32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-5.015 (2005)

Issues related to power load studies in MAST with an infrared camera

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Introduction

Negative heat fluxes are derived from infrared (IR) camera measurements during surface cooling, following a transient power influx [1] and are explained by an over-estimation of the temperature during the heating phase. This well known phenomenon, but unphysical, is one of the main issues in heat load calculations in tokamaks and is currently explained by carbon layers in bad thermal contact with the bulk. In this paper, we discuss other possibilities like a non homogenous surface temperature distribution. The target heat fluxes in MAST are deduced from IR measurements of the surface temperature using THEODOR, a 2-D inverse heat transfer code which considers the presence of a layer with a given α parameter, the ratio of the heat conductivity to the thickness of the layer [2], and more recently, TACO, a 3-D code which solves the heat transfer equation without any layer correction. Hot spot contribution to temperature measurements and flux calculations have been simulated at different wavelengths for slow and fast transient events and compared with experimental results.

Experimental set-up and simulation The Santa Barbara IR Camera (SBFP 125, 320x256 pixel) has a maximum frame rate of 10 kHz for a 8x128 pixel subwindow and 315 Hz for full frame data acquisition. Two IR filters have been used at 3.5 - 4 μm and 4.5 - 5 μm. Laboratory experiments with a flash lamp heating have also been carried out to compare the flux measurements on different graphite samples at different wavelengths. Mast experiments are characterised by the natural sweeping of the strike point along the divertor tiles. At the beginning of the 2004 campaign, negative fluxes have been measured following the strike point heat load. This observation has highlighted the over-estimation of the surface temperature on the new divertor, installed for this campaign, without any deposited layer. It has been shown previously by D.Hildebrandt [3] that the surface layer effect can apply in addition to a non uniform surface temperature distribution due to the surface morphology and both lead to an over-estimation of the surface temperature. The surface roughness, R_a (average of the surface height), measured from tiles taken from the divertor after the 2003 campaign varies between 2 and 7 μm and was much smaller than the spatial resolution of the camera (~ 1cm), with the consequence that the radiance measured by each pixel is from different zones of different temperatures. For this kind of non-blackbody spectrum, the hot spot hypothesis employed on Tore Supra has allowed simultaneous assessment of the hot spot coverage, varying between 1 and 5 %, and the main surface temperature [4]. For hot spot simulation, a first assumption is made using a model of dust in radiative equilibrium [5] to approximate the thermal behaviour of the hot spot with a size of 4 µm and a surface coverage of 5 %. The measured radiance by each pixel of the detector is assumed to be the sum of the radiance emitted by the bulk, R_{bulk}, and 5 % of the hot spot radiance, R_{hs}. R_{bulk} is calculated with the temperature given by the semi-infinite equation [3] and R_{hs} with the dust

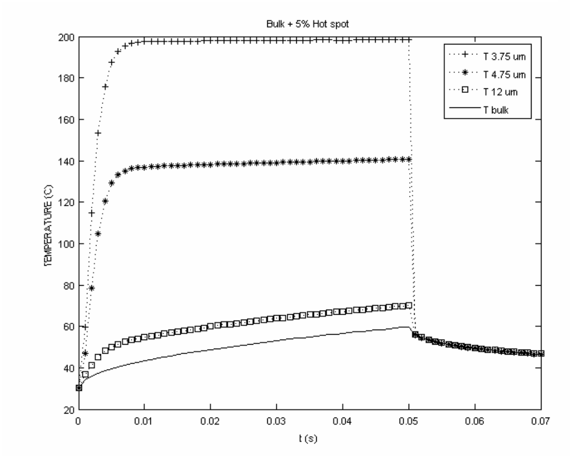

*Figure 1: Simulated temperature measurement for a power flux of 1 MW/m2 incidentfor 50 ms on a graphite surface with 5 % hot spot coverage and various wavelengths (*3.75, 4.75 and 12 µm) .

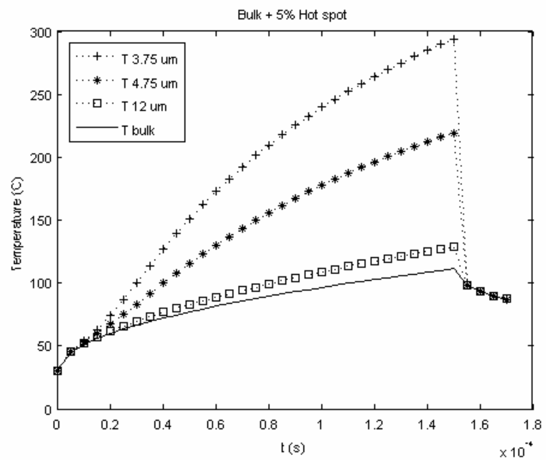

*Figure 2: Simulated temperature measurement for a power flux of 50 MW/m2 incident for 150 µs on a graphite surface with 5 % hot spot coverage and various wavelengths (*3.75, 4.75 and 12 µm) .

model [5]. The radiance has been calculated at 3.75 µm, 4.75 µm and 12 µm for a slow transient event (~ 50 ms) (figure 1) corresponding to the duration when the strike point stops on the divertor, and for an ELM (figure 2). The hot spot contribution depends on the temperature difference, ΔT, between the bulk and the hot spots and the over-estimation decreases with wavelength (figure 1 & 2). According to the Planck law, high temperature radiates more in near infrared than a low temperature which radiates mainly in the middle and the far infrared. This characteristic of the blackbody emission explains why the non uniform surface temperature leads to a higher over-estimation of the temperature in the NIR than the MIR and FIR. According to the hot spot radiative equilibrium assumption, and the chosen free parameters like hot spot size and surface coverage, the temperature calculation is significantly over-estimated by 160 %, 100% and 20% respectively at 3.75, 4.75 and 12 µm after 150 µs of an applied power flux comparable to an ELM. Calculations using the hot spot model have shown that the temperature reached by the dust depends on the power load, the time constant depends on the dust size and the intensity of the negative flux depends on the hot spot surface coverage.

Experimental approach According to the hot spot hypothesis, we should measure, for the same power load, higher temperature and higher flux at 3.75 than 4.75 µm. Experiments have been performed on MAST to reproduce identical shots in order to compare flux calculated at 2 wavelengths. Shots # 12922 (filter 3.5 - 4 µm) and #12931 (filter 4.5 - 5 µm) are comparable L-mode sawtooth free plasmas (ie same stored energy and D_α emission). As usual a negative flux is calculated with TACO which follows the strike point sweeping. Calculation at 3.5 - 4 µm have shown a flux ~ 20 - 40 % higher than at 4.5 - 5 µm. Figure 3 displays the total energy load on the divertor using THEODOR compared to the energy released from the scrape off layer for a shot repeated with identical set of parameters with two filters. In order to match the stored energy calculated by EFIT and the flux calculated with IR data, the α parameter requires infinite value (perfect layer thermal conductivity) in the range 4.5- 5 µm compared to the value 30 kW/m/K at 3.5- 4 µm. This dependence of surface thermal properties on wavelength is inconsistent with a layer phenomenon but is in agreement with the non-homogenous temperature distribution hypothesis. Moreover, it has been previously observed on MAST that the α parameter does not completely eliminate anomalous negative heat fluxes and different values of α are required for high-power events such as ELMs [6]. Use of a flash lamp with ~140 µs pulses at 20 Hz from 10 to 100 Joules has allowed the simulation of power heat load during ELMs from 24 to 240 MW/m^2. Figure 4 displays the flux calculated at the highest temperature peak measured and averaged over area (128 x 8 pixel). Only a discrepancy with wavelength, at 50J on the used graphite sample, is observed. However a clear over-estimation is measured for both graphite samples with higher over-estimation on graphite from 2003 (R_a = 3.84

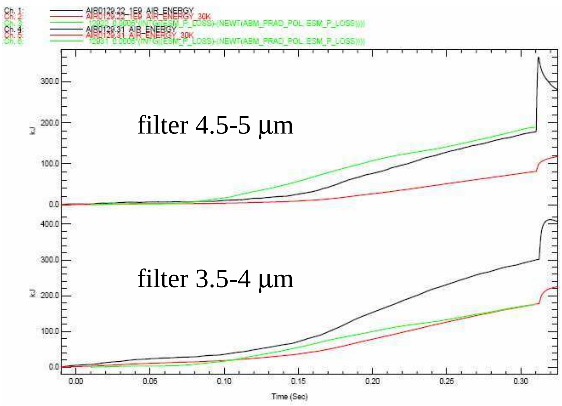

Figure 3: Total energy load on divertor (EFIT) compared to IR data with α = 30 000 W/m/K (red) and α = infinite (black) compared to energy from plasma (green).

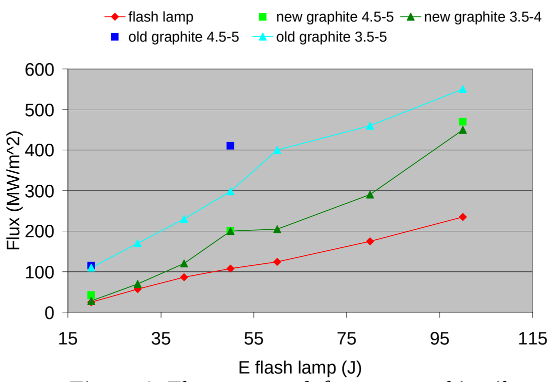

Figure 4: Flux measured for new graphite tile (green) and used tile (blue) compared to the theoretical flash lamp flux (red)

µm) compared to the ~ 3.51 µm of the new graphite. This is consistent with D.Hildebrandt [3] who measured accurate fluxes on a polished graphite (R_a = 0.4 µm) compared to an unpolished surface (R_a ~ 5 µm). Surprisingly, the over-estimation raises with power load for the new graphite and diminishes for the used one, underlining the complexity of the surface state modification during a whole campaign and its consequences on flux calculation. A second wavelength of observation above 5 µm might improve this issue. The over-estimation can be modelled by modifying the dust size and the surface coverage as shown in figure 5 which displays the flux calculated for a hot spot coverage and size respectively of 3 % and 10 µm. In this simulation, a difference with wavelength is obtained but this calculation does not take into account the frequency of the data acquisition as well as the integration time which might influence the accuracy of the temperature measurement.

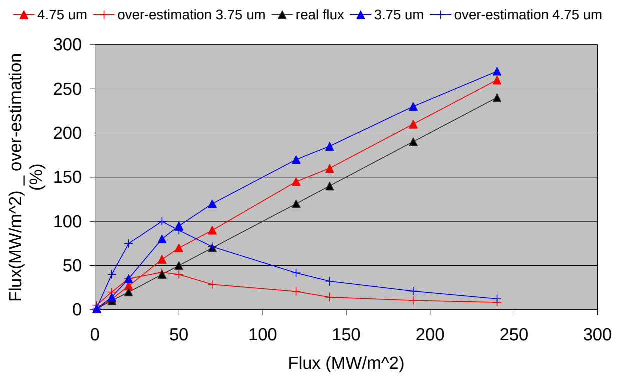

Figure 5: Simulated flux measurement at 3.75 (blue) and 4.75 µm (red) with 3 % of hot spot coverage and 10 µm size compared

Conclusion and outlook At low power load on MAST, surface effects lead to a discrepancy with filters confirming the non uniform temperature distribution hypothesis which foresees higher calculated flux at short wavelength. It has been observed in a flash lamp experiment, and in simulations that the surface state plays an important role in flux calculation. Alternative phenomena could explain the negative flux calculated. The numerical stability of heat solvers as well as the non homogenous surface temperature distribution can come in addition to the surface layer effect currently observed in others tokamak like JET, ASDEX and Tore Supra. Further investigations need to be carried out on the hot spot model to optimise it and define the range of free parameters like hot spot surface coverage and hot spot size on which depend the intensity of the over-estimation.

Acknowledgement This work is jointly funded by Euratom and the United Kingdom Engineering and Physical Sciences Research Council. Dr Delchambre would also like to acknowledge a Euratom Training Fellowship grant.

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