Melting of Tungsten by ELM Heat Loads in the JET Divertor


JET EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK
a CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
b Forschungszentrum Jülich, Jülich, Germany
c Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
d Association EURATOM-IPP.CR, AS CR, Za Slovankou 3, 18221 Praha 8, Czech Republic
e Max-Planck-Institut für Plasmaphysik, D-17491 Greifswald, Germany
f Ecole Central Lyon, Lyon, France
g Karlsruhe Institute of Technology, P.O.Box 3640, D-76021 Karlsruhe, Germany
h Laboratory for Plasma Physics, Ecole Royale Militaire/Koninklijke Militaire School
i CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
j Division of Fusion Plasma Physics, KTH, SE-10044 Stockholm, Sweden
k ITER Organisation, Route de Vinon sur Verdon, 13115 Sain-Paul-lez Durance, France
l See the Appendix of Romanelli F et al 2014, Proceedings of the 25th IAEA Fusion Energy Conference, St. Petersburg, Russia

E-mail contact of main author: guy.matthews@ccfe.ac.uk.org

Abstract. The original goals for the JET ITER-like Wall included the study of ELM induced tungsten melt events and their impact on plasma operation [14]. The recent decision by the ITER Organization to begin operations with a full tungsten divertor has increased focus on the issue of transient induced melting and its consequences. Transient tungsten melt experiments were performed in JET using a dedicated divertor module and a sequence of 3MA/2.9T H-Mode pulses with an input power 23MW, a stored energy of ∼ 6MJ and regular Type I ELMs at ∆WELM =0.3MJ. JET has sufficient thermal stored energy to produce ELMs large enough to produce transient melting of tungsten [2, 6, 7]. By moving the outer strike point onto a dedicated leading edge the base temperature was raised within ∼ 1s to a level allowing transient ELM-driven melting during the subsequent 0.5 s. Almost 1mm (∼ 6mm3) of W was moved by ∼ 150 ELMs within 7 discharges. Although significant material losses in terms of ejections into the plasma were not observed, there is indirect evidence that some small droplets (∼ 100µm) were released. The impact on the main plasma parameters was minor and no disruptions occurred. The evaporation rate determined from spectroscopy is 100 times less than expected from steady state melting and is thus consistent only with transient melting during the individual ELMs. Analysis of IR data and spectroscopy, together with melt modeling using the MEMOS code [22, 4] also show that transient melting is the main process. These experiments provide unique experimental evidence for the absence of significant melt splashing at transient events resembling mitigated ELMs on ITER and establish a key experimental benchmark for the MEMOS code simulations being used to predict transient shallow melting of the ITER tungsten monoblocks.

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1. Introduction

Until the autumn of 2013 the ITER divertor strategy was to start operation with carbon fibre composite (CFC) tiles at the strike points with tungsten (W) baffles and move to an all-W divertor prior to the nuclear phases in order to minimise tritium retention [3]. This approach was designed to benefit from years of tokamak experience with carbon plasma-facing components (PFC) and to reduce the risks of melt damage in the early (non-active) years of operation when mitigation strategies must be developed against plasma transients [13] (disruptions and Edge Localized Modes (ELMs)). The ITER Organization (IO) proposed in 2011 to eliminate the first CFC-W divertor and begin operations with a full-W variant, to be used until well into the nuclear phase [3]. After a two year period of studies both at the IO and elsewhere the ITER Council (IC) decided in Nov. 2013 to accept the proposal for a full-W start. The JET results played an influential role in this decision.

The use of tungsten imposes constraints on divertor power-handling due to possible melting by uncontrolled thermal loads. The resulting damage may hamper subsequent operation due to reduced thermo-mechanical resilience of the re-solidified surface and can also lead to increased erosion and thus increased radiation cooling of the core plasma by influx of high-Z impurities in the form of vapour, droplets or particles [6,8]. Melting by transients such as ELMs or disruptions has been a particular concern due to the difficulty of guaranteeing the mitigation strategy particularly at the start of ITER operation [13]. For this reason there was a careful evaluation of the risks associated with operating ITER with a full tungsten divertor and the results presented here provided the most relevant experimental evidence.

Existing laboratory and tokamak melt experiments have shown a range of behaviour from plasma pressure driven melt motion [9,10,11] causing severe splashing to more benign, but deep melt exposures [6]. Of the current operating tokamaks, JET is able to produce the largest transients and therefore the best place to study transient melting of W, and even in this case, the W component had to be deliberately engineered to provide an edge on which the power loading can be concentrated. These dedicated melt experiments were the top research priority for the JET 2013 Scientific Programme [14].

2. Experimental Setup in JET

The horizontal outer divertor target of JET comprises 96 tile assemblies (Fig. 1) each consisting of 4 stacks of 24 bulk W “lamellas” (Fig.1). The top surface of each lamella is shaped [20] in order to shadow the leading edges of neighbouring units due to the gaps (typically 1mm) between lamellas. Each lamella is 58mm long (in the radial direction) and typically 5mm wide (in the toroidal direction).

The heat load, $q_n$, onto the normal divertor targets is a local projection of the heat flux, $q_\parallel$, flowing along the magnetic field lines in the scrape-off layer. Due to the low poloidal field in that region, magnetic field lines strike the targets at grazing angles to the surface (typically $\theta = 1 - 4^\circ$) such that $q_n = q_\parallel \sin(\theta)$. An exposed leading edge, perpendicular to the target surface is expected from simple geometric considerations to receive a heat load ($q_s$) typically 15 to 60 times higher ($\propto 1/\tan(\theta)$) than $q_n$. The JET divertor was designed to avoid leading edges.

For the purpose of our experiments a specific tile of the horizontal, outer divertor target was modified in order to introduce a leading edge (Fig. 1) and thereby expose a W surface in JET to transient power densities relevant to the standard (i.e. not misaligned) divertor surface in ITER during an unmitigated transient. This is, however, a compromise since the JET
experiment was carried out at normal rather than grazing incidence. This is unavoidable since a full performance ITER pulse will have \( \sim 60 \) times the thermal stored energy when compared to the plasmas used for our experiment.

![Image of special bulk tungsten tile module prior to installation and schematic of heat deposition on the exposed edge and top surface.](image1)

**FIG. 1** **Top left:** Special bulk tungsten tile module prior to installation. **Bottom left:** Schematic of heat deposition on the exposed edge and top surface (\( q_{||} \) is the heat flux parallel to the magnetic field). **Right:** The IR system views the special lamella from the top and has only 4 pixels over its 5.5mm width so cannot resolve the thermal gradient due to the side component of the heat flux \( q_s \). Thermal modeling and a synthetic diagnostic are used to derive the true profile [7]. In this example the peak inter-ELM temperature is reconstructed at the end of a typical melt pulse, Fig.3.

### 2.1. Diagnostics

The vertical view of the special lamella from the top of JET was ideal for the high resolution imaging system used to monitor the melt damage intershot. This side view allowed it to measure erosion of the lamella surface with a spatial resolution of around 0.1mm, Fig.4. However, the infra-red camera used in the experiment shared the same sight line and its 1.7mm resolution was insufficient to resolve the temperature gradient into the surface, Fig. 1.

This meant that the true temperature had to be recovered using a 3 step approach [7]:

1) We use IR data from a standard lamella to infer incident heat flux parallel to the field lines.

2) The results of step 1 are used to generate a fully time dependent heat load distribution \( q_s \) and \( q_n \) on the special lamella, which is the input for the MEMOS code [4, 12, 15, 22] which then calculates the evolution of the 3D temperature distribution in the special lamella.

3) We validate the MEMOS results by generating a synthetic IR measurement and comparing it with the real measurement. An example of the measured and synthetic data is shown in Fig.1 demonstrating good agreement between model and measurement for the peak inter-ELM temperature during one of the melt pulses. This agreement is only possible if a mitigation factor \( f_s \) is applied to reduce the geometrically derived \( q_s \). The value of \( f_s \) required in H-mode is 0.4 and in L-mode 0.2.
4) Introduction of an *ad-hoc* reduction factor, $f_s$, for the power load on the side of lamella seems unsatisfactory but has been validated by creating an independent synthetic diagnostic from the MEMOS output for the WI emission (400.88nm)[18] and Planck radiation measured by an absolutely calibrated visible spectrometer. Both the implied tungsten evaporation rate and wavelength dependence of the Planck radiation provide a peak temperature consistent with the result derived from step 3 which is IR camera based [6,7].

### 2.2. Plasma conditions

A series of seven 3MA/2.9T pulses was used for the melt experiment with combined heating power of 23MW, Fig.2. The resulting H-modes had an ELM frequency of ~30Hz and ELM energy of 0.3MJ resulting in an inter-ELM $q_{||} \sim 500$MWm$^{-2}$ and $q_{||} \sim 3000$MWm$^{-2}$ during ELMs (#84778). The inter-ELM temperature on the special lamella derived by the methods described above was just below the bulk melting temperature (3422°C) at the end of the pulse Fig.3. Thermal response of the special lamella and the temperature history seen on standard (reference) lamellas was very reproducible; Fig. 2 and no disruptions were observed. Note that the peak temperature during ELMs reconstructed by MEMOS and the procedure described in section 2.1 is $\sim 4000^\circ$C, Fig.3 i.e. much higher than the value seen in the raw data due to steep thermal gradients into the side of the lamella during the fast ELM heat pulses.

![FIG 2.](image1)

**FIG 2.** Left: Input power from ICRH and NBI plus radiated power and heat flux on a Stack A standard lamella from IR vs time for a typical melt pulse. Right: Special and standard (Ref) lamella temperatures from IR for a series of 4 pulses showing the high reproducibility.

![FIG 3.](image2)

**FIG 3.** Maximum temperature measured by IR on the Special Lamella in Stack A and the actual temperature from MEMOS. Assuming $f_s=0.4$ provides the best fit to all diagnostic data (Section 2.1).
3. Results

3.1 Melt behaviour

The melt damage seen after the final pulse above the melt threshold in a series of 7 similar pulses can be seen in Fig. 4a. Fig. 4b shows the first pulse where erosion was noticed. Between 0.15mm and 0.3mm are removed per pulse corresponding to ~7µm per ELM. Peak erosion is not always in quite the same place and from the third pulse on a droplet built up on the right hand end in layers, pulse by pulse. We estimate that about 6mm³ of W was moved and that the volume of the large droplet seen on the right hand side of Fig. 4a is roughly similar (exact balance to be measured during post-mortem analysis).

![Image of melt behaviour](image1)

**FIG 4.** a) Appearance of the special lamella after all exposures (#84785) and geometric estimation of material removed. b) Erosion seen after the first pulse in the melt series #84724. c) Surface modification predicted by MEMOS with input from experimental IR data (2.1) with $f_s=0.4$[15,22].

The melt layer motion is well reproduced by the MEMOS code using time dependent IR data from #84779 as input but with mitigation factor $f_s=0.4$ applied as described in section 2.1. MEMOS shows that the dominant force on the melt is current flow due to thermionic emission leading to $j\times B$ forces on the melt layer. The code also suggests that vapour shielding may contribute to the heat load mitigation in H-mode [22].

![Image of transient tungsten sources](image2)

**FIG 5.** Transient tungsten sources and their impact on plasma radiation losses. Top frames show central soft X-ray emission, middle show VUV emission (~5nm) from W lines at mid radius and bottom the total input power and total radiated power. The pulses are Left: Laser blow off #85284. Right: Droplet ejected during the transient melt experiment #84779.
3.2 Plasma impact

Experiments in other tokamaks have shown that bulk melting of tungsten can eject large droplets leading to disruptions [6]. In JET, no droplets were directly observed leaving the special lamella due to the ELM induced melting but a few small spikes were seen in some pulses on total radiated power, VUV tungsten lines and soft X-ray which are similar to those produced by laser blow off of W, Fig. 5. Analysis of this data suggests a droplet diameter of ~0.1mm i.e. similar to those seen on the left hand side of the special lamella in Fig. 4a. These droplets were too small to cause a disruption.

4. Discussion

4.1 Heat load mitigation factor

The applicability of geometric factors for divertor heat load calculations is well established for grazing angles [5] but not for edges at normal incidence. Heat load mitigation was expected due to finite ion Larmor radius effects but calculations with the same PIC code used for ITER [16] have shown that this is a relatively small effect even during ELMs (equivalent to t_s~0.8) for the JET cases [17] and cannot explain t_s=0.4 in H-mode and certainly not t_s=0.2 in L-mode. Turbulent effects due to the specific geometry of the JET experiment or localized recycling [21] may offer alternative explanations but so far this is only speculation. Similar anomalous behaviour has been reported at a misaligned limiter tile edge in Tore Supra [19].

4.2 Melting by ELMs or bulk melting?

Given how close we needed to get to bulk W melting to get strong erosion by ELMs, there has been a concern that bulk rather than transient melting may have occurred. There is however strong evidence against such an idea. The main points are that bulk melting would almost certainly melt the whole corner of the lamella in a single pulse [1] (this has been shown by MEMOS), the time averaged W evaporation rate would be orders of magnitude higher than we observe [1] and finally the melt damage would be centred on the point of peak inter-ELM temperature rather than peak ELM temperature as we observe, Fig.6.

FIG 6. Comparison of melt damage with temperature evolution of a typical ELM as observed by IR on a standard shape reference lamella. The peak temperature during the ELM matches the melt distribution while the peak inter-ELM temperature position is further inward.
4.3 ITER implications

The most important result for ITER is that the JET experiments show that MEMOS simulations give a good match to the experimental data when consistent thermal data is used as input. This means that the transient melt layer modelling used by ITER to help justify a full W first divertor has now been benchmarked in a tokamak. The melt layers in JET are both thin and relatively stable as expected also in ITER, although the force balance is will be different [22]. In JET, only a few small droplets were detected in the core plasma in each pulse and most of the molten material moved into the private region along the lamella. Post mortem analysis will take place after removal of the test module during the coming shutdown. Plasma impact of similar transient melts in ITER will depend on the total areas involved and whether the main plasma is sensitive to high Z impurity accumulation.

5. Summary and Future Work

A dedicated experiment in support of ITER has been performed in JET to help address the uncertainties associated with predictions for the impact of ELM-induced transient W melting in ITER. The JET ELMs were of a size relevant to mitigated ELMs in ITER and produced very reproducible W melting and melt motion on a well characterized misaligned edge deliberately engineered into one module of the JET bulk W outer divertor. During a series of 7 consecutive pulses ~ 150-300µm of W was removed from the exposed edge per pulse (~ 7µm per ELM). This ELM induced melting produced an enhanced W source, including occasional expulsion of small droplets (~100µm) which do not significantly impact the main plasma. MEMOS analysis provides a close match to the observed melt layer motion and shows it to be dominated by j×B forces from thermoelectric emission, implying significant current flow during ELMs originating from the hot metal surface. Due to the magnetic geometry, the melted material moves predominantly into the private region out of the main heat flux area. The physics determining the size of the W droplets should be machine size independent whereas screening and resistance to the effects of W radiation improves with machine size hence specific calculations for ITER are still required.

An unexpectedly large mitigation of the heat-flux impinging on the exposed edge was observed in the JET experiment and suggests that under some circumstances at least, such misalignments are less vulnerable to melt damage than had been previously thought. The physics of this mitigation are not yet understood. Larmor-radius smoothing, local transport as well local recycling and particle as well as energy reflection need to be further investigated.

A new melt transient experiment is being planned in JET for 2015 based on design like the one shown on the right, Fig.7, with a surface angle ~15°. This is intended to:

- Allow direct temperature measurement during an ELM induced melt event.
- Test applicability of the geometric power factor in a simpler better diagnosed geometry.
- Study ELM induced melt motion when the magnetic field is at an acute angle to the surface plane – i.e. more ITER-like.

Fig. 7 New melt test lamella concept
6. References


[22] B.Bazylev et al., Modelling of Melt Damage of Tungsten Armour under Multiple Transients Expected in ITER and Validations Against JET-ILW Experiments, TH/P3-40 this conference