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Calorimetry of the JET ITER-Like Wall Components

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ABSTRACT
As part of the ILW project, new diagnostics have been installed in order to protect the Plasma-Facing Components (PFC). Here we present the diagnostics used to monitor the PFC temperature, thermocouples and cameras, and assess the consistency of their measurements. In dedicated limited L-mode plasmas, the surface of the limiter tiles are heated up to 900°C. The comparison of surface temperature measurements from IR and near IR cameras, which have been calibrated against a black-body source, leads to a Be emissivity of 0.18, comparable with the theoretical one. Energy calculation derived from thermocouples data, which are embedded in both limiters and divertor target plates (W-coated CFC), is compared to a 1D model based on thermal quadrupole approach (benchmarked with an ANSYS model) associated to an inversion computation. The analysis shows a good energy balance can be achieved within the errorbar of the model, assessed to be of 30 percent.

1. INTRODUCTION
The temperature control of the Plasma-Facing Components (PFC) is a key issue for plasma operations in devices such as JET or ITER. Too high a temperature could irreparably damage these components. At JET, operations with the new ITER-Like Wall [1] (ILW) have seen strong restrictions on the temperature limits that can be reached by the different components: bulk-W divertor 1000°C (re-crystallization) in the initial phase (operations will later be allowed to go up to 1600°C), W-coated Carbon Fiber Composite (CFC) 1200°C (carbidization) and Be first wall 950°C (margin on melting temperature). It is essential to precisely and reliably measure the temperature of the different components. At JET, ThermoCouples (TC), InfraRed (IR) cameras and cameras with near IR filter used for protection are available providing a unique opportunity to cross-check the different measurements. As the different measurements are not directly comparable (TCs provide bulk temperature, cameras provide surface temperature) a heat diffusion modeling is required to compare the bulk temperature provided by the TC to the surface temperature measured by IR cameras. In this paper we first present the different diagnostics available for the main chamber and divertor PFCs. The consistency between the different measurements is assessed. An indirect mean of assessing consistency is to perform energy balances. The last part of the paper discusses the model used for energy calculation and presents energy balances from thermocouples.

2. TEMPERATURE MEASUREMENTS ON THE DIVERTOR
The new JET ILW divertor is made of two different kinds of tungsten PFC: the horizontal, outer target plate is constituted of bulk tungsten lamellas and the vertical targets are made of CFC coated with a 10-20μm tungsten layer. These tiles are monitored by IR and protection cameras that provide surface temperature. They are also equipped with type-K thermocouples that have been calibrated before their in-vessel installation and provide a temperature difference up to 1200°C between their cold and hot junction (located in the tiles). The temperature of the cold junction, located outside the vessel, is assumed to be at 20°C; the validity of this assumption is established by measurements

made after operations and by the monitoring of similar part of the vessel. The analysis presented in this paper focus on the vertical targets as their geometry has already been modeled during CFC campaigns and they are well monitored by IR cameras and thermocouples, which are embedded 1cm only beneath the surface. For these vertical tiles, two different models have been applied in order to extrapolate TC data to surface temperatures: a linear 2D thermal quadrupole approach associated to an inversion method [2] and a 2D inversion model [3] using the conjugate gradient method. The extrapolated maximum surface temperatures computed for a H-mode plasma with B_T/ I_P = 2.2T/2.0MA and 10MW of auxiliary heating power (NBI) are given on fig.1a and compared to the IR wide angle camera data. This camera has been calibrated in situ in the temperature range of 200°C-600°C with an in-vessel hot source. The calibration has been confirmed by an independent method based on a pulse to pulse limiter temperature increase described here [4]. The emissivity of the tungsten coated tiles, derived from experiment carried out with the CFC wall, is assumed here to be constant in a first approximation at 0.4 for the considered temperature range (camera operates at 3985±15nm). The pretty good agreement between IR and modeling is observed above 200°C with a typical discrepancy of 50°C. A first analysis of the profiles along the target (fig.1b) derived from IR and from modeling shows that despite the fair agreement, the IR profile is much broader than the extrapolated one. This can be due to the rather low spatial resolution of the camera (~15mm/ pixel). It also suggests that profiles are probably affected by IR light reflected on the target probably coming from the inner divertor. One has also to keep in mind that these measurements stay rather close to the measurement threshold.

2. TEMPERATURE MEASUREMENTS ON THE WALL

The JET main chamber is protected by a set of 10 (+ 6 recessed) Inner Wall Guard Limiters (IWGL) and 12 Outer Poloidal Limiters (OPL) covered castellated Be tiles (see fig.2a). The two limiters seen in fig.1a are equipped with 24 type-K thermocouples embedded 5mm beneath the surface and distributed over different tiles (with 3 to 5TC per tiles). The temperature of the cold junctions is monitored with a Pt100 thermometer and has been observed to stay constant at 25°C throughout the campaigns. The temperature traces shown on fig2.b are from 4 TCs embedded in the same tile at different toroidal locations. The different evolutions observed in the time traces are explained by the construction of the tile. Each tile is sub-divided in several blocks, only thermally connected by their common carrier. Each thermocouple is located in its own block, with the exception of B and C, which share the same block. The very different temperature rises observed during the pulse (0-20secs) for B, C and D (up to 240°C for A, 190°C for D and none for E) suggest a strong non-homogeneity in the heat deposition pattern, confirmed by the IR data. The TC B is located at the rear of the same block as TC C. It sees a low temperature rise during the pulse but converge to the same temperature after 500s, when the block has thermalised. The TC measurements have been simulated with an ANSYS model. The consequence of a non-homogeneous heat flux on the tile during a pulse leads to heat waves heating the remote parts during the "cooling down" phase.

The surface temperature measured from both IR (for which a Be emissivity of 0.18 is used) and protection camera (operating at 1016±40nm) are shown in fig.2c. The discrepancy of 40°C at the maximum is within the uncertainty of the diagnostics estimated to be around 100°C. Other possible explanation is a toroidal asymmetry as the two cameras do not monitor the same limiter. One can even suspect that the protection camera does not necessarily see the hottest point on the limiter. Layers effect observed in CFC wall campaigns [5] are not expected to play a role as they were only affecting heat profiles during ELMs and not the inter-ELMS ones. This statement is reinforced by the very good agreement obtained during the cooling down phase: the temperatures are different on different parts of the limiter but they eventually converge as it thermalises.

4. ENERGY CALCULATION

In this section we present energy calculations derived from the TC data on the IWGL and OPL and compare them to WALLS, a code that predicts heat fluxes on the JET walls from the plasma input parameters and is used for the JET real time protection system. Our model for the limiters is adapted from that used for the CFC divertor tiles during the previous campaigns at JET [6]. It is based on a back extrapolation of the temperature from the cooling phase back to the maximum temperature supposedly reached during the pulse. This model assumes that the tile has been homogeneously heated and cools down by conduction only. As shown on Fig.2b, temperature is not homogeneous within the tile right after the discharge and we have to wait for the thermalisation to occur, which is usually done after 500sec. The fit is then performed on the data after this time and the beginning of the next pulse, usually 1000sec later. As the homogeneous heating condition is never fulfilled during a discharge, the method has been benchmarked against a CASTEM model of the tile with heat profile on the target derived from the experiment [7]. For an energy of 13-50MJ deposited on the tile, the temperature elevation at the TCs has been simulated (a tile of the divertor has been used for the benchmark). The fit procedure has then been applied to the simulated data and the energies derived compared to the input ones. The analysis shows that the computed energy has to be reduced by 33 percent in order to match the input energy. This value is considered in this paper as the error bar on the energy measurements.

On fig.3a is shown the energy deposited on the OPL during a pulse designed to heat this limiter to a temperature close to the 950°C operational limit, with B_T/I_P is 2.5T/2.35MA and 6MW of input power. The energy profile along the limiter obtained from WALLS [8] heat fluxes and assuming a tile surface of 290 cm^2 is in a rather good agreement with the TC energies. The profile predicted by WALLS, which has been confirmed by IR data, can be approximated by the convolution of an exponential decay and a hyperbolic tangent. The total energy deposited on the limiter can be inferred by fitting TC data with this profile. The calculated energy of 28.5MJ is again in a good agreement with the 32.2MJ energy predicted by WALLS. Another way to validate the energy calculation procedure is to perform an energy balance by comparing the energy deposited on the limiters to the expected energy EWALL. This latest quantity is obtained from $E_{WALL} = E_{IN} - E_{RAD}$, where ERAD is the radiated energy ERAD (derived from bolometry) and EIN the the total input energy EIN. Fig.3b provides the result of such an energy balance for limited pulses with BT/IP in the range 2.4-2.8T/2.0 2.5MA and a total input power of 0-6MW. All but one pulse show a systematic overestimation of the energy deposited on the limiter – the average overestimation being 22% of the expected energy. This number, compatible with the uncertainty mentioned earlier, and the fact that all the measurements stay well below the 33% limit, are a strong indication that thermocouples are a reliable way to compute the deposited energy on the main chamber PFCs. The circle on the plot stands for a diverted discharge (B_T/I_P = 2.2T/2.0MA-10MW NBI) with strike points on the vertical targets. A very good energy balance is obtained for this pulse and we plan to include more measurements (when they become available) in order to get more statistics.

CONCLUSION

Together with the ITER Like Wall new diagnostics have been installed on JET in order to monitor the temperature of its different parts. Because cameras (both IR scientific and protection cameras) and thermocouples provide surface and bulk temperatures that cannot be directly compared, different kinds of modelling have been applied for assessing the consistency of the different diagnostics. The maximum temperature IR measurements on the divertor tungsten coated targets have shown to be in a rather good agreement (within 50°C) with surface temperature extrapolated from the TC with both CASTEM and quadrupole modelling. It has also stressed out the need of further investigations concerning the reflexion on the targets. A similar exercise carried out on the outer limiter has shown the same agreement between the different camera used and the modelling. The benchmarking of the method used to deriving the energy deposited on the tiles from the TC temperature data has been assessed and found to be up to 33 percent. A detailed analysis performed over limited plasmas with and without NBI heating has shown that the energies computed are in agreement with the energy balance. Further work will be done for diverted plasmas as soon as data become available.

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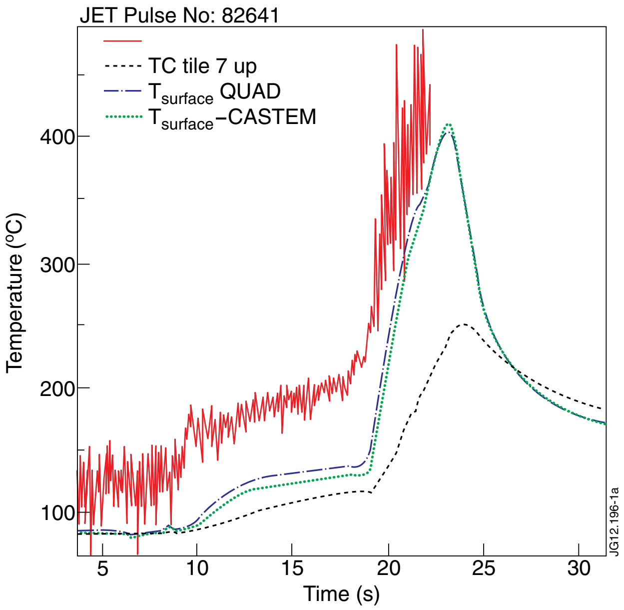

Figure 1a: Comparison of the maximum surface temperature from the IR wide angle camera (KL7) and the surface temperature extrapolated from the thermocouples data by CASTEM and a quadrupole computation (QUAD). The discrepancy of 50°C stays within the uncertainty of the camera measurement.

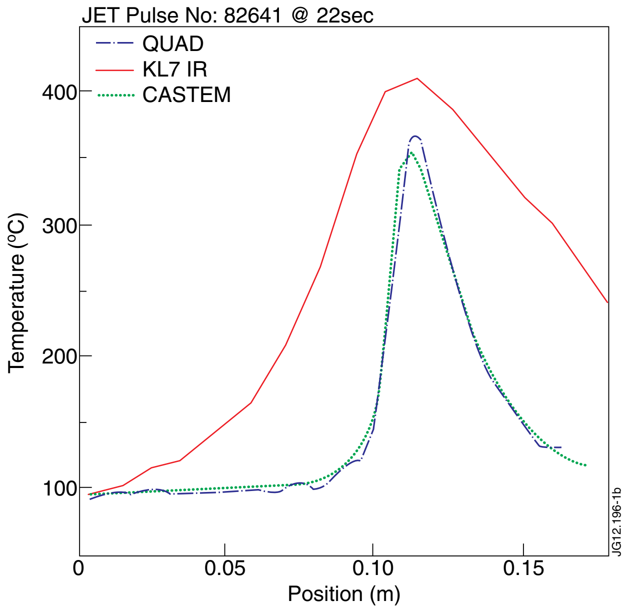

Figure 1b: Comparison of the temperature profiles along the target from the IR data and the CASTEM and quadrupole computations.

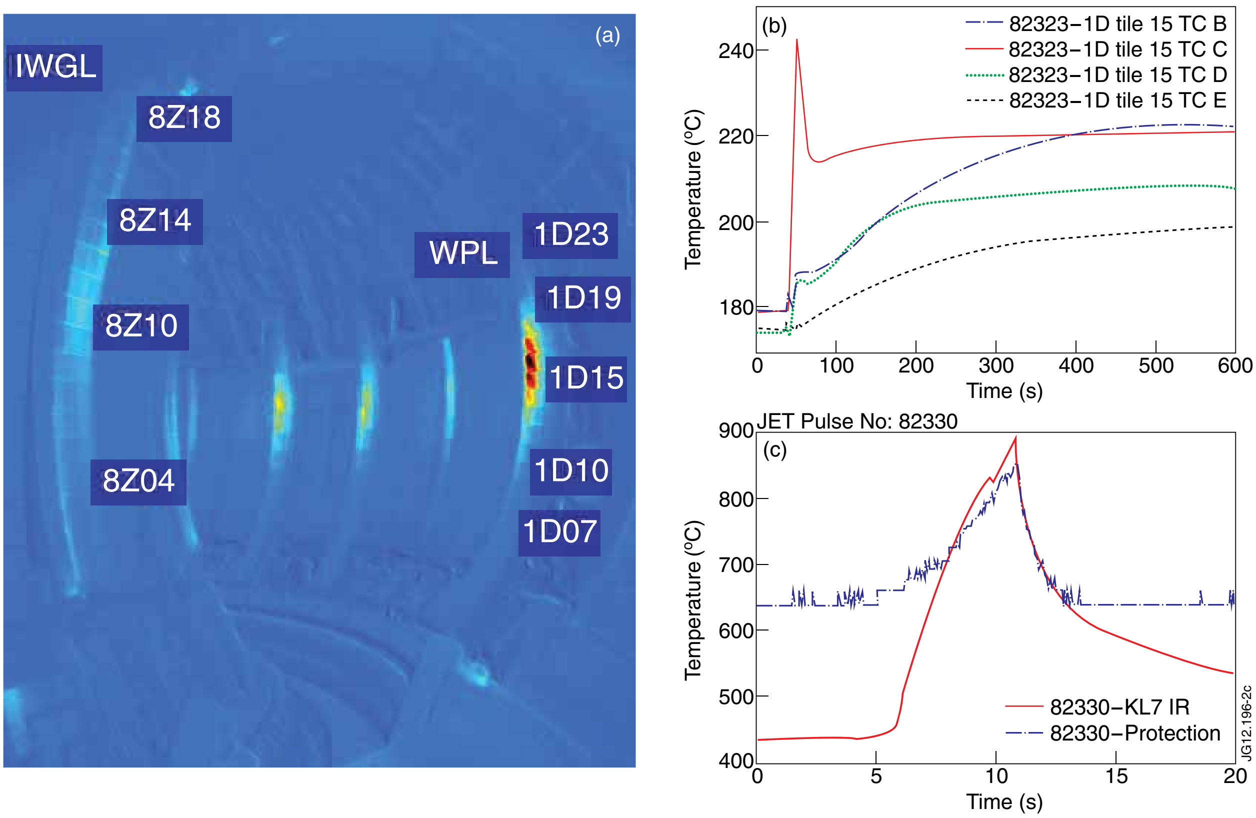

Figure 2a: Image taken with the wide angle view IR camera (KL7). The tile names on the inner wall guard limiter 8Z and the outer poloidal limiter 1D indicate the tiles fitted with thermcouples. Figure 2b: Temperature increase observed for a similar pulse. The TC C shows a greater increase due to its proximity to the plasma contact point. Thermalisation within tiles occurs after 500 sec. Figure 2c shows that the agreement between surface temperature measured by IR and protection cameras are within 100°C.

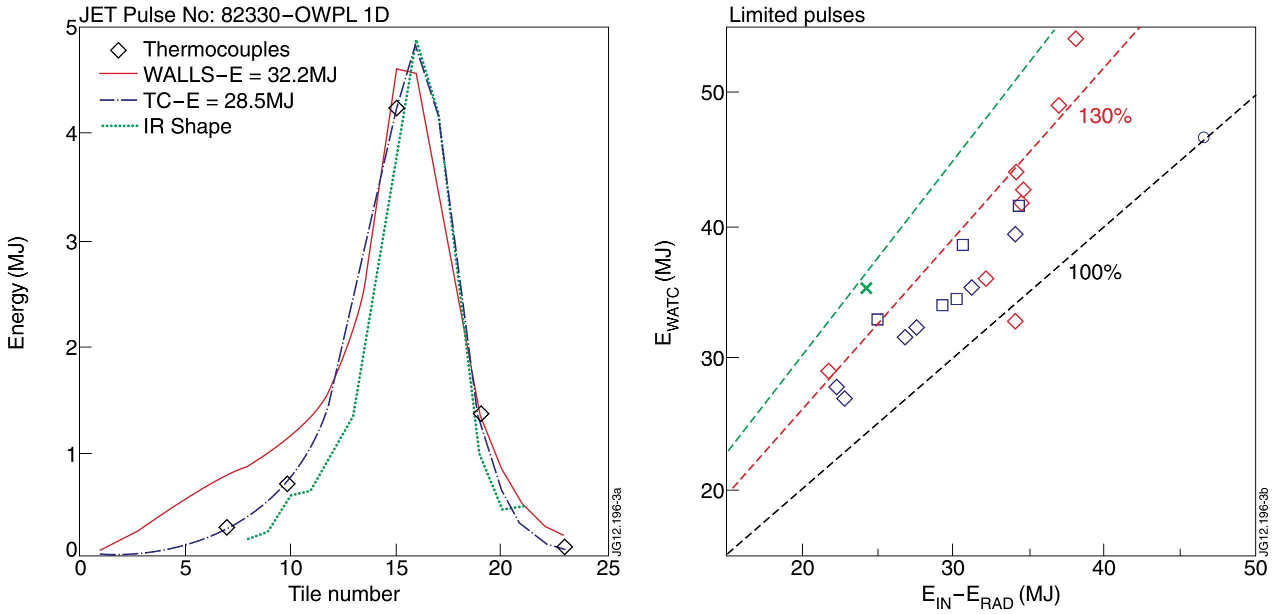

Figure 3: (a) shows the energy deposited along the outer limiter during limited plasma. The thermocouples data, diamonds, are in a good agreement with the WALLS code prediction for this pulse. The shape used to extrapolate the TC measurements (blue) to the whole limiter is based on this prediction and confirmed by IR data (green). (b) Energy balances computed from thermocouples for limited plasma. The comparison of the energy derived from TC overestimate by 22 percent the expected energy (derived from input power and bolometry) but stays within the 33% limit known as the typical overestimation of the model