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First Wall and Divertor Protection in JET-ILW: Assessment of Reliability after fifty Hours of Plasma Operation

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The ITER-like Wall protection system based on near-infrared video imaging was developed on JET-ILW *and* has been operated routinely over 12000 discharges (more than 50 hours of plasma operation) since 2011. Within the last experimental campaigns 2-3% of the plasma discharges were successfully terminated by this system, avoiding material overheating and damage. The different hot spot detection algorithms fulfil their tasks with a high reliability: triggering of false alarms occurs in less than 0.5% of all plasma discharges. Future development of the JET real time first wall protection is focused on the D-T campaign and the ITER relevant conditions. New sensitive and sophisticated cameras such as logarithmic NIR cameras with wide angle and divertor view camera systems, equipped with new mirror based optical relays to take the cameras outside of the biological shield, have been installed on JET-ILW and calibrated with an in-vessel calibration light source.

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

1. Introduction

The JET ITER-like wall (JET-ILW) combines plasma-facing components (PFC) made of bulk beryllium for main chamber limiter tiles and of bulk tungsten as well as tungsten coated CFC tiles for the divertor tiles [1]. The risk of damaging the metallic PFCs caused by beryllium melting or cracking of tungsten owing to thermal fatigue required a new reliable active protection system to avoid damage of the plasma-facing components (PFCs). To address this issue, a real-time protection system comprising newly installed imaging diagnostics, real-time algorithms for hot spot detection and alarm-handling strategy has been implemented in the JET protection system. Considering the different material properties of ILW-PFCs, the real-time imaging system must fulfil several objectives such as avoiding the melting of the beryllium tiles, minimizing the risk of delamination of the tungsten coated tiles and keeping the surface temperature below the threshold at which bulk tungsten re-crystallizes. This means that the system which monitors the surface temperature of the PFCs must be active in every plasma discharge becoming especially important during the execution of the experiments of the coming D-T campaign, where stationary plasmas with additional power of 40MW/5s and with tolerable wall heat loads and impurity concentration are required.

2. Near infrared imaging diagnostic systems

The JET-ILW imaging system for machine protection [2] is based on analogue monochrome CCD cameras (Hitachi KP-M1AP; sensor: Sony ICX423AL, Sensor size 768x576, pixel size: 11.6 µm (H)×11.2 µm (V)), equipped with near infrared (NIR) filters. *Synchronized* with the *external sync* signals (V/H scans), the cameras operate in non-interlaced mode at 50 fields per second with binning (odd and even lines are exposed together at the same time). In this mode, the spatial resolution is lost in the vertical direction: the camera delivers images with an apparent size of 720 × 288 pixels every 20ms. At the same time, the pixels are effectively larger in the vertical direction, and hence more sensitive.

3. Classification of 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.

The detailed description of different types of overheating is given in [3].

4. Real-time protection of the JET ITER-like Wall

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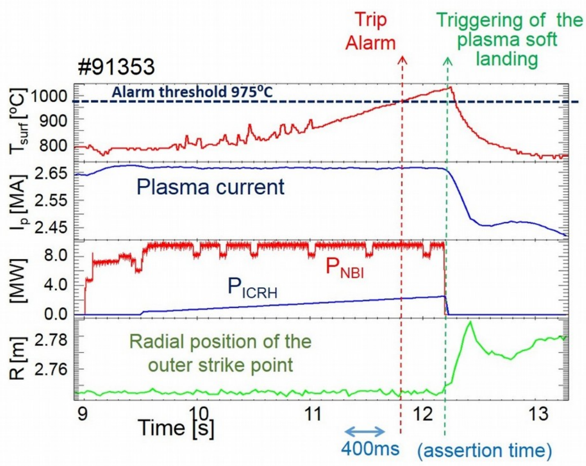

Fig.2 A discharge with a classical heat up of the divertor W bulk tiles shown in Fig.1a.

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Real Time Protection Sequencer (RTPS). The RTPS is a highly configurable system which controls the actuators and safely terminates the plasma, thereby reducing the risk of a disruption or other potentially damaging event. Detailed description of the video digitization and distribution, the real time processing system as well as real time processing algorithm can be found in [2].

Fig.1a shows a discharge demonstrating a typical classical heat-up of the divertor W tiles: 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 outer strike point, where the heat flux is maximal, is located on the bulk tungsten tile. This pulse was an ELMy high energy confinement mode (H-mode) plasma with auxiliary heating power of about 12MW (P_{NBI}=9.6MW and P_{ICRH}=1.0-2.5MW). As shown in Fig.2, the surface temperature increases with time during the auxiliary heating phase. At 11.8s the surface temperature of the bulk tungsten tile reaches the trip level of 975ºC and remains above this trip level for longer than the assertion time, which is 400 ms. At time 12.2s the VTM sends an alarm to RTPS requesting an appropriate action from the plasma control systems. As a result the plasma is carefully terminated by switching off the auxiliary power, moving the strike points away and ramping down the plasma current. The “assertion time” is the time window during which VTM checks that the temperature of the analyzed surface is consistently above the trip level. This is needed to avoid false alarms due to spurious signals on the camera image (e.g. caused by neutron impact). During the response time of the plasma control systems after receiving the tripping level, the temperature still increases and reaches the maximal value of 1030ºC, which is significantly below the specified threshold, at which the bulk tungsten re-crystallizes— (1200ºC) [7]. Another example of the classical heat up of localized region on the horizontal divertor tile is shown in fig.1b.

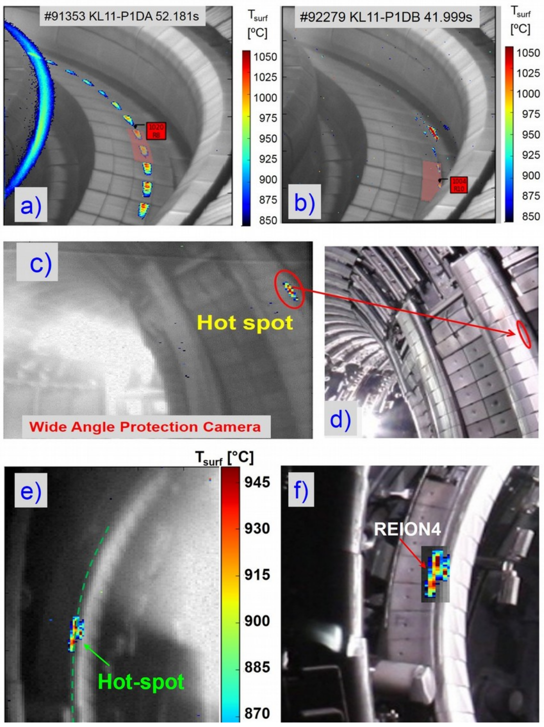

Fig.1 a,b) Classical heat up of the divertor W bulk tiles c,d) Hot spot on the inner wall guard limiter (IWGL), e,f) Hot spots on the NBI beam re-ionization zone.

Fig. 1c,d show the images taken during an ohmic discharge with a hot spot formation on the inner beryllium limiter.

At time 16.1 s the surface temperature of Be tile reaches the trip level of 925ºC and remains above this trip level for longer than the assertion time, which is 200 ms (see Fig.3). At time 16.3s VTM sends an alarm to RTPS requesting recovery action from the plasma control systems. As a result the plasma is moved to the outboard side. The cooling of the Be tile after moving the plasma and correspondingly switching off the heat loads takes place very quickly. This very fast thermal response to the applied or removed power loads is due to low thermal capacity of the thin layer and its lack of thermal attachment to the bulk material. The I_p signal shows a slight drop due to the change of the plasma internal inductance (l_i) during the plasma movement. After 0.5s the plasma controller forces I_p to the requested value. The plasma discharge was not terminated and thus, the RTPS recovery action was successful.

Fig.1e,f shows hot spot formation on the NBI beam re-ionization zones. The latter correspond to the limiters subjected to the impact of the re-ionised neutrals injected by the heating system. From the analysis of the response of the surface temperature on the heat loads we can conclude that the re-ionisation zone demonstrates 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. To avoid the overheating due to re-ionisation, the plasma is softly terminated by switching off the auxiliary power and ramping down the plasma current.

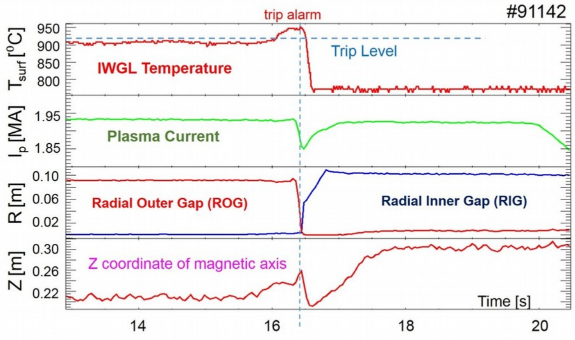

Fig.3 Evolution of temperature output of the RTPU for an ROI monitoring an inner wall guard limiter (IWGL), of the plasma current, radial outer and inner gaps, and plasma position in a pulse where the trip level is reached. .The video of this discharge with hot spot is shown in Fig.1c.

5. Reliability of the real-protection system

An analysis of the reasons for the early termination of plasma pulses is crucial for optimal machine operation. In order to provide a fast data visualization and advanced analysis of all types of VTM alarms, a new software, the

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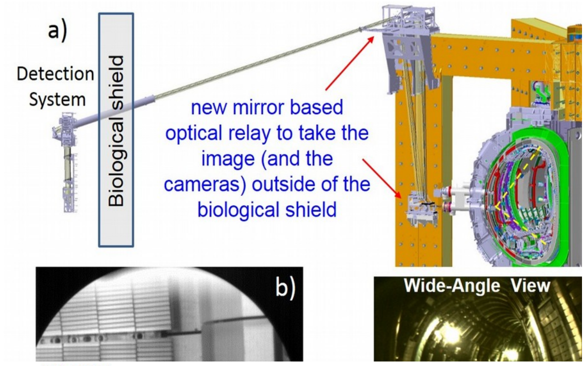
VSO (Viewing Systems Operator) Logbook Editor [4], has been developed and successfully installed at JET-ILW. Thus, all VTM alarms on the JET-ILW machine are well characterised and catalogued. An analysis of the reasons for early termination of plasma pulses is shown in Fig.4. Here the number of alarms per campaign normalized to total number of campaign shots is displayed. Directly after implementation of the protection system on JET-ILW during the campaigns C31, C32 and C33, the statistics showed a large number of VTM alarms due to classical heat up of the first wall components, to hot spots formation and to heating of the NBI beam re-ionization zones (see fig.1e,f). The majority of alarms due to classical heat up of the wall components occurred during the H-mode plasmas with additional neutral beam as well as ICRH heating. After a discharge is terminated by RTPS, the plasma operational parameters are modified (e.g. reduction of the heating time window, gas puffing increase, changes to the magnetic plasma configuration, etc.) to prevent unplanned stops in the following discharges.

During the C33 campaign, about 8% of the plasma discharges were terminated by RTPS to avoid harmful situations like dangerous overheating through classical heat up of the wall components. Also the number of hot spots (2% of the plasma pulses) as well as the alarms due the NBI beam re-ionization (2%) increased. 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 (ICRH and NBI heating systems during the C37 and C36b campaigns, respectively) 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%,to the hot spot formation. During C37, overheating was caused mainly by fast particle losses from ICRH heating. As shown in figure 4, 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.

The VSO Logbook Viewer can also display the list of VTM events on the specific segments and physical tiles as shown in fig.4b,c. The majority of alarms in the main chamber is due to classical heat up of the inner wall guide limiters (fig.4b) as well as of the re-ionisation zones (fig.4b).

VTM alarms caused by overheating events in the divertor region are shown in Fig.4c. It can be seen that about 3% of the plasma discharges were terminated by RTPS because of the protection of the divertor against overheating. During the C33 campaign, about 6.5% of the plasma discharges were terminated by 74 alarms: 71 on the horizontal divertor target Tile 6 and 3 alarms on the vertical outer divertor target Tile 7.

6. Future development of the JET real time first wall protection



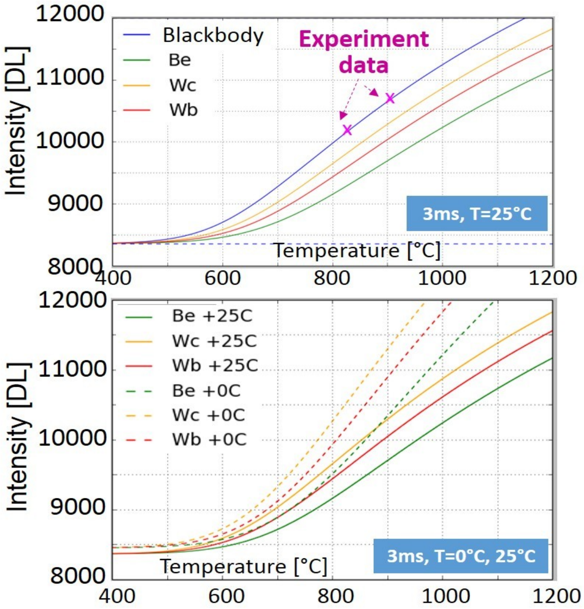


Fig.6 a) digital levels measured by the camera versus brightness temperatures of the ICLS with one lamp and with a combination of two lamps b) result of camera calibrations for two different sensor temperatures: 0°C and 25°C.

JET will cause failure of camera electronics within the Torus hall due to significant increase of the hard radiation level (neutrons/gammas). To provide the reliable wall protection needed during the coming D-T campaign, two camera systems, equipped with new optical relays to take the images and the cameras outside of the biological shield, have been installed on JET-ILW and calibrated with an in-vessel calibration light source [8,9]. The optical design concept of both systems with wide angle view as well as the divertor view is based on reflective optics, mainly to be able to sustain high neutron radiation. Similarly to the ITER conditions, it transports the light by reflective optics (mirror systems) over long distances (>40 m) to the detection system located outside the biological shield. Fig5a shows the mechanical layout of the wide angle imaging system. The location of the cameras outside the biological shield makes it possible to integrate more sensitive and sophisticated cameras in the wall protection system. The new JET imaging system for machine protection is equipped now with new digital logarithmic NIR cameras: New Imaging Technologies

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(NIT) WiDy SWIR 640U-ST camera, 640×512pixel, pixel size: 15µm ×15µm, max. 200 fps, dynamic range 14bits, USB2 or USB3 data connection interface, logarithmic response [10]. These NIR-SWIR cameras use InGaAs (Indium Gallium Arsenide) detectors, offering a high quantum efficiency (QE>70%) at the wavelength range 900 - 1700 nm. For these cameras, a band pass filter: 1200nm±10nm is used. The choice of the camera and the central wavelength of the filter is based on the analysis reported in [2]. There are advantages of the usage of the optimised wavelength (λ=1.2µm) for T_{surf} measurements: temperature independent spectral emissivity for tungsten; less sensitivity of the measurements to the surface roughness; reduced maximum relative error for the T_{surf} measurements.

All camera sensors are cooled to temperatures of about 0°C to reduce the dark noise.

One example of the calibration of the wide angle WiDy camera by ICLS is shown in Fig.6a: digital levels measured by the camera versus brightness temperatures of the ICLS with one lamp and with a combination of two lamps. The Planck radiation curve was used as a fit of the experimental data. The calibration curve could be easily adapted to the wanted material as shown in Fig.6a: yellow for W coated, red for bulk tungsten and green for beryllium.

During the calibration, it was recognised that the selected InGaAs sensor is sensitive to changes of sensor temperatures as shown in Fig6b. For the sensor temperature of 0°C, the camera demonstrates a higher sensitivity. Consequently, cameras were calibrated for all possible sets of sensor temperatures and times exposures which will be used during the experiments.

7. Summary

Reliable operation of the protection system based on video imaging was demonstrated in JET with ITER-like Wall. Safe landing of the plasma is achieved when hot spots are observed on the Be main chamber as well as in the divertor PFCs (bulk W and tungsten coated CFC tiles). It was demonstrated that the video imaging protection system can work properly under harsh conditions with neutrons and dust on the surface as well as layer deposits on the materials: about 2-3% of the plasma discharges were terminated by RTPS to avoid overheating of first wall materials within the last experimental campaigns. 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, the number of false alarms could be reduced to less than 0.5% of all plasma discharges.

Focused on the D-T campaign and the ITER relevant conditions, the real-time first wall protection system is significantly improved. New optical relays to take the images and the cameras outside of the biological shield have been installed on JET-ILW. Additionally, new highly sensitive digital logarithmic NIR cameras were integrated into the protection scheme. The real-time protection system is an essential tool for JET operation and the experience gained can contribute important ideas and methods to the design of the ITER plasma control system.

Acknowledgments

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