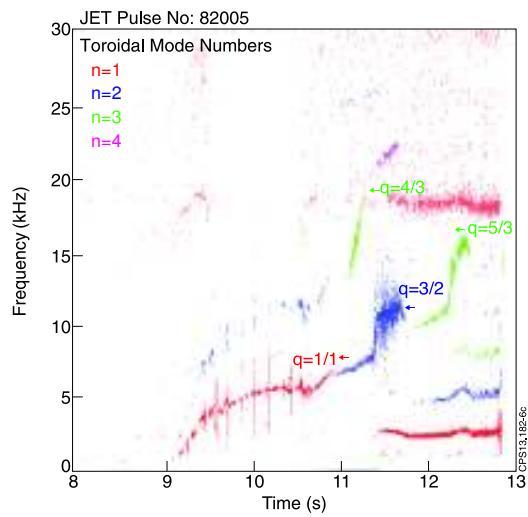


Figure 3: Spectrogram summarising the $n=1,2,3$ and 4 MHD activity in the final stages of the JET pulse 82005 (see figure 2). The triangles give the times for which CRONOS calculated the central q to increase above the respective values.

These disruptions develop slowly and provide ample warning signs for the triggering of mitigating schemes. One should note that the features described above are more common than the occurrence of disruptions (i.e. a fast current quench). The thermal quench of the actual disruption process, might have a beneficial impact on the plasma, by ejecting part of the high-Z material from the core. Hence, after the thermal quench the (core) temperature could increase significantly with the ILW, preventing a clear current quench and often yielding a soft landing [2]. A comparison of two cases is shown in figure 4, with marked drops in radiation after the thermal quench followed by an increase in the core temperature. One case results in a soft landing while the other loses shape and vertical stability control, yielding a vertical displacement event (VDE). Approximately 35-40% of all H-mode discharges developed a thermal quench as shown in figure 4, though less than half developed a fast current quench. Hence, the disruptivity and disruption rate will depend on the definition of a disruption: either only a thermal quench or at least a fast current quench. Obviously this will also complicate the assessment of disruption predictors that usually aim to detect the thermal quench [8].

Whether a fast current quench would develop after the thermal quench, or not, may depend on the post-quench stability. For example, it is more likely for high triangularity plasmas that easier develop a vertical displacement event. Furthermore, at plasma currents of $I_p \geq 2.5$ MA, ILW operation required the active mitigation by MGI that was usually triggered by the locked mode at the thermal quench [4], hence, enforcing fast current quench. The pre-emptive use of MGI therefore resulted in a higher disruptivity when operating at higher plasma currents as shown in figure 5.

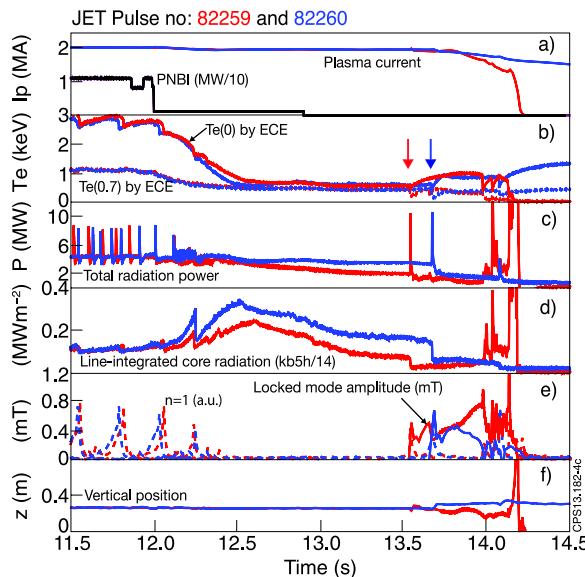


Figure 4: Comparison of two nearly identical thermal quenches (marked by arrows), one that develops a VDE and current quench while the other improves and results in a soft landing.

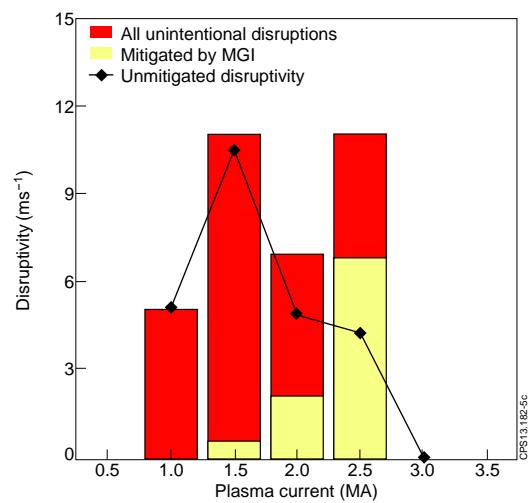


Figure 5: Disruptivity (as defined in [9]), for all unintentional and mitigated disruptions in 2011-2012 as a function of the plasma current

4. Summary

Disruptions were more frequent during the first operations with the new ILW compared to recent carbon-wall operation. The increase can be explained by the impact of the ILW on plasma behaviour requiring tuning and redevelopment of standard operation scenarios and control schemes. Further operation is expected to reduce the number of disruptions at JET. The campaigns were finalised by 2 weeks of repetitive H-mode operations, with a disruption rate of only 3.3%. Note that these numbers depend on the exact definition of a disruptive event. With the ILW, the disruptivity was found to be not only dependent on the plasma stability prior to the thermal quench, but also that thereafter. Furthermore, the pre-emptive use of MGI, triggered by the thermal quench, resulted in a higher number of (mitigated) disruptions. Operating without an active MGI mitigation system would have resulted in a lower disruption rate, although with the significant risk of melt damage at any unmitigated disruption.

The predominant disruption cause with the ILW was high core radiation due to high-Z impurities. In order to avoid these disruptions, and reduce the disruption rate, proper detection and mitigation strategies need to be developed. The root cause of this disruption class is not (yet) clearly determined. Those cases caused by a fast influx of material might suggest improvement of impurity source control. However, most showed signs of slow accumulation. Hence, it is imperative to control high-Z impurity transport in JET discharges, for example by application of core electron heating [10].

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