Beam Profiles Measurement using a Unidirectional CFC-Target and Infrared Imaging

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We present a new high resolution beam diagnostic system for particle beams at MW power levels. The technique combines unidirectional properties of the Mitsubishi MFC-1 material with infrared imaging, and is used to measure the two-dimensional beam power density distribution. The application of the technique is demonstrated in characterisation of energetic neutral particle beams extracted from the JET high current tetrode ion source.

1. INTRODUCTION

Accurate measurements of the properties of energetic particle beams is important for beam handling and injection into tokamaks. Beam alignment, divergence, and power density distribution are critical parameters which affect overall injection efficiency. Incorrectly aligned or focused beams can cause serious damage to beamline components.

Common techniques used for high power beam diagnostics are inertial and water calorimetry [1], where power density is determined from the thermal response of copper blocks or cooling fluids. Both techniques provide one-dimensional beam profiles.

We developed a new high resolution diagnostic to measure the properties of energetic particle beams. Two-dimensional beam profiles are determined from the thermal response of highly anisotropic Carbon Fibre Composite (CFC) target exposed to energetic particle beams.

2. MEASUREMENT TECHNIQUE

The 40 mm thick 150×200 mm² CFC target (Mitsubishi MFC-1) is placed at the beam centre line of the JET Neutral Beam Test Bed at a distance of 7 metres from the beam source (Figure 1). The target is exposed to particle beams with peak power densities ranging between 5 and 30 MW/m², with a pulse length ≤ 0.5 s. Power density distribution along two lines perpendicular to the beam axis can be measured by an array of inertial copper blocks (cross calorimeter). The surface temperature of the target is measured by an AGEMA Thermovision 900 SW infrared imaging system. Infrared (IR) images are recorded at a rate of 15 Hz. The IR imaging system has a temperature range 0-2000°C and the accuracy of 1%. Several thermocouples are used to monitor the CFC target bulk temperature. The emissivity of $\varepsilon=0.8$ is determined from the comparison between IR and thermocouple signals when the target was heated up to a thermal equilibrium at several hundred °C.

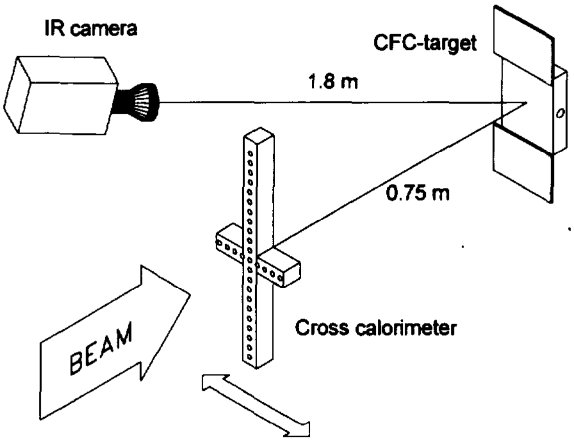

Figure 1. Experimental layout.

Figure 2 shows two IR images of the CFC target recorded 0.15 seconds after the target was exposed for 0.3 seconds to a 25 MW/m² Helium beam. The first image clearly shows two separate beams originating from two grid halves of the JET high current tetrode PINI. The second image was obtained for the same ion source parameters, except that the beam was steered so that the upper half of

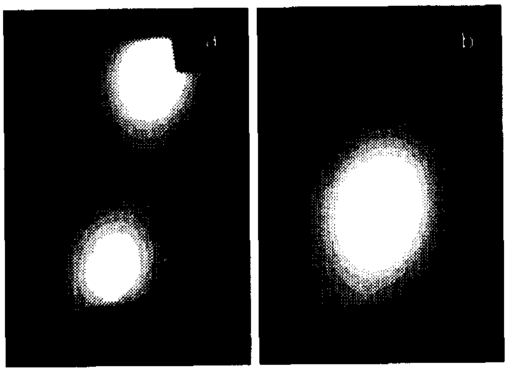

Figure 2. Infrared images of the CFC target exposed to a 25 MW/m² Helium beam for 0.3 s.

the beam is centred on the target. The footprint of the beam is clearly visible long after the pulse. This is illustrated in Figure 3, where the horizontal profile through the beam centre (Figure 2.b) is plotted versus the elapsed time after the pulse. The temperature is corrected for the initial target temperature.

The fact that the target surface temperature distribution reflects the beam power density distribution long after the beam pulse is the consequence of the unidirectional thermal properties of the Mitsubishi MFC-1 target. This material has high thermal conductivity in the direction of the beam (k_z) and low lateral thermal conductivity ($k_{x,y}$) [2]. The ratio $k_z/k_{x,y} \approx 20$ remains practically constant over the wide temperature range (Figure 4). For that reason the thermal equilibrium in the beam direction is reached within seconds while the lateral thermal equilibrium is reached after ~10 minutes.

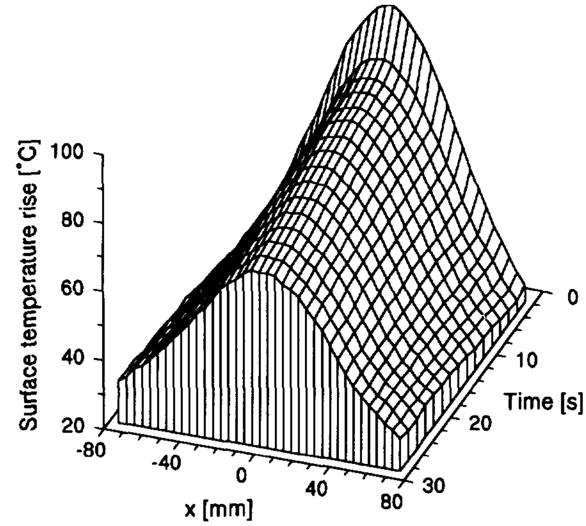

Figure 3. Horizontal temperature profile through the centre of the beam during the target cooldown.

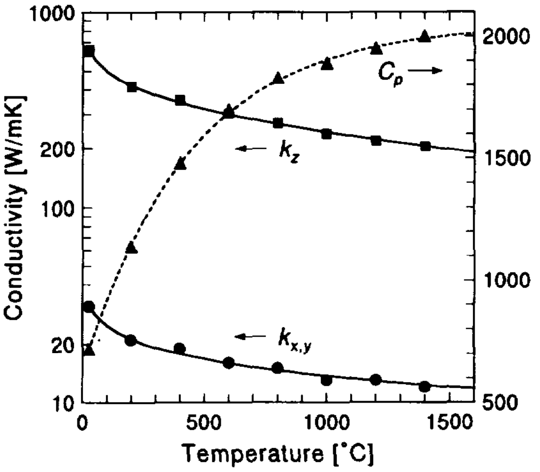

Figure 4. Thermal properties of the MFC-1 target.

3. POWER DENSITY EVALUATION

The particle beam power density distribution can be obtained by normalising the surface temperature to the power density determined by the inertial calorimeter. However, as thermal properties of the Mitsubishi MFC-1 material are known, it is possible to determine the power density directly from the temperature distribution.

The relation between the beam power density and the target temperature is

$$p = \frac{T - T_0}{F\tau}, \qquad (1)$$

where p is the power density, τ is the pulse length, and T and T_0 are the equilibrium target temperatures before and after the pulse. If the material properties do not vary with temperature, F is a constant determined by the size , density and heat capacity of the inertial block. Factor F defines the increase in equilibrium temperature per unit energy density on the target. Since thermal properties of the MFC-1 material are strongly dependent on temperature, one should run a finite element code to determine the factor F which is, in this case, temperature dependent - F=$F(T_0)$. It is sufficient to run the code in a one-dimensional approximation due to the highly anisotropic thermal conductivity of the material. To check this assumption, the measured surface temperature for power densities of 9.8 and 4.4 MW/m² and the beam pulse length of 5 s is compared to the results of TOPAZ2D [3] finite element simulation in Figure 5. The numbers in brackets are the actual power densities used in the simulation.

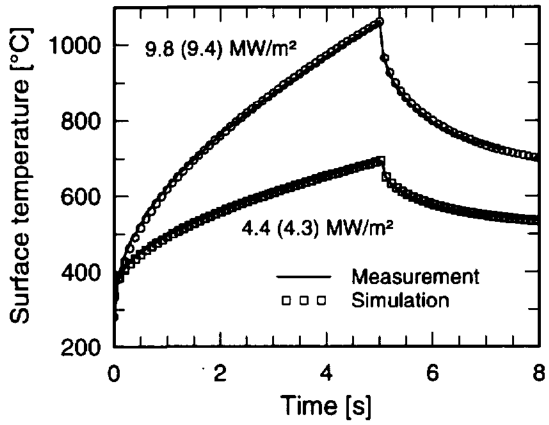

Figure 5. Surface temperature of the MFC-1 target exposed to high power hydrogen beam for 5 s.

The time required to reach thermal equilibrium is dependent on the energy deposited on the target. To avoid long cooldown times, the maximum energy density should be below 10 MJ/m². The finite element simulation was used to determine function $F(T_0)$. The initial target temperature was varied between 25 and 250°C for the heat flux range 1-50 MW/m². The energy flux was maintained at 3 MJ/m² by varying the heat flux pulse length between 0.06 and 3 s. Calculated values of $F(T_0)$ decrease from 16 to 10 °Cm²/MJ for the considered temperature range and 40 mm thick MFC-1 target. From the measurements (and simulation) we found that the target is in thermal equilibrium (in the beam direction) after ~4s.

Power density at point (x,y) on the surface is determined by:

$$p(x,y) = \frac{T(x,y) - T_0(x,y)}{F(T_0)\tau}. \qquad (2)$$

T and T_0 are surface temperatures before and 4s after the beam pulse.

A computer code was developed to calculate power density distribution from two IR images. The code reads binary image files and transforms them into a rectangular $p(x, y)$-grid. The code requires 4 reference points on the IR image defining a rectangle in the (x,y)-space. Surface temperature at point (x,y) is determined by overlaying the rectangular mesh on an IR image and by calculating the temperature in the grid nodes from the temperature in the four neighbouring pixels. The code produces power density contour plots or colour zone plots and runs under MS-Windows. The code also provides tools for interactive analysis of the beam power density distribution (normalisation, averaging, curve fitting, profiles, etc.).

RESULTS AND DISCUSSION

The technique described above was used to analyse the properties of particle beams from the JET high current tetrode PINI 11A. As an illustration the power density contours for a 51 kV, 17.5 A Helium beam are shown in Figure 6. This power density distribution is obtained from the IR image shown in Figure 2b. The peak power density is above 25 MW/m² and the beam divergence is 0.38°.

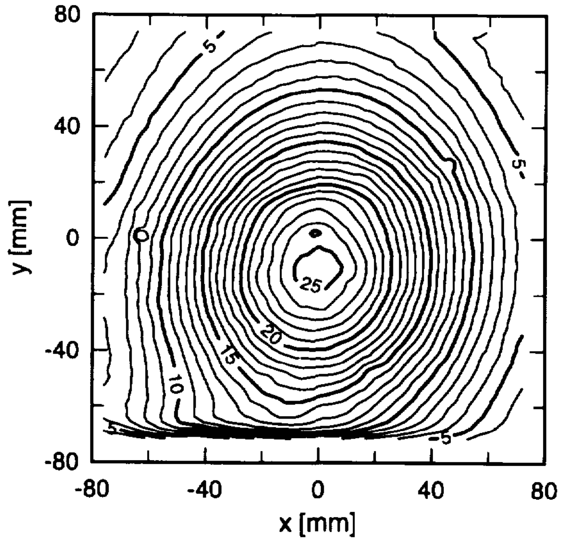

Figure 6. Power density contours of the 51 kV, 17.5 A Helium beam.

The one-dimensional beam power density profiles measured by conventional inertial and IR calorimetry agree very well (Figure 7). The error bar in Figure 7 represents 5% standard deviation which, in this particular case, corresponds to 1.3°C. From Figure 7 we can conclude that the noise level in the IR calorimetry is considerably lower, and that the resolution of this method is much higher - for 1.8 m distance between the target and the IR camera the resolution is ~2x2 mm².

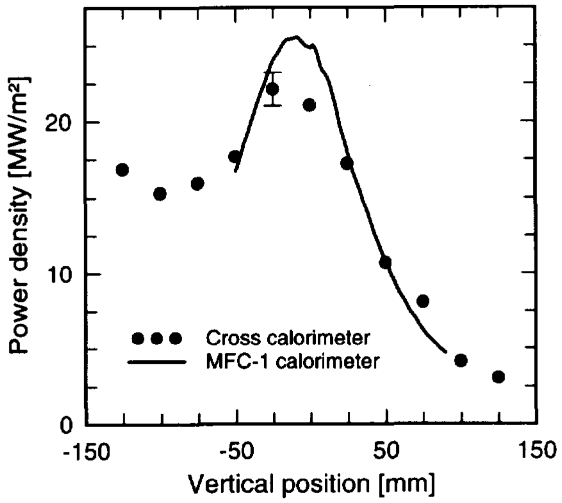

Figure 7. Comparison between conventional and infrared calorimetry.

Although the lateral heat diffusion is significantly lower then the longitudinal one, it is not negligible (Figure 2). To account for this effect the power density distribution is determined by normalising the temperature distribution recorded immediately after the pulse to the equilibrium one.

The IR calorimetry using the anisotropic CFC target is far superior compared to the conventional calorimetry methods. This is clearly demonstrated by power density distribution shown in Figure 8. The power density contours shown in Figure 8 correspond to the IR image given in Figure 2a. The horizontal profile along the *y*=0 line shows perfectly aligned beam with peak power density of ~14 MW/m², while the actual beam has two separate components with peak power density of 25 MW/m².

The resolution of the IR calorimetry is considerably higher, the accuracy is comparable, and the information much more detailed then in the conventional calorimetry. Since the CFC target can withstand temperatures in excess of 1500°C, the IR calorimetry can be used for very high power beams (>200 MW/m²). One limitation of the method is relatively short pulse length. To avoid overheating of the target, the maximum energy density should be below 10 MJ/m². The method does not require very fast IR imaging systems as the time between two recorded images is a few seconds.

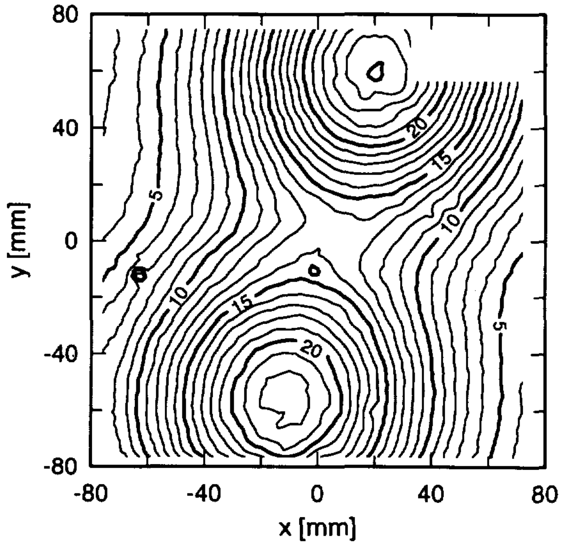

Figure 8. Power density distribution for a 51 kV, 17.5 A Helium beam (infrared image in Figure 2a).

A new 20 mm thick 400x200 mm² calorimeter made of Mitsubishi MFC-1A material is presently being constructed and will be used for the characterisation of the JET neutral injector ion sources as a routine diagnostic.

ACKNOWLEDGEMENT

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