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# Transient induced tungsten melting at the Joint European Torus (JET)

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## Abstract

Melting is one of the major risks associated with Tungsten. PFCs in tokamaks like JET or ITER are designed such that leading edges and hence excessive plasma heat loads deposited at near normal incidence are avoided. Due to the high stored energies in ITER discharges, shallow surface melting can occur under insufficiently mitigated disruption and ELM power load transients.

A dedicated program was carried out at JET to study the physics and consequences of W transient melting. Following initial exposures in 2013 (ILW-1) of a lamella with leading edge, new experiments have been performed on a sloped surface (15° slope) during the 2015/2016 (ILW-2) campaign. This new experiments allows significantly improved IR thermography measurements and thus resolved important issue of power loading in the context of the previous leading edge exposures. The new lamella was monitored by local diagnostics: spectroscopy, thermography and high resolution photography in between discharges. No impact on the main plasma was observed despite a strong increase of the local W source consistent with evaporation. In contrast to the earlier exposure, no droplet emission was observed from the sloped surface. Topological modifications resulting from the melting are clearly visible between discharges on the photographic images. Melt damage can be clearly linked to the IR measurements: the emissivity drops in zones where melting occurs.

In comparison with the previous leading edge experiment, no run-away melt motion is observed, consistent with the hypothesis that the escape of thermionic electrons emitted from the melt zone is largely suppressed in this geometry, where the magnetic field intersects the surface at lower angles than in the case of perpendicular impact on a leading edge. Utilising both exposures allows to further further test the model of the forces driving melt motion which successfully reproduced the findings from the original leading edge exposure.

Since the ILW-1 experiments, the exposed misaligned lamella has now been retrieved from the JET machine and post mortem analysis has been performed. No obvious mass loss is observed. Profilometry of the ILW-1 Lamella shows the structure of the melt damage which is in line with the MEMOS predictions allowing further model validation. NRA Analysis shows a ten fold reduction in surface deuterium concentration in the molten surface in comparison to the non molten part of the lamella.

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## 1. Introduction

Tungsten (W) is among the main candidate-plasma facing components (PFC) for a fusion reactor [1] and will be exclusively used in the ITER divertor [2]. Melting is one of the major risks associated with the material and so PFCs in tokamaks like JET or ITER are designed in such a way that leading edges and hence excessive plasma heat load ( $q_{||}$ ) are avoided. It was shown during multiple experiments [3, 4] that deep W melting can

cause severe damage to components and can degrade plasma performance [5]. In 2013 experiments [6, 7, 8] were performed to assess how transient melting during ELMs might affect the operation of JET and potentially ITER. The high stored energies of which ITER will be capable means that even with all PFC edges protected, shallow surface melting can still occur under disruption and ELM transients. The impact and physics of melting need to be studied in a relevant environment. JET is

17 able to produce transients / ELMs large enough ( $> 300$  kJ per  
 18 ELM) to facilitate melting of W. Such ELMs are comparable to  
 19 mitigated ELMs expected in ITER [9].

20 In 2013 (ILW-1) a dedicated misaligned element (lamella)  
 21 was installed in one part of the bulk W outer divertor, using a  
 22 tapered exposed edge ( $0.25 - 2.5$  mm) allowing exposure to the  
 23 full parallel heat flux ( $q_{\parallel}$ ). For the 2013 experiments the con-  
 24 clusion was that plasma impact was minimal and that melt layer  
 25 motion was inline with the predicted melt layer modelling. It  
 26 also opened up questions about the interpretation of IR mea-  
 27 surements Discrepancies were apparent in the JET experiment  
 28 between the parallel heat flux required to reproduce the mis-  
 29 aligned lamella surface temperature and that derived from ob-  
 30 servations on non-misaligned surfaces. So called mitigation  
 31 factors, or perhaps more correctly, reduction factors (0.2 for  
 32 L-mode and 0.4 for H-mode [7, 8]) were derived from these  
 33 measurements by using MEMOS-3D to generate temperature  
 34 profiles based on the input heat fluxes and from them produc-  
 35 ing synthetic signals to compare with the IR data

36 In a joint international effort new experiments [10] have thus  
 37 been aimed at both further elaborating the influence of tran-  
 38 sient melting on edges and surfaces, but also to elucidate the  
 39 issue of power loading of edges [11] and IR interpretation.  
 40 A crucial point with respect to all experiments is the temper-  
 41 ature evolution of the exposed lamella and its front surface  
 42 and hence the actual relation of heat fluxes to the melt be-  
 43 haviour and melt layer motion. One particular experiment in  
 44 ASDEX Upgrade [12] was designed as companion experiment  
 45 to the JET exposures to also measure the thermo-electric emis-  
 46 sion [13, 14, 15] causing melt layer motion in fusion devices  
 47 [3, 4, 16, 17, 18, 19].

48 In this contribution the general overview of the experiments  
 49 for the ILW-2 exposure (2015/2016) will be given together with  
 50 the rational linking the old and the new exposure. Material  
 51 damage evolution, material losses and plasma impact are dis-  
 52 cussed. Issues related to the actual  $q_{\parallel}$  determination are pre-  
 53 sented and compared to the ILW-1 experiment. The presenta-  
 54 tion of the new experiments is followed by an update on the  
 55 postmortem analysis of the old ILW-1 2013 edge lamella. Here  
 56 the main focus lies on the surface characterisation and metal-  
 57 lography.

## 58 2. Setup

59 Due to power handling considerations [20] the outer diver-  
 60 tor is split up in four so-called Stacks (A,B,C,D) with A be-  
 61 ing located closest to the High Field Side (HFS). Figure 1 dis-  
 62 plays a view onto divertor modules with its four stacks. Each  
 63 Stack is split in a number of individually shaped lamellas [20].  
 64 The lamellas have a poloidal extent of 5.9cm and are 5.5mm  
 65 wide toroidally. Stack A is used for exposing the specialised  
 66 Lamellas for these experiments as operation at JET is usually  
 67 contained to the Low Field Side of the horizontal target namely  
 68 Stack C & D.

69 When considering both experiments two special lamellas  
 70 were used. a Leading Edge and sloped Lamella (Fig. 2).

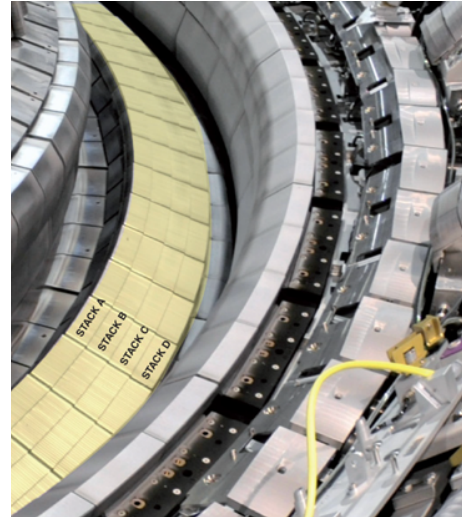


Figure 1: Modules of the JET outer divertor depicting the position of the dedicated lamella.

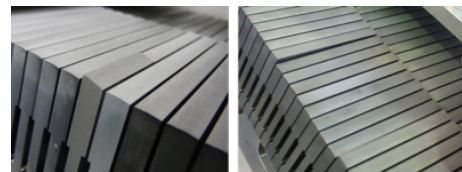


Figure 2: Dedicated lamellas for both experiments - as installed

71 The toroidal installation position of the lamellas during both  
 72 experiments was chosen to allow the existing IR diagnostics  
 73 [21, 22] to be used. For the first experiment (ILW-1) the spe-  
 74 cial lamella was designed to allow significant preheating due  
 75 to the front surface being exposed to the parallel heat flux [7].  
 76 The exposure to the parallel heat flux is achieved by producing  
 77 a chamfered leading edge of  $0.25-2.5$ mm and also lowering of  
 78 the 8 lamellas in front of the exposed edge to mitigate poten-  
 79 tial shadowing (fig. 1). This top viewing of the IR diagnostic did  
 80 however mean that during the ILW-1 exposure only the propa-  
 81 gation of the heat pulse into the lamella from the side could be  
 82 observed [7, 8].

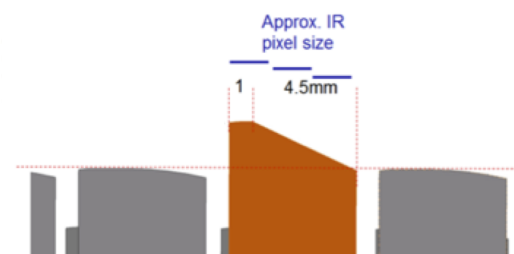


Figure 3: New IR View

83 For the second experiment the issue about IR interpretation  
 84 was taken into account. It was determined that it was necessary  
 85 to use a geometry where simple power factors are more likely to

86 apply and also a direct observation of melt zone by IR was possible. This was aimed at an easy access to the parallel heat-flux  $q_{\parallel}$ . In figure 3 the rationale for the lamella shape is given. With the resolution of the IR being in the order of one mm the aim was to allow for multiple data points along a sloped surfaces. The sloped surface (15° slope) in the bulk W outer divertor is contained to the high-field side part (2cm) of the Stack A lamella used.

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94 In order to quantitatively interpret the outcome of the experiment and also be able to follow the progress of potential melt damage several other diagnostics were employed. To be able to monitor changes to the installed lamella a high-resolution camera was installed (SBIG ST-8300 Monochrome [23]). With a resolution of  $\sim 100 \mu\text{m}$  one can clearly follow the evolution of the lamella and the surrounding areas.

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101 A direct observation of the emitted W from either evaporation or droplet emission is realized by a localised viewing cord as installed during both experiments [7]. A small observation volume covering the area of the special lamella and part of Stack A allows dedicated measurements. Based on the WI 400.88nm line one can calculate the released amount of W as demonstrated in [24, 3]. In the interest of brevity we would refer to previously published work for the previous experiments in 2013 for the details [7, 8].

### 110 3. ILW-2 Experiments

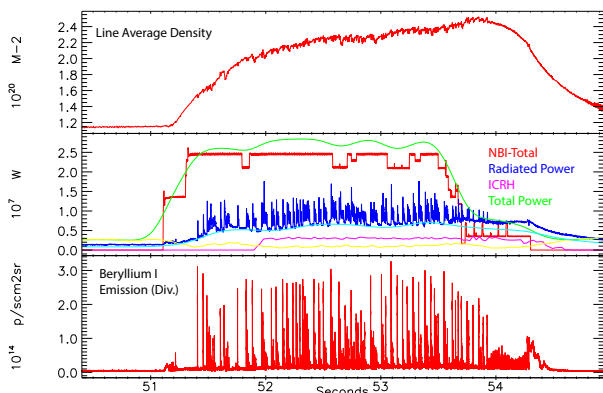


Figure 4: Pulse Overview for the ILW-2 Melt pulse #91965

111 A sequence of 3.25MA/2.7T H-Mode JET pulses with 27MW input power and regular Type-I ELMs ( $P_{ped} \sim 12\text{kPa}$ ) was used to obtain repeated, transient melting (melt depth 5-10  $\mu\text{m}$ ) of a the modified sloped W lamella.

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115 As shown in fig. 4 both Neutral Beam and ICRH were employed to reach the total heating power. In fig. 4 also traces for the line average density and the Beryllium I emission from the divertor are given. The density is reasonably stable during the exposure of the Stack A lamella between 51.5 and 53.5s. The ELM characteristic, given by the BeI signal is not as even between the individual ELMs as desired but did allow a successful experiment.

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123 In figure 5 the details for the strike-line position are given. The exposure duration of the lamella was increased to increase

the base temperature and allow transient melting by the heat-flux originating from the individual ELMs in line with the ILW-1 exposures [7]. By increasing the exposure duration the base temperature was increase following a simple  $\text{sqrt}(t)$  relation as expected.

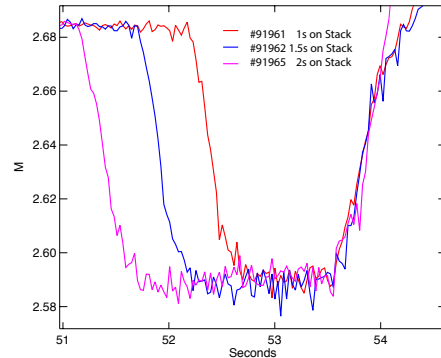


Figure 5: Exposure of sloped lamella given by strikeline position

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133 During #91965 the base temperature together with the ELM heatflux was enough to facilitate melting. Figure 6 shows one example of the HF calculated for the individual ELMS and the phase in-between ELMS.

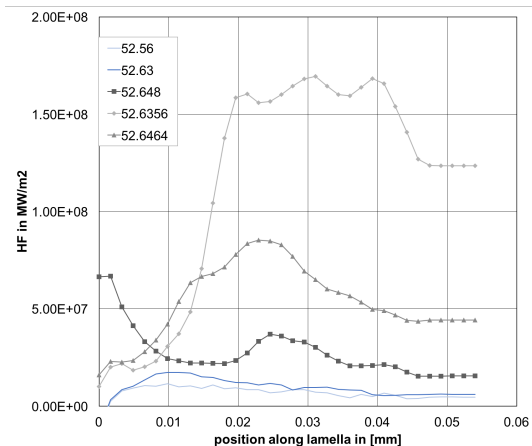


Figure 6: Heat-Flux calculated for #91965. The maximum heat-flux corresponds to the peak ELM heat-flux whereas the blue curves show the inter-ELM period.

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146 When looking at the heat-flux deposited during this particular ELM it becomes clear that the extend of the slope introduced is marginal in terms of exposure area. Only the ELM heat-load between 0 and 0.2 cm is impacting the sloped part of the special lamella.

This fact can be clearly seen also in figure 7. On the left the Infrared emission from the sloped part is clearly visible above the non sloped part. On the right hand side the lamella is shown, undamaged and damaged. When looking carefully also the fact actual melting can be determined from the IR pictures. in the bottom IR image lower emissivity from the molten mirror like surface cause the IR emission to drop and thus make the damage visible in the IR.

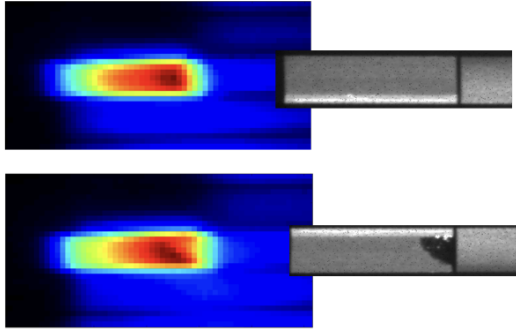


Figure 7: Lamella and Lamella Damage is given in comparison to the IR-emission footprint.

147 Topological modifications resulting from the melting are  
 148 clearly visible between discharges on the photographic images.  
 149 No run-away melt motion is observed. To elaborate a bit more  
 150 clearly the damage inflicted figure 8 is used. Differential pic-  
 151 tures are produced always subtracting subsequent images.

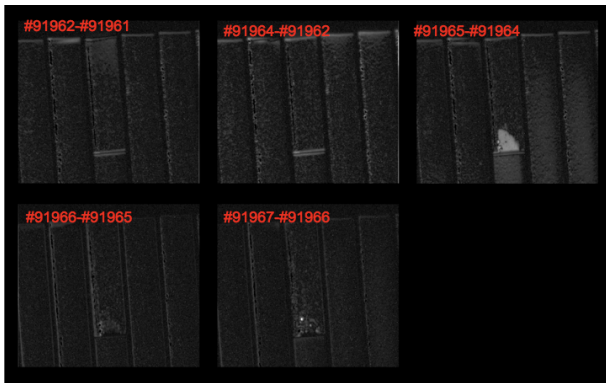


Figure 8:

152 Clearly the appearance of the melt damage during #91965  
 153 can be observed. Subsequent Pulse, with lower energy input did  
 154 only produce minor surface modification. Thus only one melt-  
 155 layer droplet produced in the ILW-1 exposures [7]. From pre-  
 156 vious experiments and modelling it is assumed that the domi-  
 157 nant forces leading to this material redistribution are related to a  
 158 thermo-electric current driven  $j \times B$  force, as seen from previous  
 159 melt experiments [13]. From recent collaborative experiments  
 160 in ASDEX Upgrade it is however assumed that the escape of  
 161 thermionic electrons emitted from the melt zone seems largely  
 162 suppressed in a more sloped or flat geometry [12, 10]. The  
 163 much lower net current then leads to a reduced  $j \times B$  force on the  
 164 melt, poloidal melt motion is considerably reduced. Instead,  
 165 other forces, probably dominated by surface tension as the melt-  
 166 layer repeatedly re-solidifies, produce the observed final corru-  
 167 gated surface topology.

169 In addition to the surface damage it is also of crucial interest  
 170 to study the impact of the melt damage onto the plasma oper-  
 171 ation. During the 2013 ILW-1 exposure droplet emission was  
 172 observed, likely due to the large acceleration of the melt.

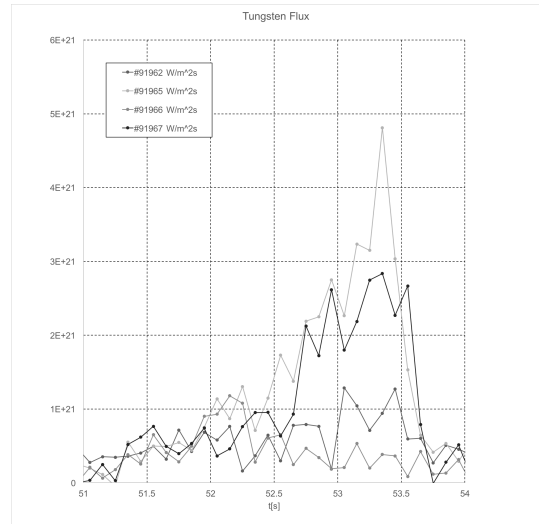


Figure 9: W emission based spectroscopic measurements on top of the exposed Lamella.

173 For the new sloped lamella no droplets impacting the plasma  
 174 were found. Only a rise in W emission (fig. 9) consistent with  
 175 evaporation was found ( $\sim 1E22 \text{ 1}/(\text{m}^2\text{s})$ ) [25]. The emission  
 176 measured is typical for evaporation fluxes at the given melt tem-  
 177 perature of 3695 K. the influx rises as the temperature increase.

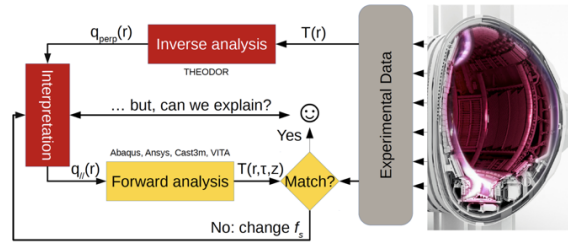


Figure 10: Scheme of forward and inverse analysis to match modelling approaches and finalise the determination of the parallel heatflux.

One of the main aims of the experiment was to tackle the so called mitigation factors required to match experiment and modelling [7, 8]. L-Mode required a mitigation factor of 0.2, while H-mode required a mitigation factor of 0.4 on the parallel heat-flux to match experimental data on temperature rise.

Fig. 10 shows the actual issues face and tackled. Typically an inverse analysis is performed to determine the perpendicular heat-flux on the impinged surface. Using this heat-flux one should then be able to calculate the temperature evolution using forward analysis based on finite element methods. A very detailed analysis of geometrical factors was undertaken [26] and also detailed forward modelling was performed [26, 27]. It was show that, at least in L-mode, the assumption of optical heat flux projection is justified and for H-Mode the measured heat-flux can be reasonably well matched to allow forward modelling of the melt geometry. Using the same model and same plasma parameters, good agreement is obtained for all three geometries, validating the assumption of optical heat load projection after accounting for observed background on



256 elling with the actual material moved, in 14 the data is pre-281  
 257 sented. Clearly the issue of reflection has limited the ability to282

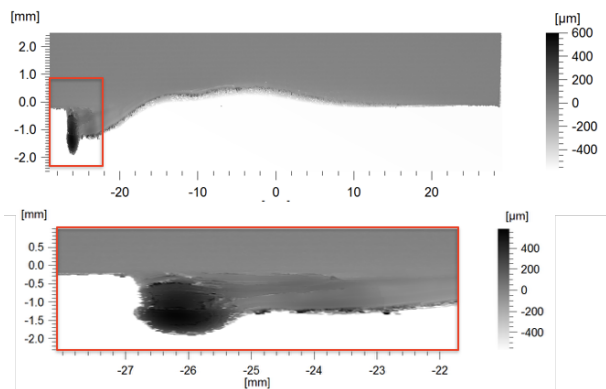


Figure 14: Profilometer Data for the melt damage.

258 measure the depth near the melt layer damage and thus more an299  
 259 outline of the melt damage is visible. The material moved is in300  
 260 line with the previous estimation of around  $6\text{mm}^3$  as determined301  
 261 in [7]. The droplet stand out 1.7 mm from the leading edge and302  
 262 contains nearly all of the material moved from the central part303  
 263 of the lamella.

264 This profile can now be compared with the Melt Layer Mod-305  
 265 elling by the MEMOS Code [13]. In fig. 15 6 consecutive melt306  
 266 pulses using the input data from 2013 were modelled in contrast307  
 to one pulse in the previous publication [7]. With the qualitative308

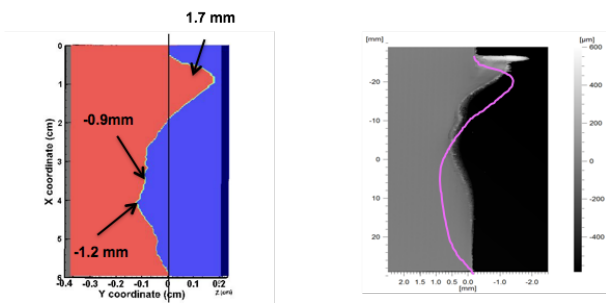


Figure 15: Updated Melt Layer Modelling after 6 consecutive pulses relevant for the 2013 exposure. (r) comparison to the actual profile measurement.

267 agreement documented before [7] the profilometry data now al-320  
 268 lows a quantitative comparison of the full melt experiment with321  
 269 the actual data. Here a deviation can be clearly observed. Work322  
 270 is ongoing to re-evaluate the heat-flux data used but also to im-323  
 271 prove the understanding of the model. Here especially also the324  
 272 experiment regarding the  $j \times B$  forces and thermionic emission at325  
 273 ASDEX-Upgrade are crucial [12]326  
 274

## 275 5. Summary

276 In conclusion it can be said that the experiment success-333  
 277 fully achieved transient melting in the desired geometry. The334  
 278 JET ELMs were of a size relevant to mitigated ELMs in ITER335  
 279 and shallow melting of sloped surfaces causes almost no visi-336  
 280 ble plasma impact. The ILW-2 2015/16 experiment improved338

significantly the ability of IR analysis. No mitigation factor is  
 required to understand the outcome of the experiments in L-  
 Mode and the mitigation factors have mainly been identified as  
 systematic uncertainties in the calculation. The ILW-2 2015/16  
 experiment did show that when exposing a sloped surface instead  
 of a leading edge far less melt motion is visible - here the  
 reduced effect of the  $j \times B$  forces can be seen as main driver.

From the SEM possible during the post-mortem analysis of  
 the ILW-1 2013 Lamella it can be seen that the droplet produced  
 might eventually come off and potentially disrupt the plasma if  
 exposed to future heat-flux. It is observed that the surface structures  
 seen on the droplets are partly reflected in the grain structure.  
 A weight loss is not apparent from the postmortem measurement  
 but can be expected as droplets were released during the 2013  
 experiments. Melting impacts the hydrogen retention - D is  
 driven out of the 2013 lamella when compared to the non molten  
 surfaces. From the EDX map of the flat lamella it is observed that  
 Stack A as expected shows deposition of Be, C and other light  
 elements. During the post mortem analysis of the ILW-12013  
 lamella a comparison with profilometry and MEMOS showed only  
 small discrepancies

Obviously ITER has the potential to produce similar damage  
 over the whole area of the strike point. The number of droplets  
 produced could therefore be much larger especially for leading  
 edges. Whether or not this would be sufficient to disrupt an  
 ITER plasma cannot be simply concluded but the JET results  
 do provide the basis for such a calculation. The JET results are  
 directly relevant to what would happen in the case of molten  
 surface. The JET results also suggest that provided such an  
 event is detected in ITER and is not repeated too many times  
 such that large droplets build up, there would be no risk of a  
 disruption

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 herein do not necessarily reflect those of the European Com-  
 mission

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