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Test of 1D carbon-carbon composite prototype tiles for the SPIDER diagnostic calorimeter

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Abstract. Additional heating will be provided to the thermonuclear fusion experiment ITER by injection of neutral beams from accelerated negative ions. In the SPIDER test facility, under construction at Consorzio RFX in Padova (Italy), the production of negative ions will be studied and optimised. To this purpose the STRIKE (Short-Time Retractable Instrumented Kalorimeter Experiment) diagnostic will be used to characterise the SPIDER beam during short operation (several seconds) and to verify if the beam meets the ITER requirement regarding the maximum allowed beam non-uniformity (below ±10%). The most important measurements performed by STRIKE are beam uniformity, beamlet divergence and stripping losses. The major components of STRIKE are 16 1D-CFC (Carbon matrix-Carbon Fibre reinforced Composite) tiles, observed at the rear side by a thermal camera. The requirements of the 1D CFC material include a large thermal conductivity along the tile thickness (at least 10 times larger than in the other directions); low specific heat and density; uniform parameters over the tile surface; capability to withstand localised heat loads resulting in steep temperature gradients. So 1D CFC is a very anisotropic and delicate material, not commercially available, and prototypes are being specifically realised. This contribution gives an overview of the tests performed on the CFC prototype tiles, aimed at verifying their thermal behaviour. The spatial uniformity of the parameters and the ratio between the thermal conductivities are assessed by means of a power laser at Consorzio RFX. Dedicated linear and non-linear simulations are carried out to interpret the experiments and to estimate the thermal conductivities; these simulations are described and a comparison of the experimental data with the simulation results is presented.

INTRODUCTION

The thermonuclear fusion experiment ITER requires additional heating by injection of neutral beams resulting from the acceleration of negative ions. The SPIDER test facility is under construction at Consorzio RFX in Padova (Italy) to study and optimise the production of negative ions and their extraction from the ion source [1]. STRIKE (Short-Time Retractable Instrumented Kalorimeter Experiment) is a diagnostic system dedicated to characterise the SPIDER beam during short pulse operation (several seconds) and to verify if the beam meets the ITER requirement regarding the maximum allowed beam non-uniformity (below ±10%). The most important measurements performed by STRIKE will be beam uniformity, beamlet divergence and stripping losses: as described in [2], the beam uniformity is measured by the variation of the thermal profile across the tiles and the beamlet divergence can be determined form the thermal profiles measured at two positions from the accelerator (the measurement is performed quite close to the accelerator, so that the size of the beamlets at the accelerator exit is not negligible when individual beamlets are clearly resolved and adjacent beamlets do not significantly overlap); stripping losses can be estimated by the synergy of thermal and electrical STRIKE measurements and the currents at the grids and power supplies.

The major components of STRIKE are 16 1D-CFC (Carbon matrix-Carbon Fibre reinforced Composite) tiles, observed at the rear side by a thermal camera. The 1D CFC material requires: thermal conductivity through the tile thickness at least 10 times larger than in the two transverse directions; low specific heat and density; uniform parameters over the tile surface; capability to withstand localised heat loads resulting in steep temperature gradients. So 1D CFC is a very anisotropic and delicate material, not commercially available, and prototypes are being specifically realised. This contribution gives an overview of the tests of the CFC prototype tiles manufactured by the Japanese company Toyo Tanso (material grade CX-1001U) and reports about the corresponding numerical

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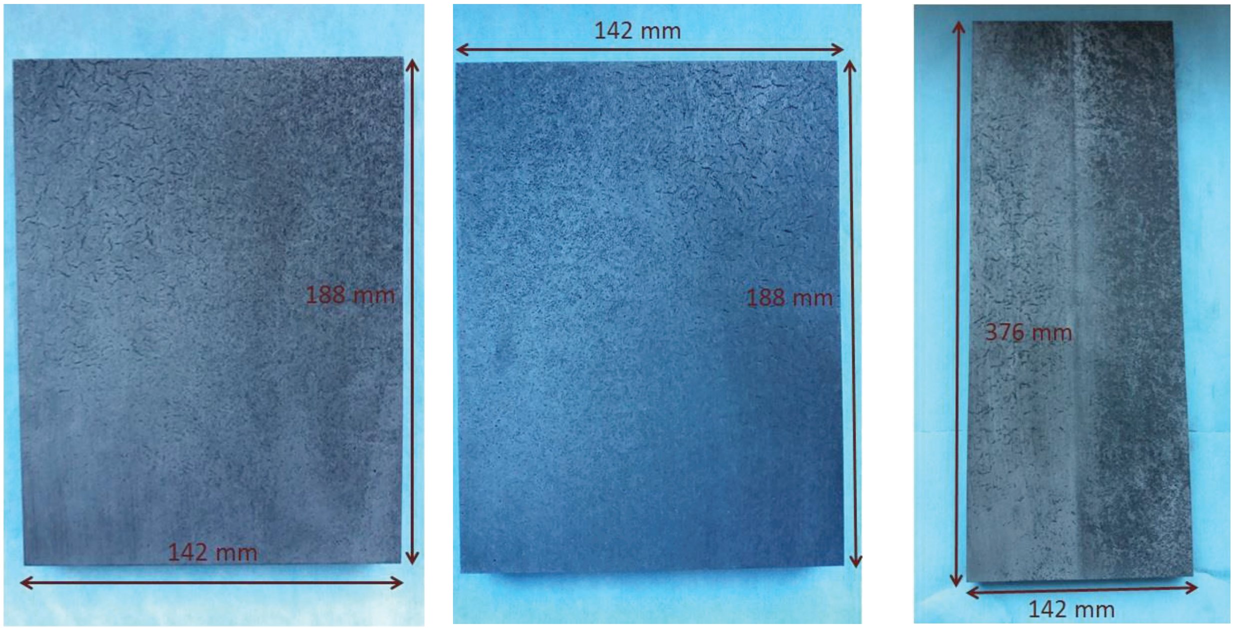
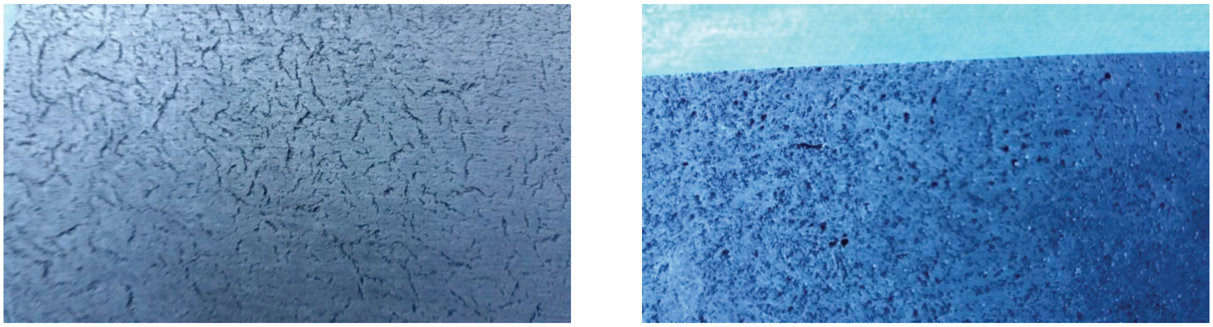
simulations, aimed to verify the spatial uniformity of the thermal parameters and to assess the ratio between the thermal conductivities by means of a power laser at Consorzio RFX.

In the last years Consorzio RFX has already tested similar prototype tiles produced by two different companies and a testing procedure was developed [3, 4], aiming both at assessing uniformity and temperature dependence of the thermal parameters and at verifying the thermo-mechanical resistance of the tiles under irradiation by a huge and localised energy flux. The prototypes which proved to satisfy the requirements on anisotropy and on resistance to thermo-mechanical stresses, produced by Mitsubishi, were successfully employed to verify their diagnostic capabilities in different ion source test facilities, such as BATMAN (IPP, Garching) [5], NIFS-RNIS (Toki, Japan) [6] and NIO1 (Padova Italy) [7]. The size of those prototypes ($120\times90\times20$ mm^3) was smaller than required by the present STRIKE design, namely $376\times142\times20$ mm^3 [8]; moreover in the meantime the production of those tiles has been discontinued leading to the necessity of qualifying another supplier. As the manufacturing processes are quite delicate, the feasibility of producing large tiles with suitably uniform thermal parameters and not prone to cracks when huge localised heat loads are applied has not to be taken for granted and the production of a full size prototype has to be considered as a necessary step in the direction of setting up STRIKE as a beam diagnostic. Due to these manufacturing issues, the company provided one full size (in the following called C3 – $376\times142\times20$ mm^3) and two half-size (C1 and C2 – $188\times142\times20$ mm^3) prototypes. A photo of each of the three prototypes is given in Figure 1.



(a) (b) (c)

Figure 1. Photos of the three prototype tiles. (a) tile C1 , (b) tile C2, (c) tile C3.



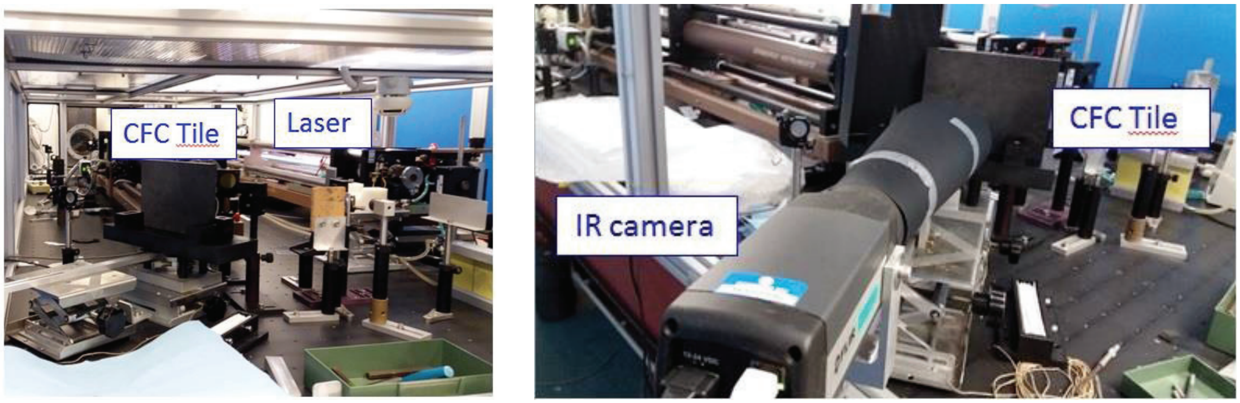
(a) (b)

Figure 2. Details of the tile surface. (a) Tile C2, (b) Tile C3.

A visual inspection of the prototypes reveals many localised defects on their surface. Some of them are highlighted in Figure 2. Similar signs were found also in previous prototypes without reduction of the diagnostic and thermo-mechanical properties of the samples [4].

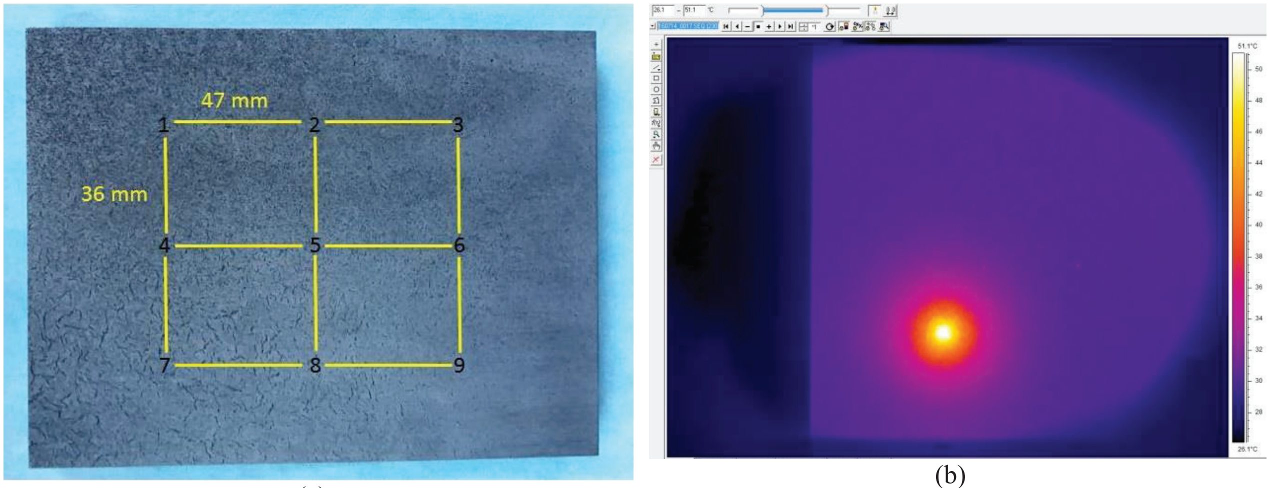
TEST OF THERMAL PROPERTIES BY LASER IRRADIATION

To verify the thermal parameters (thermal conductivities and specific heat) provided by the company and their uniformity within each tile, the prototypes were irradiated by a 60W laser. The temperature of the rear surface of the tile was measured by an infrared (IR) camera. The experimental setup used for the measurements is given in Figure 3. The tiles were placed so that the longer dimension lay in the horizontal direction.



(a) (b)

Figure 3. (a) Overall view of the experimental setup. (b) Camera field of view to the tile.

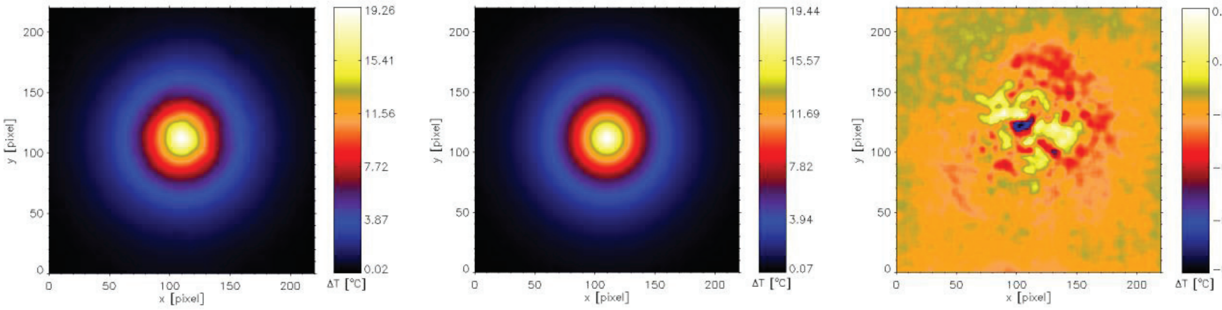


(a) (b)

Figure 4 (a) Position of the 9 measure points used for tile C1 and C2. (b)Temperature measurement from IR camera software in position #7.

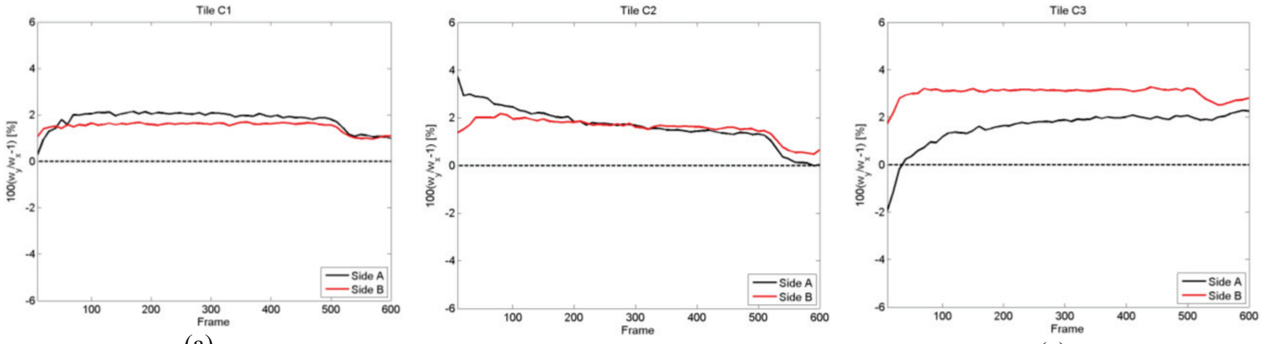
The uniformity of the thermal parameters within the tile was assessed by applying the laser pulse in different positions. For tiles C1 and C2 in particular, irradiation was performed in 9 positions arranged in a 3×3 matrix, by moving the tile support upward or downward and by moving the tile left or right. These measurements were repeated by exposing both sides to the laser beam. In any case, spacing equal to one quarter of the tile dimension was adopted. The spacing in the horizontal (x) and vertical (y) directions is then Δx=36mm and Δy=47 mm respectively. These 9 positions are shown in Figure 4a. In the following, the notation introduced in this figure will be used. The same spacing was used for tile C3, identifying 21 measurement positions. The laser power was P_{laser}=60W throughout the tests. The laser pulse duration was t_{laser}=20s and the number of frames per second f_s=25fps. Data were acquired for about 60s so as to monitor also the cooling phase. The emissivity of the surface is expected to be in the range [0.8-1.0]. The typical maximum ΔT measured with a 20s pulse is about 25K and the spatial resolution of the measurement is about 0.31mm/pixel. An instance of the infrared camera images is given in Figure 4b.

As no automatic triggering was used for the laser and the camera but they were both controlled by the operators, the first frame of each laser pulse has to be deduced from the data. The simplest way to do this is to determine when the temperature of the spot hit by the laser starts to increase. As heat takes some time to propagate from the front to the rear side of the tile it is reasonable to assume an uncertainty of a few frames (100-200ms) in this determination. Once the first frame is found, a background temperature profile can be evaluated as the average of the ten previous frames and is subtracted from the measured one. The ΔT(x,y) map is then fitted by a Hubbert function, which was found in the past to accurately fit the thermal pattern under localised heat loads [4]. Thus the amplitude and the half width at half maximum (HWHM) of the peak can be determined; the fitting procedure permits different HWHFs in the x and y directions to verify whether they are equal. An example of the fitting is given in Figure 5. The width of the thermal pattern is small during the beam-on phase, in which both thermal conductivities play a role. When the laser is switched off, the profile rapidly widens and the dynamics of this broadening is mainly determined by the conductivity in the direction perpendicular to the fibres and by the border effect due to the finite extension of the tile. A first test can be performed on the ellipticity of the profile, defined as the percentage difference between HWHMy and HWHMx. Figure 6 shows the trend of the ellipticity for the central position of all three prototypes.



(a) (b) (c)

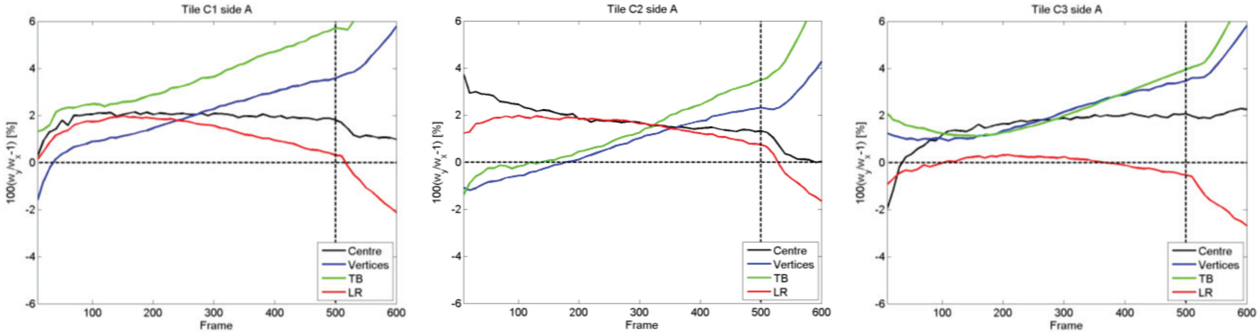
Figure 5. (a) Smoothed profile of measured ΔT(x,y). (b) Fit of data by 2D Hubbert function. (c) Residuals of the fit.



(a) (b) (c)

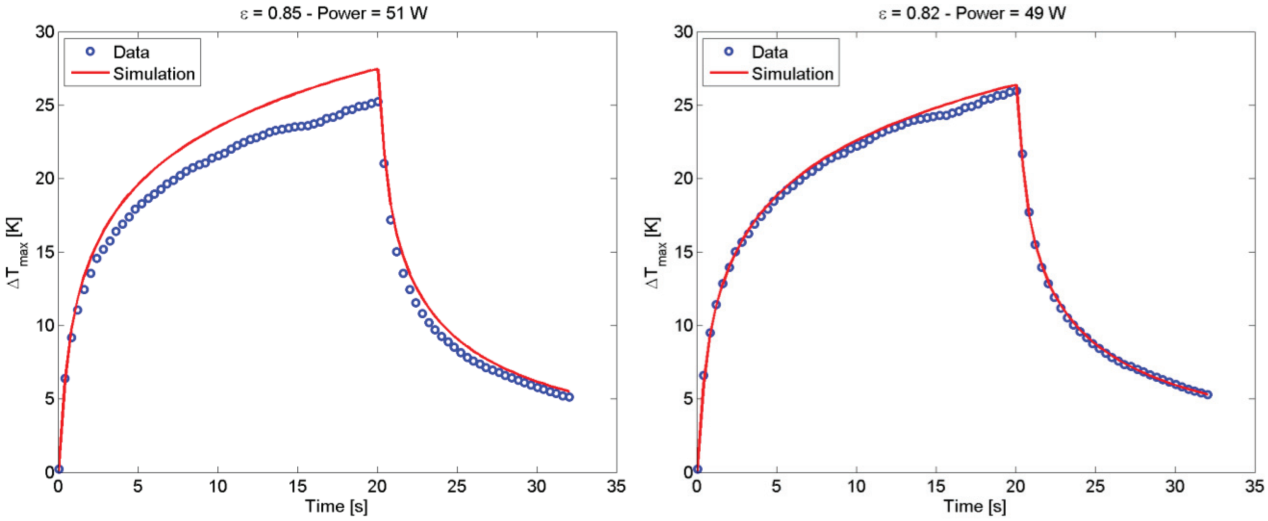
Figure 6. Time trace (25 frames per second) of the ellipticity of the temperature peak measured in the centre of the tile (position #5). (a) Tile C1, (b) Tile C2, (c) Tile C3.

The ellipticity is found to be about 2-3% and is found to be almost constant throughout the laser pulse; it generally decreases at the end of the irradiation, as expected, due to the aforementioned widening of the thermal pattern. The constancy of the ratio suggests that for the central position no deformation due to border effects occurs. A summary of the ellipticity measurement for all positions is given in Figure 7. For ease of visualisation, the measurements related to positions that are symmetric with respect to the centre of the tiles, and so have the same distance from the borders, are averaged together. As shown in Figure 7, when considering the outer positions, the ratio between FWHMx and FWHMy changes with time. This variation is consistent with the position in which the measurements are taken. The vertices for example, are closer to the tile border along the x direction than along the y direction. Heat propagation is then easier along y explaining why the ellipticity grows with time. The same effect is expected to be even larger for positions #2 and #8, whereas an opposite trend is expected for positions #4 and #6 and this is indeed observed. It can be concluded that 2-3% is a good measure of the ellipticity throughout the tile. The error on this measure is estimated to be around one percentage point, resulting from a possible misalignment of the infrared camera with respect to the tile surface and the corresponding distortion of the infrared image; the specific structure of the laser beam is not expected to affect the ellipticity, since the laser spot size is much smaller than the thermal pattern on the rear side so that it can be assumed as point-like.



(a) (b) (c)

Figure 7. Time trace (25 frames per second) of the ellipticity of the thermal image in different positions; the vertical dashed line indicates the end of the laser pulse. Measurements in symmetric positions are averaged together. Legend “TB” stands for the top and bottom position at x= $L_x/2$, i.e. position #2 and #8. Legend “LR” stands for the left and right position at y= $L_y/2$, i.e. position #4 and #6. (a) Tile C1, (b) Tile C2, (c) Tile C3.



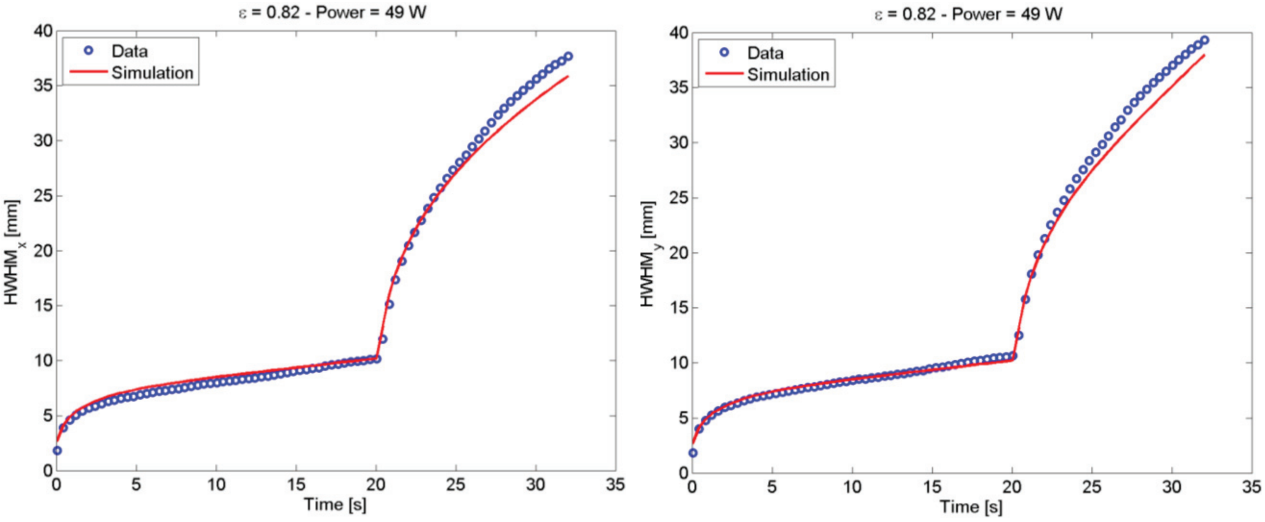
(a) (b)

Figure 8. Time trace (25 frames per second) of the maximum temperature increase for different values of emissivity. (a) ε = 0.85, (b) ε = 0.82.

FINITE ELEMENT SIMULATIONS

To check the thermal parameters provided by the manufacturer finite, element simulations were performed by means of the COMSOL code. Thanks to the geometrical symmetry, only one quarter of the domain was simulated. The laser heat flux was modelled as a Gaussian with HWHM equal to 1.5mm. The following thermal parameters at room temperature were used in the simulations: bulk density 1980kg/m^3, specific heat 710J/kg/K, parallel thermal conductivity 726W/m/K, perpendicular thermal conductivity 37W/m/K. It is worth mentioning that the mesh size where the heat load is applied has to be very small to guarantee that the power is correctly reproduced in the model; to this purpose the mesh size in the area where the heat load is applied was limited to 120µm (it is not the purpose of this simulation to describe the behaviour of the single fibre bundles making the 1D-CFC). Another parameter which has to be properly set is the emissivity of the surface as this parameter plays a role both in the measurements and in the simulations. If the emissivity is reduced, for example, the measured temperature is larger, whereas the temperature resulting from the simulations decreases since the power effectively entering the tile is not the nominal power P_{laser} but it reduces to εP_{laser} when the fraction $(1-\varepsilon)P_{laser}$ is reflected. The latter effect is of course much more important. The same fitting procedure applied to experimental data was adopted for the simulated profiles. A comparison between data and simulation is given in Figure 8: it can be seen that for $\varepsilon=0.82$ the increase of the simulated maximum temperature matches the experimental data, and that a large degradation is obtained with only a slight variation to $\varepsilon = 0.85$.

To verify the correctness of the thermal parameters provided by the manufacturer also the HWHMs obtained from the fits were compared. Considering the case $\varepsilon = 0.82$, the agreement is quite good both for the vertical and the horizontal directions generally within few percentage points (see Figure 9). This can be improved by slight modification of the thermal conductivity used in the numerical model.



(a) (b)

Figure 9. Time trace (25 frames per second) of the HWHM of the peak. (a) horizontal direction, (b) vertical direction.

CONCLUSIONS

The present paper reports on the test of the prototype tiles for the diagnostic calorimeter STRIKE for the SPIDER device, under construction at Consorzio RFX. The calorimeter requires the tiles to be made of a very anisotropic material (CFC) in order to reduce the deterioration of the thermal image observed on the rear side when the tile is heated by the particle beam impinging on the front side. As this particular material is not commonly available, a prototyping phase is in progress to qualify the tiles for the supply of the 16 items (and also spares) necessary for STRIKE.

A first campaign was carried out to verify the uniformity of the response of the tiles to the heat load and to assess the correspondence between the thermal parameters provided by the supplier and the results of simulations, and ultimately to guarantee the capability of numerically reproducing the thermal behaviour of the tiles; this is a necessary step towards the interpretation of the data measured by STRIKE as a diagnostic of the SPIDER beam properties. The results of the characterisation of the prototypes are satisfying: a residual ellipticity (2-3%) is found in the thermal image under laser irradiation, which can be attributed to a small difference between the thermal conductivities in the plane perpendicular to the fibre direction; the thermal parameters provided by the supplier seem correct to reproduce the measured data; a reasonable value of the thermal emissivity is estimated.

Future refinements in the assessment of the prototypes will be, from the numerical point of view, the simulation of the laser tests by slightly modifying the thermal parameters, including the introduction of a small difference between the perpendicular thermal conductivities (to reproduce the tiny ellipticity). Such small corrections are anyway expected to lie within the reproducibility of the construction process of this unique material. To qualify the material for the harsh operating conditions of the STRIKE calorimeter thermo-mechanical tests are also required ascertaining the capability of the prototypes to withstand huge and localised energy fluxes like those performed in [9]. They will be carried out in the very next future. As a final remark, the mechanical structure, which will support the 1D-CFC tiles is presently under construction and delivery is expected before the end of 2016.

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