Heat Loads on Plasma Facing Components During Disruptions on JET
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G. Arnoux¹, A. Loarte², V. Riccardo¹, W. Fundamenski¹, A. Huber³ and JET EFDA contributors*

1EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
2ITER organisation, Fusion Science and Technology Department, Cadarache, 13108 St Paul-Lez-Durance, France.
3Institut für Energieforschung - Plasma Physik, Forschungszentrum Jülich, Trilateral Euregio Cluster, EURATOM-Assoziation, D-5225 Jülich, Germany

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ABSTRACT.
For the first time, fast measurements of heat loads on the main chamber plasma facing components (about 1ms time resolution) during disruptions are taken on JET. The timescale of energy deposition during the thermal quench is estimated and compared with the timescale of the core plasma collapse measured with soft X-ray. The energy deposition time is 3-8 times longer than the plasma energy collapse during density limit disruptions or radiative limit disruptions. This factor is rather in the range 1.5-4 for vertical displacement events. The heat load profiles measured during the thermal quench show substantial broadening of the power footprint on the upper dump plate. The scrape off layer power width is increased by a factor 3 for the density limit disruptions. The far scrape off layer is characterised by a steeper gradient which could be explained by shadowing of the dump plate by other main chamber plasma facing components such as the outer limiter.

1. INTRODUCTION
During a disruption, the thermal energy, $W_{\text{dia}}$, is quickly lost (thermal quench) leading to a fast decrease of the plasma temperature. Consequently the plasma resistivity increases and the plasma current decays (current quench). During the Thermal Quench (TQ), the energy is quickly lost mainly by conduction onto the Plasma Facing Components (PFCs).

As shown in Figure 1a, in Density Limit Disruptions (DLD) (or Radiated Limit Disruptions (RLD)), the stored energy at the TQ is typically 25% of that at full performance plasmas [1]. Part of the stored energy is deposited onto the divertor prior to the thermal quench on a timescale of the energy confinement time. However, at the thermal quench, a significant part of the remaining energy flows to the main chamber PFCs, in particular to the upper dump plate (see Figure 2a for magnetic equilibrium). This confirms recent published results [2] and is consistent with former observation [3, 4], showing that between 50% and 90% of the energy is not owing to the divertor, even in diverted configuration. During the Current Quench (CQ), part of the energy stored in the poloidal magnetic field is radiated leading to additional heat loads to the PFCs [3].

In a Vertical Displacement Event (VDE), the control of the position is lost and the plasma moves upward on JET (see Figure 2c) resulting in limited plasma until it disrupts. When the plasma displaces upward, most of the energy is expected to flow onto the upper main chamber PFCs (upper dump plate). Because of the short warning they offer and the small fraction of stored energy that can be lost gradually before the instability, the VDEs (together with other sudden loss of confinement, like ITB collapse) are of most concern regarding the damage to the main chamber PFCs [4].

The questions we address in this paper are:

- How quickly the energy flows onto the main chamber PFCs during the thermal quench?
- How is this energy distributed onto the main chamber PFCs?

An accurate description of the energy transfer from the plasma to the PFCs is necessary to assess the potential PFCs erosion/melting in future fusion devices such as ITER. JET is certainly the most appropriate machine to scale heat loads to ITER because of its size and its plasma stored energy.
The wide angle InfraRed (IR) camera installed in JET [5] and the recent upgrade of the bolometer systems for $P_{\text{rad}}$ measurement [6] allow us to answer partly to the two questions above. We compare the timescales of the energy deposition (on the upper dump plate) and of the core plasma collapse during the TQ. The poloidal heat load profiles on the upper dump plate are then analysed and scrape off layer power width is estimated. Mainly three plasma discharges are investigated with similar thermal energy (about 2MJ at full plasma performance) where the disruptions is triggered by: 1) a density limit, 2) a radiation limit and 3) a vertical displacement event (see Figure 2a-c for magnetic equilibrium around TQ).

2. MEASUREMENTS
2.1. FAST IR MEASUREMENTS AND DIAGNOSTIC ISSUES
The heat load distribution onto the main chamber PFCs is measured with a wide angle IR camera. The IR radiation measurements (see examples in Figure 3a and b) provides the surface temperature of the PFCs (the PFC is assumed to be a black body radiator). In order to measure temperatures at a time resolution of the order of 1ms, the active area of the IR detector must be reduced by about an eighth of the initial image (see white rectangles in Figure 3a and b). Such measurements can be taken only in dedicated experiments when the disruptions are purposely triggered and the camera set with optimised parameters. This has two consequences: 1) a statistical study cannot (yet) be achieved with high time resolution data, and 2) the low repetition rate of dedicated experiments on disruptions led us to make choices on the area we want to observe. The coverage of the main chamber PFCs is therefore partial. However, slow time resolution measurements with wide angle view guided us in our choices. The IR data discussed in Section 3 have a time resolution in the range: $1.1\text{ms} \leq t_{\text{IR}} \leq 1.8\text{ms}$. The exact time resolution for each pulse analysed in this paper is listed in Table 1.

The IR data will be compared in the next section with Soft X-ray measurements for timescales determination. The synchronisation between the two diagnostics must be as accurate as possible since we measure the time scale with respect to the TQ time determined from the SXR signal. The time vector of the IR signal suffers a random delay (due to the method applied for triggering the acquisition) that can be of the order of 10ms. In order to synchronise the IR time vector with other JET diagnostics, we compare the maximum amplitude induced by ELMs events on the IR and on the D$_\alpha$ line emission measurements. (Note that the D$_\alpha$ and SXR signals are synchronised). Let us consider that $t_{\alpha,i}$ and $t_{\text{IR},i}$ are the times of the i-th ELM event identified on the D$_\alpha$ and IR signals respectively. The delay correction, $t_{\text{IR}}^{\text{shift}}$, that we apply to the IR signal is then defined by:

$$t_{\text{IR}}^{\text{shift}} = \frac{1}{N} \sum_{i=1}^{N} [t_{\text{IR},i} - t_{\alpha,i}]$$

(1)

where N is the number of ELMs selected, which in our case is typically in the range: $20 < N < 40$. The times $t_{\alpha,i}$ and $t_{\text{IR},i}$ are taken at the maximum amplitude of the signals. This identification method...
leads to a limited accuracy of $t_{\text{IR}}^{\text{shift}}$ for two main reasons: 1) the maximum ELM amplitudes are not necessarily synchronised (transport times and different physics that governs the two measurements), 2) the time resolution of the IR signal is not high enough to fully resolve the time behaviour of the ELM. In Section 3, we include this limited accuracy in error bars, $t_{\text{IR}}$, defined as

$$\delta t_{IR} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ (t_{IR,i} - t_{\alpha,i}) - t_{IR,i}^{\text{shift}} \right]^2}$$

Over our pulse list, the standard deviation calculation (Equation (2)) gives us an error bar on the IR timing in the range: $0.3 \leq \delta t \leq 1.2\text{ms}$, which is lower than the time resolution ($\Delta t_{\text{IR}}$).

### 2.2. HEAT LOAD DISTRIBUTION AND SCRAPE-OFF LAYER PROFILES

Figure 3a and b illustrate the heat load distribution a few ms after the thermal quench of a VDE and of a DLD respectively. The hottest parts of the PFCs are denoted by the dark red areas (note that the images in Figure 3 do not show the temperature but the IR radiation intensity). These images present very complex patterns due to the many PFCs in the field of view. In the two cases of Figure 3 we observe a strong interaction with the upper dump plate (top of the image) and for the DLD with the inner poloidal limiters (on the left). The inner part of the divertor (bottom left of the images) seems very hot but this is dominated by surface layers that heat up very quickly with not necessarily high heat loads [7]. In this paper we will concentrate our study on the upper dump plate as it is an area exposed to significant heat loads for every type of disruptions.

The complexity of the heat load footprint on the upper dump plate can be better appreciated when the image is mapped in the $(s, \phi)$ coordinate system, where $s$ is the distance along the dump plate in the poloidal direction (taken from the edge on the high-field side) and $\phi$ is the toroidal angle. Figure 3c and d show the dump plate images, re-mapped for the two examples of Figure 3a and b respectively. In this paper, we reduce the complexity of the 2D pattern to a 1D poloidal profile by averaging the IR measurement in the toroidal direction (the averaging is applied to the IR radiation intensity, not to the temperature). The spatial resolution of the profiles at the dump plate is $\Delta s = 60\text{mm}$.

From the poloidal temperature profiles, $T(s, t)$, heat load profiles, $q(s, t)$ are computed using the non linear finite element code THEODOR [8] (non linear here means that thermal conductivity and diffusivity depend on the temperature). In our case the lateral diffusion (parallel to the surface) of the PFC is neglected since the whole disruption lasts not more than 100ms (pre-disruption phase included). The heat diffusivity of graphite is such that the temperature would diffuse on few mm after 100ms, which is much lower than the spatial resolution of the profiles ($\Delta s = 60\text{mm}$). The toroidal averaging leads to underestimating the peak heat loads, but nonetheless allows us to estimate the timescale and poloidal distribution of the energy deposition during the thermal quench. We reserve the study of the toroidal asymmetry of the heat load distribution for a later work. At first sight, the heat load pattern seems to be dominated by the geometry of the tiles rather than the power distribution in the SOL.
The question that matters in addition of the time scale of the thermal quench is how much does the scrape-off layer (SOL) broaden during the thermal quench. The SOL power width evolution, $\lambda_q(t)$, is defined by the following expression

$$\lambda_q = \frac{1}{q_{||,pk}} \int_{r=0}^{\infty} q_{||}(r, t)dt$$

(3)

where $q_{||}$ is the parallel (to the magnetic field lines) power flux into the SOL and $r$ is the outer mid-plane radius ($r = 0$ denotes the separatrix). The peak power flux is such that: $q_{||,pk}(t) = \max_r \{q_{||}(r, t)\}$. Determining $\lambda_q$ from the heat load profiles measurement requires 2 main processing steps:

- Mapping the heat load profiles at the outer mid-plane radius: $q(s, t) \rightarrow q(r, t)$
- Computing the parallel heat flux: $q_{||}(r, t) = q(r, t) \sin(\theta(r))$ with $\sin(\theta) = \hat{n} \cdot \hat{B}$ where $\hat{n}$ is the normal vector to the surface of the PFC and $\hat{B}$ is the magnetic field at the PFCx.

In Figure 2, we show magnetic equilibrium that can be used to map the poloidal profiles to the outer mid-plane radius ($r = r(s)$) and calculate the parallel heat flux. However, as $\theta$ can be very close to 0 on the upper dump plate and taking account the errors on the equilibrium reconstruction and on the IR images mapping, the calculation of $\lambda_q$ gave us satisfactory results only in one of the cases studied in this paper, and only for few time slices (see Section 3). For comparing the SOL broadening between pulses we rather use instead of $\lambda_q$ the SOL heat load width, $w_q(t)$, defined by:

$$w_q(t) = \frac{1}{q_{||,pk}(t)} \int_{r=0}^{\infty} q_{||}(r, t)dt$$

(4)

The results show however that the broadening observed during the TQ (see Section 3) seems to be overestimated when using $w_q$.

3. RESULTS

3.1. TIMESCALES OF ENERGY DEPOSITION AND PLASMA COLLAPSE DURING THERMAL QUENCH

In this section we aim to compare the timescale of the plasma collapse with the timescale of the energy deposition during the TQ. The measurement of the plasma collapse is provided by the fast soft X-ray diagnostic ($\Delta_{\text{SXR}} = 0.2\text{ms}$) as illustrated in Figure 1. A central and off axis channels (see Figure 2c for channel numbers) are shown, and by taking the maximum amplitude of all the channels: $\text{SXR}_{\text{max}}$ (thick black curve), we can follow the core plasma collapse, even during a VDE where the plasma moves. We observe consecutive crashes of $\text{SXR}_{\text{max}}$ 7 to 25ms before the thermal quench actually starts. The early crashes denote either a strong redistribution of the energy within the core plasma ($W_{\text{dia}}$ remains constant in that case) or an early loss of plasma energy (drop of $W_{\text{dia}}$ in that case) as described in [9]. The start time of the thermal quench, $t_{\text{th,quench}}$, is taken at the beginning of the last crash. In this paper, we always present time evolutions relatively to the thermal quench time: $t-t_{\text{th,quench}}$. The timescale of the energy collapse, $\tau_{\text{TQ,SXR}}$, is estimated by taking the decay time
between 90% and 20% of the amplitude evaluated at \( t - t_{\text{th,quench}} = 0 \) (see example in Figure 5a). With this definition, \( \tau_{TQ,SXR} \), was measured to be in the range: 1ms \( \leq \tau_{TQ,SXR} \leq \) 3ms on a large database of JET pulses [1]. The values found for our pulses are listed in Table 1.

Figure 4 shows a time sequence 70ms around the TQ for two different disruptions (a DLD and an RLD) and for a VDE. The main parameters (\( W_{\text{dia}}, I_p, \tau_{TQ,SXR} \)) and related JET pulse numbers are listed in Table 1. The timescale of the energy deposition, \( \tau_{TQ,IR} \), is estimated from the peak heat load, \( q_{pk}(t) \), defined as the maximum of the poloidal heat load profiles: \( q_{pk}(t) = \max_s \{ q(s, t) \} \). In the 3 cases of Figure 4, \( q_{pk} \) reaches a first maximum quickly after \( t - t_{\text{th,quench}} = 0 \). As illustrated in Figure 5a, we take that first peak as an indicator for the timescale, \( \tau_{TQ,IR} \), of the energy deposition due to the TQ. The second peak, observed for all pulses (see Figure 4), is not relevant since it is probably dominated by radiation (it roughly corresponds with the maximum of \( P_{\text{rad}} \)), and corresponds to the CQ phase. Note that even for the first peak we cannot exclude that part of the heat load is due to radiation but we will assume that it is dominated by conduction.

Figure 5b shows \( TQ;IR \) as a function of \( \tau_{TQ,SXR} \) for the 5 discharges listed in Table 1. The error bars denote the IR accuracy, as defined in Equation (2). It shows that the energy deposition time is 3-8 times longer than that of the plasma collapse for the DLD and the RLD. For VDEs, the energy deposition seems to be rather 1.5-4 times longer. The smaller ratio, \( \frac{\tau_{TQ,IR}}{\tau_{TQ,SXR}} \), for the VDEs could be explained by the fact that the vertical movement shortens the heat load deposition time on the upper dump plate. The results of Figure 5b are the first experimental confirmation that the transport in the plasma edge plays a major role on the power flux toward the main chamber PFCs during disruptions in JET.

3.2. HEAT LOAD PROFILES AND SOL WIDTH

In this sub-section, we analyse the heat load profiles evolution for the 3 pulses shown in Figure 4. The bottom plot in the figure shows the evolution of the SOL heat load width, \( w_q \), for these 3 pulses. This plot deserves two particular remarks on the data quality: 1) The gaps in the DLD data (no data points between \( t = 6.2\text{ms} \) and \( t = 1.6\text{ms} \)) and the late start of the RLD data (first data point at \( t = 1.1\text{ms} \)) are due to the very small interaction with the upper dump plate before the TQ (see \( q_{pk}(t) \)). As a consequence, the IR measurement is too weak for computing heat load profiles. Of course this is not the case for the VDE where \( q_{pk} \) becomes significant about 25ms before the TQ. 2) The magnetic equilibrium reconstructions do not necessarily converge for all the data points. The transitions from the plain lines to the dashed lines indicate the data point of the last available equilibrium, and the following data points are based on this last available equilibrium.

The evolution of \( w_q \) indicates a significant broadening of the profiles during the TQ for the DLD and the RLD. From \( w_q = 30\text{mm} \) at \( t = 0 \), they increase by a factor 1.3-2.6 during the TQ (value taken at \( t = \tau_{TQ,SXR} \)) with the larger broadening observed for the DLD and the lower one for the VDE (see values listed in Table 2). This broadening is slightly smaller than that used in the 1999 ITER Physics Basis [10, 9]. However the SOL heat load width seems to broaden well before the
The few data points we have collected before the TQ indicate that for the DLD, \( w_q = 17\text{mm} \) at \( t = -10\text{ms} \) and that for the VDE, \( w_q = 10\text{mm} \) at \( t = -23\text{ms} \). The value of 10mm is consistent with what we would expect and if we take that value as a starting reference, the profiles broaden rather by a factor 4-6.8, which is more consistent with results observed in the ASDEX Upgrade divertor [11] and used for present ITER predictions [12]. It is however lower than the broadening (a factor 8) observed on the MAST divertor [13].

In the case of the DLD we have been able to calculate the SOL power width, \( q \) for few time slices. We have selected four time slices of the \( q_{||} \) profiles that are shown in Figure 6. The \( q_{||} \) profiles in Figure 6b have been represented in a log scale, which show that for the three first time slices (\( t = -9.7, 2.0 \) and 3.2ms), the approximation of an exponential power decay is reasonable (\( q_{||} = q_{||pk} \exp\{-r/\lambda_{q}\} \)). The last profile (\( t = 7.9\text{ms} \)) is not considered as it is thought to be dominated by radiation (it corresponds to the second maximum of \( q_{pk} \)). As illustrated by the thick lines in Figure 6b, we derive \( q \) using a linear \( t \). The values of \( q \) are listed in Table 3. By comparing these values with \( w_q \), we find that the broadening is rather a factor 2.6 instead of 3.8. Note that for the VDE, we find an e-folding length of \( q = 9\text{mm} \) at \( t = -21.7\text{ms} \), which leads to a factor 3.8 broadening (if we follow the same logic as in the previous paragraph) instead of 6.8 with \( w_q \). This is a lower but still significant broadening that is again more in agreement with the value suggested in the 1999 ITER Physics basis for the divertor [10].

On the \( q_{||} \) profile at \( t = 3.2\text{ms} \) (red triangles in Figure 6b), we can actually identify two different slopes, one in the near SOL, \( \lambda_{q,\text{near}} = 34\text{mm} \), for \( 0 \leq r \leq 52\text{mm} \) and one in the far SOL, \( \lambda_{q,\text{far}} = 24\text{mm} \), for \( r \geq 52\text{mm} \). The two values are listed in Table 3 and separated by a / symbol. The lower value of \( \lambda_{q,\text{far}} \) indicates that the power gradient is steeper (by a factor 2.6) in the far SOL. We could speculate that the upper dump plate is shadowed with other main chamber PFCs like the outer limiters or the divertor, which would explain the steeper gradient [14]. The magnetic equilibrium in Figure 2a indicates that for \( r \leq 80\text{mm} \) the plasma is limited by the upper tile in the inner divertor. For \( r \geq 80\text{mm} \), the power is only shared between the upper dump plate and the upper part of the inner limiters. If one refers to the wide angle IR view (Pulse No: 69327 in Figure 3b), it suggests that the interaction is rather on the outer limiters than the outer divertor, which would be even more consistent with a steeper gradient. Anyway, this results is indicative rather than conclusive taking account the poor amount of data. Further experiments should be carried out to confirm this result.

CONCLUSION
In this paper we show the first fast measurement (about 1ms time resolution) of heat load on the main chamber PFC during disruptions at JET. Based on the heat load measured on the upper part of the main chamber, the timescale for energy deposition during the thermal quench is estimated and compared with timescales for energy loss from the main plasma, measured with soft X-rays. It is found that for density limit and radiative limit disruptions the timescale for energy deposition at the upper wall during the thermal quench is substantially longer (by a factor 3-8) than the core plasma.
collapse time. For vertical displacement events, this ratio is smaller (a factor 1.5-4).

This provides strong evidence that energy transport in the (probably) ergodised edge plasma during the thermal quench plays a major role in determining the duration of the power flux pulse.

The heat load profiles measured on the upper dump plate during the thermal quench show substantial broadening of the power footprint in agreement with previous observations made on the divertor. With a SOL power decay length of 30mm estimated 3.2ms after the thermal quench, we find a factor 3 broadening compared to the value estimated few ms before the thermal quench. Despite this broadening near the separatrix contact point with the upper wall, shadowing of the power fluxes to remote elements in the vacuum vessel by the JET inner wall and outer limiters leads to noticeable steeper gradient of the power flux in the far scrape off layer. This provides a guideline to be taken into account for the optimisation of the detailed design of the main wall plasma facing components in ITER.

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REFERENCES


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<tr>
<th>Pulse No:</th>
<th>(W_{\text{dia,\text{max}}}) (MJ)</th>
<th>(I_p) (MA)</th>
<th>(\Delta t_{\text{IR}}) (ms)</th>
<th>(\tau_{\text{TQ,IR}}) (ms)</th>
<th>(\tau_{\text{TQ,SXR}}) (ms)</th>
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<tr>
<td>69787 (DLD)</td>
<td>2.1</td>
<td>1.5</td>
<td>1.18</td>
<td>3.2 ± 1.2</td>
<td>0.4</td>
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<tr>
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<td>2.1</td>
<td>1.5</td>
<td>1.43</td>
<td>4.6 ± 0.5</td>
<td>1.6</td>
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<tr>
<td>69792 (VDE)</td>
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<td>1.5</td>
<td>1.82</td>
<td>2.0 ± 1.0</td>
<td>1.6</td>
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<tr>
<td>72925 (VDE)</td>
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<td>1.5</td>
<td>0.71</td>
<td>1.0 ± 0.3</td>
<td>1.0</td>
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<tr>
<td>73124 (VDE)</td>
<td>5.0</td>
<td>2.2</td>
<td>0.71</td>
<td>3.7 ± 0.8</td>
<td>0.8</td>
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Table 1: List of pulses covering different type of disruptions (DLD, RLD and VDE) at various thermal energies, \(W_{\text{dia,\text{max}}}\), and plasma current, \(I_p\). The 3 last columns show the IR time resolution, \(\Delta t_{\text{IR}}\), the timescales of the energy deposition, \(\tau_{\text{TQ,IR}}\) (the error bar is given by \(\Delta t_{\text{IR}}\) as defined in Equation (2)), and of the plasma collapse, \(\tau_{\text{TQ,SXR}}\), during the TQ.
Table 2: SOL heat load width, $w_q$, evaluated at the thermal quench ($t = 0$) and at the maximum heat load on the upper dump plate ($t = \Delta_T_{QIR}$) for the three disruptions shown in Figure 4.

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<td>68</td>
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<tr>
<td>69791 (RLD)</td>
<td>28</td>
<td>53</td>
</tr>
<tr>
<td>69792 (VDE)</td>
<td>31</td>
<td>40</td>
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Table 3: SOL power width, $\lambda_q$, and SOL heat load width, $w_q$, determined for the three time slices of a density limit disruption (JET Pulse No: 69787) as shown in Figure 6. Note that $\lambda_q$ corresponds to an e-folding length. In the last row, the two values of $\lambda_q$ separated by a / indicate the near and far SOL e-folding length respectively.

<table>
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<th>$t$ (ms)</th>
<th>$w_q$ (mm)</th>
<th>$\lambda_q$ (mm)</th>
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<tr>
<td>-9.7</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>2.0</td>
<td>51</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>68</td>
<td>32/24</td>
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Figure 1. Normalised plasma current, $I_p$, diamagnetic energy, $W_{dia}$, total radiated power, $P_{rad}$, line averaged density, $n_{e,av}$, and absolute intensity of SXR channels (the thick line represents the envelope of all the channels), for (a) a Density Limit Disruption (DLD) and (b) a Vertical Displacement Event (VDE). On the left, the time scale is in (s) within a time window of 8s prior to the thermal quench ($t=0$). On the right, the time scale is in (ms) within a time window of 100ms around the thermal quench.
Figure 2: Magnetic equilibrium reconstruction for: (a) a density limit disruption at $t = 100$, 0 and 4 ms around the TQ, (b) a radiation limit disruption at $t = 0$, 3 and 5 ms after the TQ (c) a vertical displacement event at $t = -104$, -11 and 1 ms before the TQ. The magnetic surfaces are at 40 and 80 mm from the separatrix at the outer mid-plane. In (c), the SXR lines of sight are superimposed.
Figure 3: Images from the wide angle IR camera during a VDE (a) and a DLD (b) The white rectangles indicate the sub-windows taken for high time resolution measurements ($1.1\text{ms} \leq t_{IR} \leq 2.3\text{ms}$). (c) and (d) show the, remapping of the upper dump plate image taken from (a) and (b) respectively in a $(\phi, s)$ coordinate system. The vertical axis is the poloidal distance, $s$, along the upper dump plate (0 is on the high field side and 800mm is on the low field side) and $s$ is the toroidal angle.

Figure 4: From top to bottom: The normalised maximum amplitude of the Soft Xray signal, the radiated power, the peak heat load measured on the upper dump plate, and the SOL heat load width, $w_q$, derived from IR measurement on the upper dump plate (Note the log scale of the vertical axis). Two disruptions: a DLD (blue +) and an RLD (green ) are compared with a VDE (red $\times$).
Figure 5: (a) Example of thermal quench timescales determined from SXR signal, $\tau_{TQ,SXR}$, and determined from the peak heat load on the upper dump plate, $\tau_{TQ,IR}$ for a DLD. (b) $\tau_{TQ,IR}$ as a function of $\tau_{TQ,SXR}$ for a DLD (Circles), an RLD (triangles) and 3 VDEs (squares).

Figure 6: (a) Evolution of the peak heat load, $q_{pk}$, around the thermal quench of a DLD. The symbols indicate the times of the corresponding profiles in (b). (b) SOL power flux profiles parallel to the magnetic field lines, $q_{||}(r)$, derived from the heat load measurement on the upper dump plate, and mapped at the outer mid-plane radius, $r$ (note the log scale). When applicable, the power e-folding length, $\lambda_q$, is illustrated by the straight thick lines fitting the profiles.