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INTRODUCTION

Installation of the JET ITER-Like Wall (ILW)[1] has brought on the need of a reliable protection system as too high a temperature of the plasma facing components (PFCs) can result in beryllium (Be) melting or thermal fatigue of tungsten (W). A proper temperature measurement relies on the knowledge of three different parameters of equal importance: the sensitivity of the camera sensor, the transmission factor of the optics used and the emissivity of the monitored PFCs. In this paper we first present the calibration process of a wide angle infrared (IR) camera, which has involved the capabilities of the remote handling for introducing a calibrated hot source into the JET vacuum vessel. Then, we describe how the PFCs equipped with embedded thermocouples have been used to assess the emissivity of both Be and W.

1. CALIBRATION OF THE JET WIDE ANGLE IR CAMERA

The protection system of the JET ILW (PIW) [2], which monitors PFCs surface temperature, relies on cross-checked measurements from different independent diagnostics. Among them the wide angle IR camera, a FLIR ATS with an InSb sensor, is particularly important as it is the only one that has been calibrated both in laboratory and in situ. The laboratory calibration was performed using a calibrated black body, a 1cm x 4cm cavity for which temperature has been raised up to 600°C. The number of photons emitted from the source and detected by the camera is computed assuming the Planck formula for the black body:

$$Ph(\lambda, T) = \frac{\lambda}{hc} \frac{2\pi hc^2}{\lambda^5} \exp\left[-\frac{hc}{\lambda k_B T}\right] \quad (1)$$

where λ is the wavelength, h the Planck constant, c the speed velocity and k_B the Boltzmann constant, and taking into account the spectral response of both camera and pass-band filter (0.6 transmission between 3.97 and 4 μ m). Results of two calibrations performed in 2012 and 2013 with an identical black body source are shown on Fig.1. Temperature has been varied from room temperature to 600°C and integration time from 300 μ s to 1900 μ s (sensor linearity is different below 300 μ sec). Comparison of the two data sets does not show any significant modification of the camera sensitivity, making us confident on the reliability of the data produced by the camera.

The second important step for a reliable temperature measurement is a good characterization of the in situ optical system. To assess its transmission during the 2013 shutdown, Remote Handling has been used to introduce a 20x20cm extended hot source in JET. Its surface emissivity, determined thanks to a laboratory cross-calibration against the black body source, is of 0.46 \pm 0.05. Temperature measurements recorded in vessel are in the range of 200-600°C with integration times from 200 μ sec to 1900 μ sec. Comparison of data from calibration performed in 2013 with the previous one performed in 2012 does not show any deviation from each other (red and blue lines, respectively). As these calibrations have been performed with calibrated hot sources and the same optics and camera, conclusion of the consistency of the two sets of data is that the transmission of the overall system has not been altered by plasma operations.

W EMISSIVITY ASSESSMENT

The JET ILW divertor is made of two different kinds of tungsten PFCs. Horizontal targets are constituted of 6x60x40mm bulk tungsten lamellas while vertical targets are CFC coated tiles with a 12–20 μ m tungsten layer on top. In order to correctly measure the surface temperature one has to know their emissivity, which depends on material. In situ assessments of these quantities are possible thanks to embedded thermocouples in some of the PFCs [3]. Unfortunately, TC monitoring the lamellas are too far from the lamella surface, preventing us to assess bulk W emissivity. In the present analysis we then focus on the W-coated tiles and assume they behave like black bodies with a constant emissivity ϵ_{Wc} . For a series of 7 JET pulses, the outer strike point has been positioned on one of the vertical targets, leading to an increase of the surface temperature up to 600°C. Using the IR camera, one can compare the number of photons (N_{ph}) detected to N_{ph} expected from a black body source at the temperature given by the thermocouples, which are embedded 1cm beneath the surface of the tiles. The ratio between the two gives the emissivity if the tile temperature is homogeneous. Such a comparison is provided on Fig.3. Each pulse starts at the lower left hand corner. Then, N_{ph} from IR increases faster than N_{ph} derived from TC, which is expected as the surface heats up faster than the bulk of the tile. During the cooling down phase, a linear decay is observed when bulk and surface temperature decrease at the same rate. The emissivity derived from this analysis is $\epsilon_{Wc}=0.43\pm 0.09$, compatible with a previous analysis performed at JET [4]. This value is derived from the experimental dispersion illustrated by the two black lines on Fig.3.

Be emissivity assessment

The JET main chamber is protected by guard limiters are covered with castellated Be tiles. In divertor plasma operations, these limiters do not receive high heat fluxes and their temperature stays rather low, close to the heating temperature of the wall. During dedicated discharges in limited configuration, plasmas have been pushed toward either inner or outer wall, leading to temperature up to 1200°C on the components. Data from these experiment are used here to assess Be emissivity ϵ_{Be} . Strategy applied is to look on the IR camera for the locations of castellation where TCs are embedded and to retrieve the corresponding digital levels. Measurement is taken at the end of a pulse when tiles have homogeneous temperature. Fig.4 show digital levels (DL) detected by the camera versus the number of photons expected for a black body at a temperature by the TC from the in vessel source, inner limiter and outer limiter, with an emissivity of 1 for the limiters. Emissivity ϵ_{Be} is then computed from the ratio between the slopes derived from the in vessel calibration and the limiter ones. Results from inner and outer limiters give $\epsilon_{Be}= 0.22 \pm 0.04$, compatible with what is found in literature.

CONCLUSIONS

A careful calibration of the JET wide angle IR camera has been performed during the 2013 shutdown. Laboratory calibration has proved that the camera properties haven't changed since the previous shutdown. In vessel calibration, carried out with the calibrated hot source introduced in the JET vacuum

vessel thanks to the Remote Handling capabilities has not shown any significant modification of the optics exposed to the plasma. Using thermocouples embedded in the different PFCs, emissivity of Be and W coating have been estimated at $\epsilon_{Be} = 0.22 \pm 0.04$ and $\epsilon_{W} = 0.43 \pm 0.09$. These results are a first attempt to assess emissivity in such a way, using available data. Main drawback of the method is the need to wait for tiles to be homogeneous, time at which the camera usually does not record data anymore. In the next campaign, we intend to increase the accuracy of the measurement by recording data during the whole cooling down phase.

ACKNOWLEDGEMENTS

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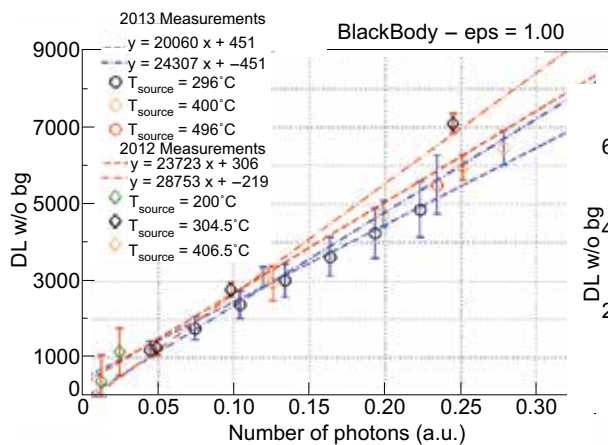


Figure 1: IR camera calibration performed in 2012 (blue lines) and 2013 (red lines) performed with a black body source of which temperature has been raised up to 600°C (saturated), with integration times from $200\mu\text{s}$ to $1900\mu\text{s}$. Comparison of the two data sets does not show a significant modification of the sensor sensitivity.

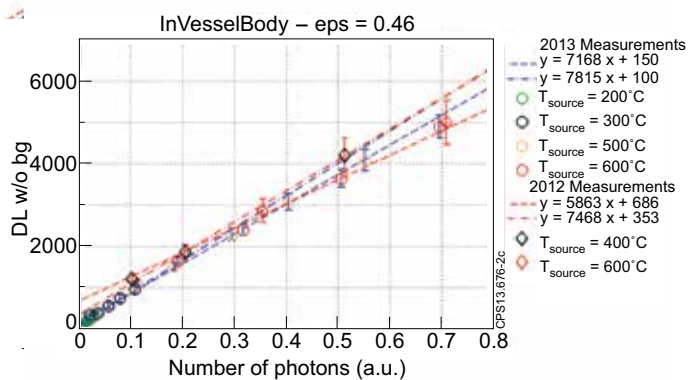


Figure 2: In Vessel calibration of JET IR wide angle camera in 2012 (red lines) and in 2013 (blue lines) using calibrated hot sources. Temperature ranges from 200°C to 600°C , with integration time in $200\mu\text{s}$ – $1900\mu\text{s}$. Comparison of the sets of data show a pretty good agreement indicating no modification of the in situ optics transmission.

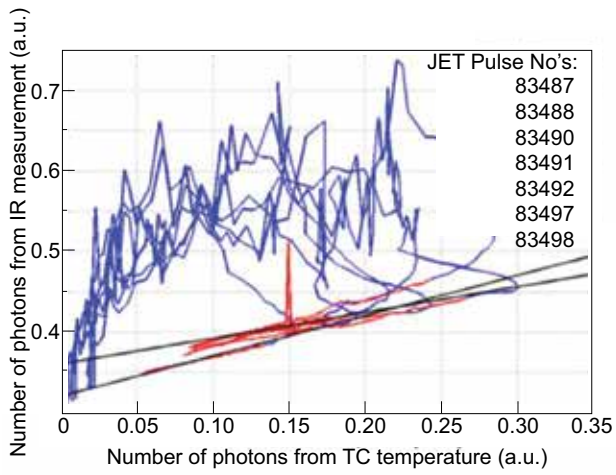


Figure 3: Number of photons detected by IR from the JET vertical targets vs the number of photons expected from a black body source at the temperature given by the embedded thermocouples. Ratio during the cooling down phase provides the W-coated emissivity.

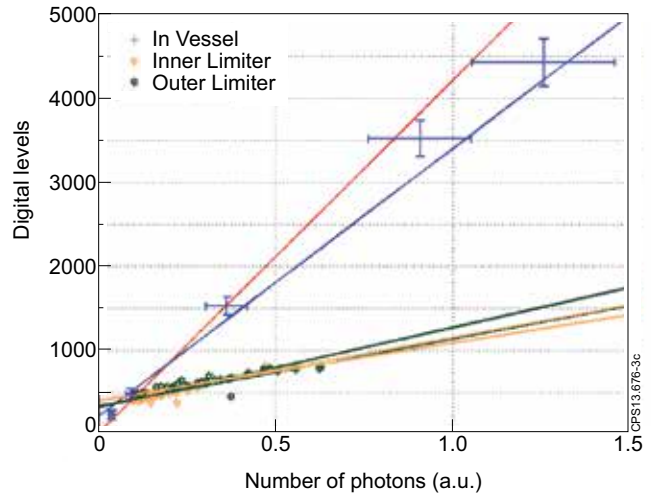


Figure 4: Digital levels detected from the camera vs number of photons extected from a black body at a temperature given by TCs. "In vessel" data stand for a calibrated hot source. Limiters data are derived from temperatures measured by TCs embedded in the tiles.