Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 1006–1010
journal of nuclear materials
www.elsevier.com/locate/jnucmat

First measurements of main chamber power load during JET disruptions

P. Andrew [a,*], A. Alonzo [b], G. Arnoux [c], E. Gauthier [c], J.I. Paley [d], V. Riccardo [a], JET EFDA Contributors [1]

[a] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK*
[b] *Association EURATOM-CEIMAT, Madrid, Spain*
[c] *Association EURATOM-CEA Cadarache, 13018 St. Paul lez Durance, France*
[d] *Plasma Physics Group, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK*

Abstract

Interaction of the plasma with the main chamber is observed with infrared thermography during disruption of JET plasmas. Taking into account the effect of surface layers on some of the limiter surfaces, we make the first estimates of the energy density deposited on the walls. Assuming toroidal symmetry and extrapolating over the whole JET vessel gives a good energy balance with the pre-disruption stored energy.

PACS: 52.55.Fa

Keywords: Disruption; First wall; JET; Power balance; Thermography

1. Introduction

Disruption of the plasma in a divertor tokamak can lead to heat being deposited outside the divertor. Firstly, in vertical displacement events (VDE's) the control of the plasma vertical position is lost prior to disruption. This results in a limiter plasma at the moment the plasma actually disrupts. Secondly, during the plasma current decay, stored magnetic energy is radiated over the whole vessel. Finally, energy balance studies of the JET disruptions [1] have indicated that in disruption of plasmas with an internal transport barrier (ITB), the thermal energy cannot be accounted by the measured power flow to the divertor. Because conducted power in JET could previously only be measured in the divertor (by thermocouples [2] and IR thermography [1]), it may be that conducted power to the main chamber is responsible for the apparent deficit.

JET has recently installed an IR viewing system [3] allowing a view of both the divertor and main chamber. In this paper we present the first observations of disruptions with this system.

* Corresponding author. Fax: +44 1235 464535.
E-mail address: pla@jet.uk (P. Andrew).
[1] See Annex of J. Pamela et al., Fusion Energy 2002 (Proc. 19th Int. Conf. Lyon, 2002), IAEA, Vienna.

0022-3115/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.jnucmat.2007.01.285

2. Results and discussion

2.1. Vertically displaced plasma

JET plasmas have vertically elongated cross section making their vertical position unstable. Occasionally position control is lost and the plasma moves typically 50 m/s vertically either up or down, and simultaneously shrinks in cross section. During collision with the top or bottom of the vessel, currents flow through the vacuum vessel resulting in large forces; typically 100's of tonnes in JET. The vessel force depends on the plasma configuration, i.e. the current in the poloidal field coils, and in JET different configurations are tested for the vessel forces produced by a VDE. Fig. 1 shows the visible and IR images during the disruption of a plasma which was intentionally allowed to become vertically unstable in order to establish the maximum safe plasma current for the pre-disruption plasma configuration. Although the visible and IR images suggest a similar interaction pattern, it is noted that the two cameras view from diametrically opposite toriodal locations.

From the infrared image it can be seen that there has been heating of the protection tiles at the top of the torus up to about 600 °C. The maximum temperature may be higher depending how soon the first IR camera exposure occurred after the disruption. Some of the midplane limiters are also significantly above the 200 °C starting temperature which is not a result of the disruption; these surfaces are still cooling after the start up limiter phase.

When the full view of the IR camera is used, the frame rate (up to 100 Hz) is too slow to deduce the power density evolution, $q(t)$, during the disruption, however it is possible to deduce the total energy density $q\Delta t$ deposited from the temperature, T, cool down after the disruption. This was done by applying the equation for a one-dimensional analytical formula

$$\Delta T = q[\surd(\Delta t + t) - \surd(t)]/k$$

for the response to a rectangular heat pulse [4] to the surface averaged temperature. The material parameter k is given by $k = \surd(\pi\lambda\rho c_p/4)$, where λ, ρ and c_p are, respectively, the thermal conductivity, density and heat capacity. For the CFC tiles in JET, k is 9700 or 20400 $\mathrm{Wm^{-2}\,s^{1/2}}$ depending on the orientation of the carbon fibres. For the ~3 s period over which the fit is applied lateral diffusion (~0.01 m^2/s) may be neglected, and the fit only depends on a single parameter: the energy density deposited. Assuming toroidal symmetry and applying the result to the whole of the upper protection

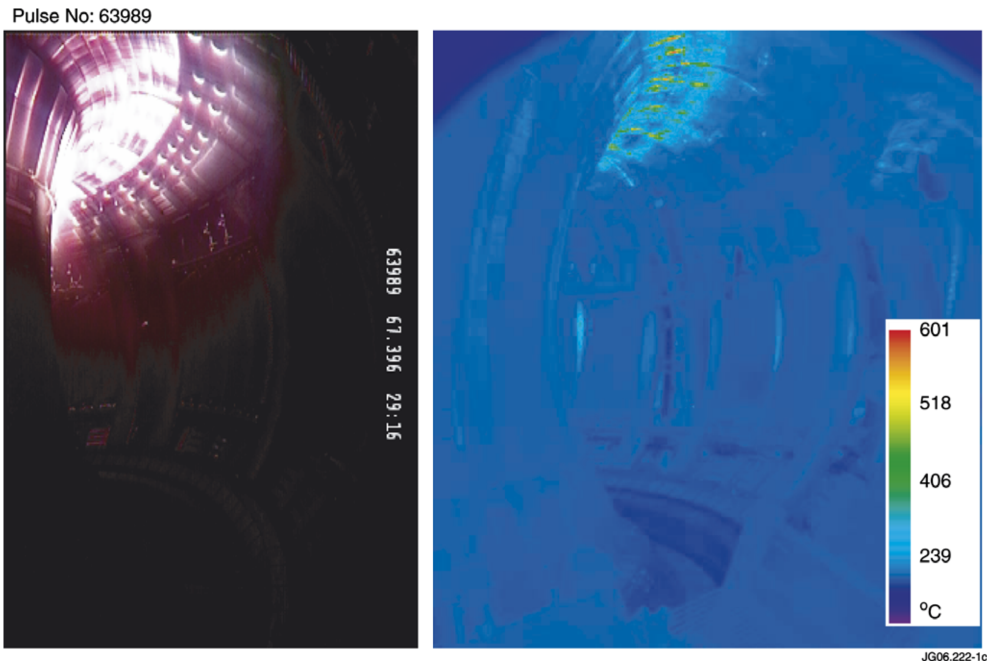

Fig. 1. Visible (left) and infrared images during the disruption of a vertically displaced plasma.

tiles, of which we only see a 60° toriodal section, gives 1.1 MJ energy deposited on these tiles.

The 1.1 MJ of energy to the top tiles is significantly larger than the 0.5 MJ pre-disruption stored energy. It is also the case, however, that the 0.6 MJ of the total radiated energy falls short of the magnetic energy released during the disruption: 1.2 MJ. From the plasma configuration during the disruption, it is estimated that 20% of the radiated power might fall on the top tiles. Taken together, it appears that there is good balance between pre-disruption stored energy $0.5 + 1.2 = 1.7$ MJ and the energy deposited on the walls $0.6 * 80\% + 1.1 = 1.6$ MJ, but that some of the magnetic energy has been conducted instead of radiated. In contrast, a previous study [1] found that 94% of the magnetic energy released could be account as radiation. This study, however, covered a range of magnetic energy released between 5 and 20 MJ. It is reasonable to expect that contact with the walls during the current decay would result in some wall heating. If this were at the level of 1 MJ, it would be consistent with our present result, and have been an negligible offset in the previous study.

2.2. Disruption on inner wall

Fig. 2 shows visible and IR images during the disruption of an ITB diverted plasma, having 2.5 MJ thermal energy prior to disruption. The pre-disruption configuration is lower single null with the strike points in the corners of the divertor. The IR image is actually the difference image between the frame before and after the loss of thermal energy. As with previous observation of ITB disruptions, the thermal energy loss cannot be accounted as deposited heat in the divertor. The present plasma, however, is distinctly different in the evolution of the stored energy and plasma current. The stored energy is released slowly, over 40 ms, and the plasma current decays 60 ms later. This delayed current decay is helpful in making a clear distinction between the release of thermal and magnetic energy since, again, we are using the camera in its slow, wide-angle mode.

The visible camera images are often corrupted during a disruption, as can be seen in the right side of the image where there is a line synchronization problem. It is unclear whether the green light indicates impurity radiation, or if it is an artifact of the way in which the camera saturates. What can be clearly seen, however, is that unlike the IR image, there does not seem to be any sign of interaction with the inner divertor shoulder. Since the two views are from opposite sides of the torus, this might indicate toroidal asymmetry in the interaction pattern. There have been other disruptions which have shown interaction at inner divertor shoulder with both cameras (i.e. at both sides of the torus).

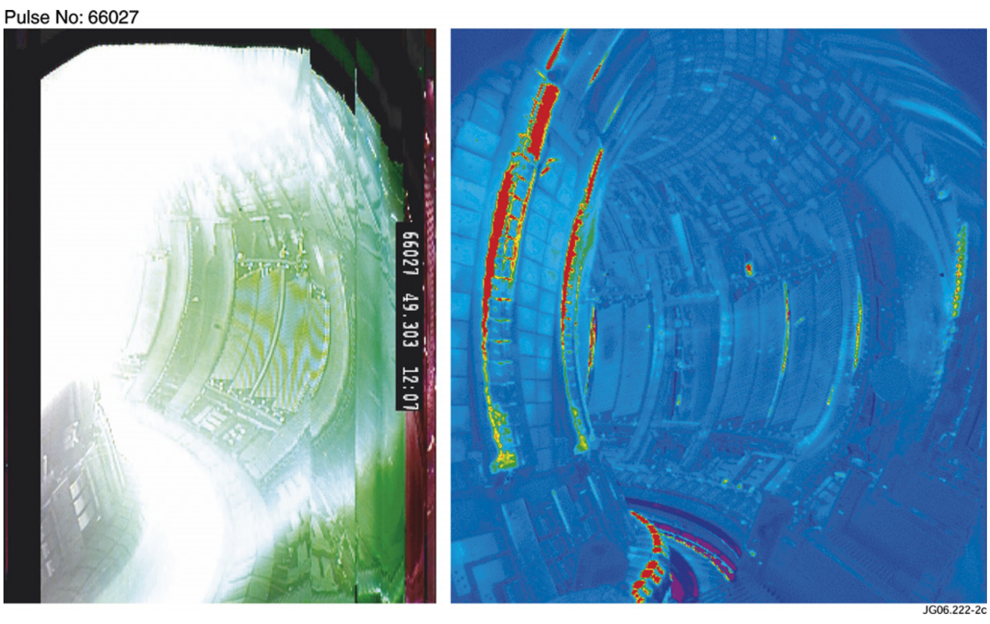

Fig. 2. Visible (left) and infrared images during the disruption of a plasma contacting the inner limiters.

The temperature footprint of this disruption is characteristic of most JET disruptions observed with the wide angle IR system. The hottest surfaces are on the sides, of the inner limiter tiles, and on the inner divertor shoulder tiles. Both these regions are known to be areas of deposited surface layers, which experience much higher surface temperature rise per unit power compared to layer-free regions [5–7].

The effect of the layer on the inner divertor shoulder is clear. Firstly, one of the tiles in the view is relatively cold compared to all the others, which is also the case during steady state divertor plasmas. This is a tile which was replaced during the last major shutdown, and therefore has not had time to build up a significant layer like the neighboring tiles. Futhermore, thermocouples in these tiles with surface layers reveal the bulk temperature of the tile is inconsistent with the surface temperature unless there is excess thermal resistance at the surface.

As for the inner limiter tiles, the regions of surface layers can also be seen during limiter discharges. Fig. 3 shows the temperature profile across a single limiter tile during and a few seconds after plasma contact. The profile after the heating is as expected given the tile geometry, but the profile during heating has an extra peak on top of this, corresponding to the brightest regions in Fig. 2. The time between the profiles, 5 s, is too small for the heat to have smoothed out by lateral diffusion (~0.01 m^2/s).

Fig. 4 shows the time evolution of the temperature for the case of the disruption both on and off the region affected by a thermally resistive surface layer. Off the layer, it is possible to model the temperature with the simple model used for the upper protection tiles. On the layer, however, the time evolution of the temperature, characterized by several seconds of cool down time for a few ms heat pulse, cannot not be describe by the layer-free model. This temporal behavior was previously noted for JET inner divertor tiles [7] and was modelled as a layer of finite thermal mass which was in poor thermal contact with the bulk, therefore taking much longer (5 ms) to cool down than to heat up (<1 ms). The present layers on the limiter, however, are taking seconds to cool down, so they would have to be much more resistive and/or have a much higher heat capacity (e.g. thicker).

For the purpose of estimating the heating of the inner limiters, the regions affected by surfaces layers are omitted, and the energy density on these regions is obtained by interpolating from the surrounding layer-free areas. Adding over all the limiter tiles in the IR view (2 out of 16), and extrapolating to the full torus gives ~2 MJ of energy deposited on the inner limiter during the loss of the plasma thermal energy, ~2.5 MJ.

The rapid collapse of the thermal energy during a disruption causes and inward shift of the plasma

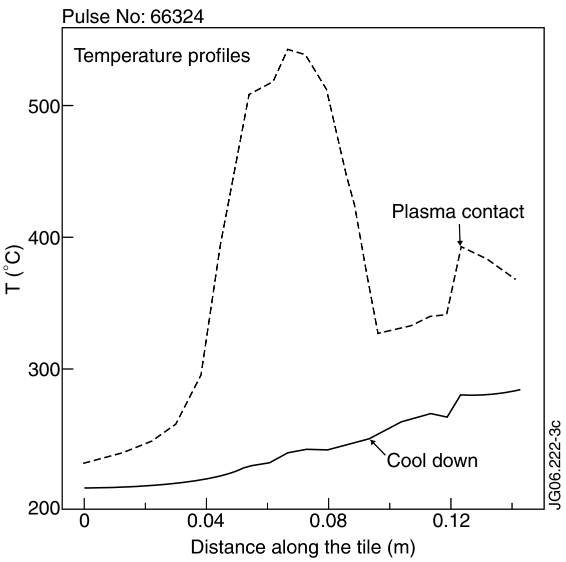

Fig. 3. Temperature profile across a single limiter tile during and after contact with an auxiliary heated limiter plasma. The tile is inclined so that the plasma is closest at the right hand side of the figure.

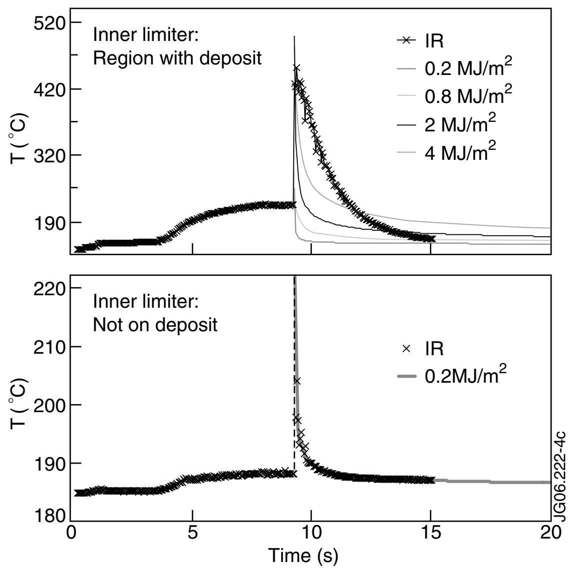

Fig. 4. Temperature evolution of two positions on the limiter tile: with and without a deposited layer.

because the vertical field cannot change fast enough to the reduced demand to maintain the plasma position [8]. This is indeed observed by magnetic measurements of the plasma position; both the current center major radius and the inner wall clearance are reduced. From the magnetic measurements, the present plasma has contacted the inner limiter during the disruption, so it is no surprise that the thermal energy has been conducted to the inner limiters. With previous ITB disruptions, with a prompt thermal quench, the plasma maintained a divertor configuration during the disruption, according to magnetic measurements. We do not yet have a wide angle IR observation of such a disruption to assess whether the inner wall is the recipient of the energy lost from the plasma but not found in the divertor.

3. Conclusions

A wide angle infrared view of the JET first wall has allowed direct observation of power conducted to the main chamber walls. In a VDE, there is reasonable agreement between the total pre-disruption energy, and the sum of radiated and conducted energy. However, it appears that magnetic energy has contributed to the energy conducted to the walls. Most disruptions are seen to conduct energy to the inner walls. For a slowly (40 ms) cooling ITB disruption, there was a good balance between thermal energy lost from the plasma and energy conducted to the limiters. Further observations are required to establish if the inner wall is also the sink for thermal energy, in prompt ITB thermal quenches ($\sim$1 ms), previously observed to be absent from the divertor.

Acknowledgements

This work has been conducted under the European Fusion Development Agreement and is partly funded by Euratom and the United Kingdom Engineering and Physical Sciences Research Council. The views and opinions expressed herein do necessarily reflect those of the European Commission.

References

[1] J.I. Paley et al., J. Nucl. Mater. 337–339 (2005) 702.
[2] V. Riccardo et al., Plasma Phys. Contr. Fusion 44 (2002) 905.
[3] E. Gauthier et al., J. Nucl. Mater., these Proceedings.
[4] A. Herrmann and ASDEX Upgrade Team, Europhysics Conference, Abstracts (CD-ROM, Proc. of the 28th EPS Conference on Controlled Fusion and Plasma Physics, Madeira 2001), p. 2109 (2001).
[5] J.P. Coad et al., Nucl. Fusion 46 (2006) 350.
[6] P. Andrew et al., J. Nucl. Mater 313–316 (2003) 135.
[7] P. Andrew et al., J. Nucl. Mater. 337–339 (2005) 99.
[8] Y. Nakamura et al., Plasma Phys. Contr. Fusion 38 (1996) 1791.