WPJET1-CPR(18) 19917

V Huber et al.

Investigation of hot spots development on metallic PFCs in the JET-ILW

Preprint of Paper to be submitted for publication in Proceeding of 30th Symposium on Fusion Technology (SOFT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Investigation of hot spot development on metallic PFCs in the JET-ILW

*V. Huber[a], A. Huber[b], G.F. Matthews[c], D. Kinna[c], A. Drenik[d], J. Mailloux[c], Ph. Mertens[b], G. Sergienko[b], K.-D. Zastrow[c] and JET contributors**

[a]Forschungszentrum Jülich GmbH, Supercomputing Centre, 52425 Jülich, Germany

[b]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, 52425 Jülich, Germany

[c]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK

[d]Max-Planck-Institut für Plasmaphysik, 85748 Garching b. München, Germany

**See the author list of "X. Litaudon et al 2017 Nucl. Fusion 57 102001"*

To investigate the formation and development of hot spots, an algorithm of automated hot spot detection-identification and analysis was developed. It provides the detection of individual hot spots with help of the Near Infra-Red (NIR) protection imaging system as well as the analysis of hots spot formation in relation to the diverse plasma parameters. To perform post-pulse analysis, new software tools, the Hotspot Editor and Viewer, were developed and integrated into the JUVIL framework [1] to enable easy tracking of the hot spots history and of their evolution. The Hotspot Editor and Viewer are now routinely used at JET for analysis of alarms from the wall protection system (VTM), edge plasma physics studies and post-pulse analysis of data required for the preparation of plasma pulses. As a result, the number of VTM alarms was significantly reduced during the last campaigns.

Keywords: Hot spot Editor, Hot spots, Real-Time first Wall Protection, Video Imaging

1. Introduction

Plasma Facing Components (PFC) in JET with all metal Be/W ITER-like wall are subjected to high heat fluxes which can lead to damage such as beryllium melting or thermal fatigue of tungsten. Hot spot formation at the re-ionization zones due to impact of the re-ionised neutrals injected by the neutral beam heating systems and RF-induced fast ion losses is recognized as a big threat due to the rapid surface temperature rise. These hot spots sometimes trigger wall protection alarms via the Vessel Thermal Map (VTM) causing the real-time protection system (RTPS) to stop a pulse where it may not be necessary ("false alarms"). It is therefore important to identify the mechanisms and conditions responsible for the formation of such hot spots as well as the conditions responsible for the disappearance of existing hot spots so that false alarms can be understood and managed.

To address this issue an algorithm of automated hot spot detection, identification and analysis was developed. It provides the detection of individual hot spots with the help of a NIR protection imaging system as well as the analysis of hots spot formation in relation to the diverse plasma parameters with the new software tools.

In this contribution, we report on new software tools, the Hotspot Editor and Viewer, which were developed and integrated into the JUVIL framework [1] to enable easy tracking of the hot spot behaviour and parameters as well as their evolution. We also report on the statistics of the hot spot temperatures, locations, sizes and shapes for the previous campaigns. The plasma conditions leading to the hot-spot formation, the correlation between hot spot temperatures and the main plasma parameters of different experiments as well as conditions of possible disappearance of hot spots. We also discuss the recommendations for avoiding or minimizing false alarms generated by hot spots [2].

2. First Wall Overheating Events

2.1 Classification the overheating events

The main goal of the real-time protection system is to protect bulk material components as well as the tungsten-coated tiles against overheating, especially against the formation of so-called hot spots. Hot spots are defined as localized regions on the surface of the wall tiles that have higher temperatures than the surrounding regions.

We will consider two types of overheating:

- An increase of the surface temperature above a given value could lead to the severe damage of the wall tiles and is an important objective for the protection (genuine hot spots):
  - The overheating of the PFCs due to heat flux overload
  - Overheating caused by fast particle losses from the NBI as well as ICRH heating
  - Overheating of the wall component edges due to small misalignment of components exceeding the engineering tolerances during their mounting and maintenance
- A surface temperature increases due to other causes than genuine overheating (false hot spots):
  - Dust particles on the surface are poorly thermally connected with the underlying material and become quickly very hot, generating false hot spots smaller than the camera resolution. A hot spot validation algorithm has been used in this case to avoid alarms caused by these false hot spots.
  - Thin surface layers can develop on the PFCs due to redeposition and lead to high-temperature hot spot formation due to their low thermal capacity and their poor thermal contact with the underlying material. The overheating of the redeposited layers does not pose a risk to the PFCs integrity but may be a cause for false alarms.
  - The delamination of the coating can lead to flakes and droplets which have a poor thermal connection to the bulk substrate. Overheating of the flakes, droplets and jagged edges does not lead to a global damage of the divertor tiles, which could have an impact on the machine operation and, therefore, the hot spots

author's email: Valentina.Huber@ukaea.uk

produced by delamination of the coating are considered as false hot spots.

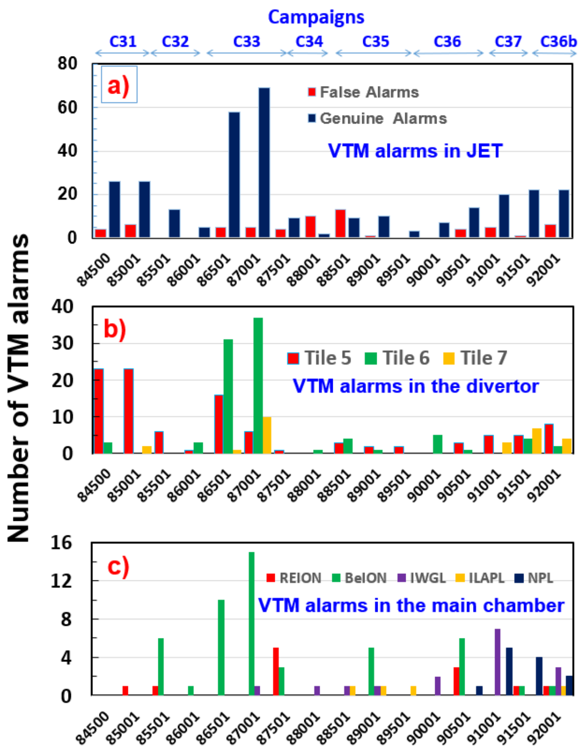

Fig.1 Number of a) total VTM alarms b) in the main chamber and c) in the divertor region since C31 campaign.

2.2 Statistic of the VTM alarms

All VTM alarms on the JET-ILW machine are well characterised and catalogued. Figure 1 shows VTM alarms recorded since the C31 campaign. Here the number of alarms per bin of 500 plasma discharges is displayed. The genuine alarms include the genuine hot spots as well as classical heat load events which demonstrate a classical heat up and cool down behaviour: a slow increase of the temperature by applying heat loads as well as a slow temperature reduction after removal of the heat load source. The Real-Time Protection system (RTPS) started to operate routinely since the C31 campaign triggering a large number of VTM alarms during the first 3 campaigns, C31, C32 and C33. The majority of these alarms was due to classical heat up of the first wall components, due to hot spots formation and due to heating of the NBI beam re-ionization zones (see fig.1b and 1c). The re-ionization zones are the areas on the outer limiters which are subjected to the impact of the re-ionised neutrals injected by the heating system. The classical heat up of the wall components occurred mainly during the H-mode plasmas with additional neutral beam as well as ICRH heating. In the early pulses, the predominant location of the alarms in the divertor region was the divertor tile 5 (horizontal target), while later on, the number of alarms from tile 6 signals increased significantly.
In the binned pulse data marked 86501 and 87000, an increase in alarm numbers can be seen. This is mostly triggered by temperature signals from divertor tiles 5, 6 and 7. The maximal number of alarms of about 70 was triggered at bin 87001 which correspond to the pulse range of 87001-87500. During this pulse range about 14% of plasma discharges were terminated to avoid harmful situations like dangerous overheating through classical heat up of the wall components. Averaged over the entire C33 campaign, about 8% of the plasma discharges were terminated by RTPS. Also the number of alarms due the NBI beam re-ionization during the C33 campaign reached the maximum of 2%-3%. The following campaigns C34-C36 show a general tendency of reduction of the VTM alarms because of the continuous improvement of the real-time protection system as well as a better understanding of the physics of events leading to the alarms. Within the last experimental campaigns (C37 and C36b) a significant improvement of the auxiliary heating systems on JET-ILW has been performed leading to a marginal increase of the plasma terminations due to the RTPS safety system: about 2-3% are due to the classical heat up and about 1-1.5%, due to hot spot formation. As shown in Figure 1, the false alarms were reduced to less than 0.5% of all plasma discharges, even though the total additional heating power increased significantly in these campaigns.

3. Tools for the Study of Hot Spots

The Hotspot Editor and Viewer are new tools for the investigation of the development and evolution of the formation of hot spots, localized micro-regions on the surface that appear to have much higher temperatures than the surrounding regions. They enable to study the appearances of new hot spots and the conditions of disappearance of the existing hot spots, as well as to track the history of their sizes, locations and temperatures.
The Hotspot Editor automatically loads the hot spots for a specific camera stored in the catalogue and shows their mapping (see Fig.2). It enables editing of locations, shapes, sizes, detected times, as well as the calculation of temperatures of hot spots and flags indicating whether they caused VTM alarms. It is also possible to set a shot number and time if a hot spot clearly disappeared (e.g. after the cleaning up or replacement of tiles) and to load automatically the videos from times when a specific hot spot was detected or modified.
The Hotspot Viewer displays the catalogue of all detected hot spots and shows their evolution. It provides also the filter options for extraction of new or already existing hot spots during a specific pulse range.

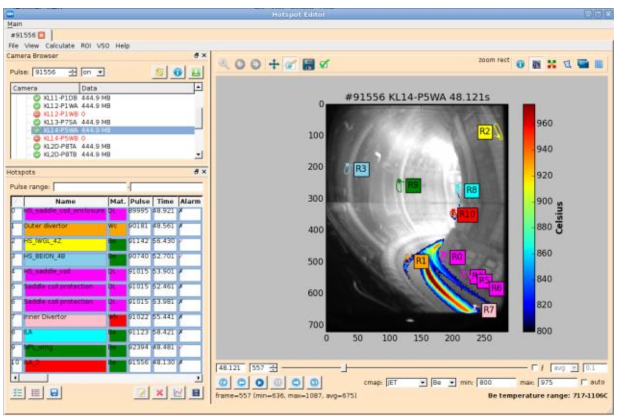

Fig. 2. Hotspot Editor

author's email: Valentina.Huber@ukaea.uk

3. Analysis of hot spot behaviour on the Inner Wall Guard Limiter

Figure 3a shows an example of a hot spot formation in the main chamber of JET. The hot spot is located at the upper part of the inner wall guard limiter (IWGL). Thanks to the hotspot viewer, the evolution of this specific hot spot could be followed (Fig.3b). The first time IWGL hot spot was observed during an ohmic discharge at pulse number 87643. In this pulse the surface temperature of Be tile

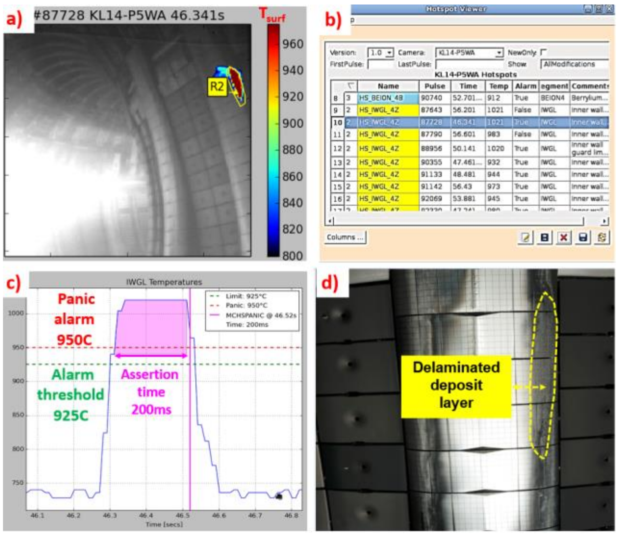

Fig3. a) Hot spot on the inner wall guard (IWGL) b) Surface temperature profile of the IWGL hot spot; b) Hotspot Viewer catalogue of detected hot spots and their evolution; d) High-resolution image of the inner wall guard limiter

reaches the trip level of 925ºC and remains above this trip level for time window shorter than the assertion time, which is 200ms. Correspondingly, the alarm was not triggered during this pulse. During the following pulses (e.g. #87728), the surface temperature remains beyond the trip level longer than the assertion time (see Fig.3c). As a result, the trip alarm is triggered and VTM sends an alarm to RTPS requesting a recovery action from the plasma control systems. The action of the real-time protection system during this hot spot formation is described in detail in [4] demonstrating successful RTPS recovery actions where the plasma discharge was not terminated. The analysis shows the growth of the size of IWGL spot. However, the surface temperature measured by the protection system shows a fast initial rise which suggests that the measurement is not the result of thermal radiation from the bulk. Such a temporal response of the temperature (quick temperature increase and decrease) is the typical signature for a deposited layer with poor thermal contact with the material substrate. Such a growth of the hot spot size could be explained by the progressing delamination of the deposited layer from the bulk material substrate. That was confirmed by the high-resolution images taken during the in-vessel survey (see Fig.3d).

4. Analysis of hot spot behaviour on the ITER-like Antenna

The hot spot editor is designed for the analysis of the hot spots with temperatures below as well as beyond the trip level. It calculates temperatures of hot spots for a pulse as well as enabling plotting or storage of the history of temperatures for specific pulses or pulse ranges using a thresholding technique to study hot spot temperature evolution. Figure 4 shows the hot spot behaviour on the ITER like antenna (ILA) in a pulse range spanning over 5000 pulses. The ILA is one of the additional heating systems at JET which was designed to couple 7.2MW (8MW/m^2) across the frequency range 30-55MHz [3]. Hot spots are the potentially most dangerous events related to ILA operation. If left uncontrolled they can produce damage and cause plasma disruption by impurity influx.

The surface temperature threshold was set for this analysis to 950°C. The assertion time has been taken at 120ms. Fig. 4c demonstrates the formation of 10 hot spots on the antenna grids and how they correlate with plasma shape parameters: Radial Inner and Outer Gaps (RIGs and ROGs) which define the distance between the inner and outer limiter, respectively, and the plasma.

Furthermore, the figure gives the values of the additional heating power by NBIs as well as by ICRH heating systems. The hot spots around the pulse 8900 were formed in the pulses with small RIG and large ROG values. Additionally, the temperatures remained beyond the temperature threshold for relatively short times (below 300ms). These are indicators that these hot spots have causes which are not related to the overheating of the antenna components.

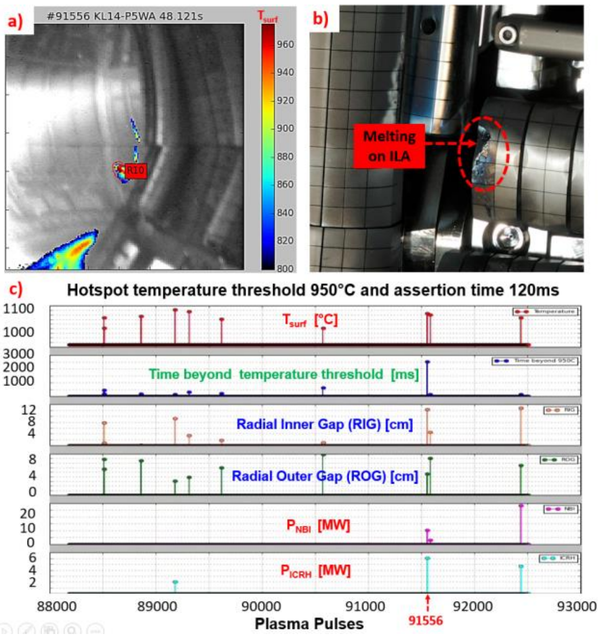

Fig.4 Hot spot behaviour on the ITER like antenna in a pulse range from #88000 and #92504.

Analysis shows that these hot spots were triggered by the bremsstrahlung during the wall MARFE formation at the end of the plasma discharge during the disruption phases. These are clearly "false hot spots". This knowledge was used to deselect these "false hot spots" from the data base. Additionally, the hot spot editor cross-checked these criteria with the disruption database which contains the full information about the disruptions: pulse, time of disruption, reason of the disruption, etc. The genuine hot spot at pulse

author's email: Valentina.Huber@ukaea.uk

91556 is related to the overheating of the antenna structure of Faraday screen.

5. Hot Spots on Partly Delaminated Divertor Tiles

Delamination of tungsten coatings on a few CFC based tiles was observed after the campaigns in 2013-2014 [5]. In-vessel inspection of the JET-ILW first wall with a high resolution camera, shown in figure 5b, demonstrates clearly the delamination on the lower outer vertical target.

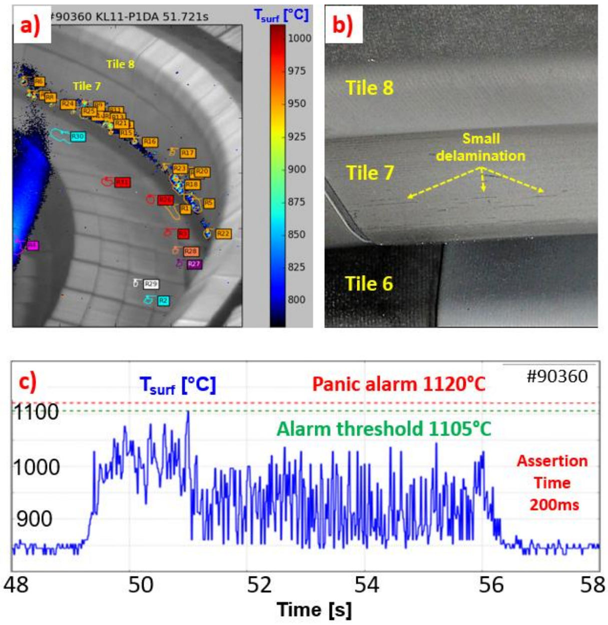

Fig. 5 a) Hot spot formation on the lower outer vertical target (tile7) during the ELMy H-mode plasma discharge; b) Delamination on the lower outer vertical target (Tile 7); c) Measured surface temperature profile of the W-coated outer divertor target.

Significant heat loads in this region have resulted in a pattern of W-coating cracking and delamination along CFC fibre planes in a toroidal orientation along the tile. There is also a known mechanism for failure of the coatings by carbidisation if surface temperatures exceed 1350°C for more than two hours [6]. However, this mechanism has not been identified in the samples analysed so far because the protection limit is below this temperature. Delamination along fibre planes is also created by a fatigue due to the mismatch in thermal expansion and is intrinsically variable due to complex 3D structure of CFC materials.

Figure 5a shows the hot spot mapping on the vessel structure. The majority of these hot spots form during the ELMy H-mode plasma discharge ($B_T \approx 2.6$ T, Ip=2.5 MA) with the additional input power of about 18.0 MW in low-triangularity magnetic equilibria with the strike points located on the vertical targets. The temperature of the hot spots rises quickly during the ELM and cools down abruptly when the ELM is over (Fig.5c). This is a typical behaviour of overheated edges of delaminated layers. In the case shown, the ELM frequency is about 15Hz. At such a frequency the hot spots are seen on every third image frame. The temperature of the hotspots remains below the trip level (here 1105ºC) during the entire pulse and therefore does not trigger the VTM alarm. Even if the temperature of the hot spots would have exceeded the trip level, at such ELM frequencies the time duration when the surface temperature is above the trip level (in this case 20ms) is shorter than the assertion time, hence the transient temperature rise would not have triggered an alarm. The NIR cameras used for protection [7] operate in non-interlaced mode at 50 fields per second. ELMs with frequency below 25Hz will lead to transient hot spot formation during alternate frame images and, correspondingly, will be ignored by the protection system. The strength of ELMs can be deduced from the loss in stored plasma energy. With an increase of the ELM frequency the loss in stored plasma energy during the ELM, the ELM energy loss, decreases because the ELM size is inversely proportional to the ELM frequency [8]. For JET-ILW plasmas with an available auxiliary heating power of about 28MW and the heating power duration according the JET-ILW requirements, the ELMs with frequency beyond 25Hz do not lead to an increase of the temperature of the jagged edges to values above the tripping level. The effect of small delamination on JET operation is tolerable and has not increased with time.

6. Summary

New software tools, the Hotspot Editor and Viewer, were developed and integrated into the JUVIL framework. These tools enable an easy tracking of the history of hot spots and of their evolution. They are now routinely used at JET for analysis of VTM events and alarms which allows to detect overheated areas with reduced false positives. In the future we are planning to integrate automated detection and recognition of the hot spots [8].

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Huber V. *et al* 2017 *Fusion Eng. Des.* **123** 979-985, http://dx.doi.org/10.1016/j.fusengdes.2017.03.005
[2] Alves D. *et al* 2012 *Phys. Rev. ST Accel. Beams* **15** 054701
[3] Nightingale M. P. S. *et a*l 2009 *AIP Conf. Proc*. **1187**, 213; doi: 10.1063/1.3273731
[4] Huber A. *et a*l, these proceedings
[5] Widdowson A. *et a*l 2017 *Nuclear Materials and Energy* **12** 499-505, http://dx.doi.org/10.1016/j.nme.2016.12.008
[6] Maier H. *et a*l 2016 *Phys. Scr*. **T167** 014048. http://dx.doi.org/10.1088/0031-8949/**T167**/1/014048 .
[7] Huber A. *et al* 2018 *Nucl. Fusion* **58** 106021
[8] Drenik A. *et a*l submitted for publication in *Nucl. Fusion*

author's email: Valentina.Huber@ukaea.uk