Experimental determination of the transient heat absorption of W divertor materials

H Greuner*, B Böswirth, T Eich, A Herrmann, H Maier and B Sieglin

Max Planck Institute for Plasma Physics, EURATOM Association, 85748 Garching, Germany

Corresponding author: henri.greuner@ipp.mpg.de

Abstract

Fast infrared thermography resolves the transient ELM induced heat fluxes on divertor components on time scales of a few hundred microseconds. These heat loads range from 10MW/m² to several 100MW/m² and energy densities of 15 - 200kJ/m². The calculation of the local ELM heat flux depends on the so called surface heat transfer coefficient very sensitively. Therefore we performed dedicated experiments in the high heat flux test facility GLADIS with well defined temporal and spatial shape of heat fluxes to reduce the uncertainties of the ELM heat flux calculations in JET. We have experimentally determined the surface heat transfer coefficient for the W components used as divertor components of the JET ILW-project. Based on the results of the measured transient heat absorption, the coefficient was deduced in a temperature range from 400 to 1200°C for the bulk W lamella and for 10 and 20µm W coated CFC tiles, respectively. The measurements allow an improved estimation of ELM heat loads in JET on W and on W coated tiles and an error estimate of the absorbed heat flux.

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1. Introduction

The extrapolation of transient heat fluxes induces by edge localized modes (ELM) from current devices such as JET and ASDEX Upgrade (AUG) to ITER is a challenging but vital task in order to assess the lifetime of the ITER divertor target, the acceptable ELM loss energies and hence the operational range. Fast infrared thermography at both devices resolves the fast ELM induced heat fluxes on time scales of a few hundred microseconds [1, 2]. These transient heat loads range from 10MW/m² to several 100MW/m² and ELM energy densities of 15-200kJ/m². However, uncertainties of these measurements are comparably large due to the unknown thermal behaviour of the W divertor target surfaces for such short time scales arising from surface inhomogeneities and possible changes of the thermal properties during plasma operation. The calculation of the local ELM heat flux depends on the so called surface heat transfer coefficient α. Large error bars are in particular worrying when comparing two devices of different linear dimension and often equipped with different plasma-facing components in order to derive a multi-machine based scaling for ELMs. The reference ELM energy density for ITER that shall not be exceeded in steady state operation is 500kJ/m². The transient energy densities investigated here are in the range of up to 200kJ/m² in JET and up to 120kJ/m² in our experiments. Both latter experiments are hence only a factor of 3-4 lower than the currently thought maximum tolerable ELM induced energy density. Notably the time scales observed in JET and e.g. AUG, and expected in ITER are in the range of 1-3ms and thus similar to our experiments. [2].

The derived power densities depend on the local emissivity as well as on the surface heat transfer coefficient α employed in the data evaluation model. The numerical code THEODOR (THermal Energy Onto DivertOR) calculates the local power density on the basis of the measured temporal evolution of the surface temperature. The coefficient α simulates the thermal resistivity of a virtual surface layer or a coating. However, the heat loaded surface of plasma facing materials is continuously modified by erosion and deposition processes during plasma operation. The variation of the thermal surface properties introduces uncertainties in the calculation of heat flux densities using measured surface temperatures. This effect is especially strong for carbon based materials due to the intrinsic microstructure [3, 4] and in addition the deposition of amorphous hydrocarbon layers with low thermal conductivity λ [5, 6]. For example, reference [7] reports a partially overestimated heat flux calculation on the W7-AS divertor up to a factor of four due to such layers.

For the metallic plasma facing components of JET, in particular W, the low emissivity (ε) is crucial for the determination of the surface temperature. The strong dependence of ε on the surface treatment, the temperature and the wavelength is well known, however difficult to handle. For W with a surface roughness of 0.5µm, the published thermal emissivity ranges from ε= 0.55 to 0.09 for wavelengths of 1.5 to 10µm [8]. Furthermore, the change of ε due to surface morphology changes during the combined particle and heat flux loading during operation has to be taken into account.

Therefore, dedicated experiments were performed with well defined heat fluxes in the high heat flux test facility GLADIS [9] to reduce the uncertainties of the ELM heat flux calculations in JET. The knowledge of the local power density allows to determine α from the measured surface temperature evolution. Tungsten samples of divertor materials from JET have been investigated at a power density of 27MW/m² and pulse lengths between 5 and 20ms. The temporally and spatially well characterized loading in GLADIS allows the experimental determination of ε and α on the required timescales. Results for the bulk W lamellae and for the W coatings on carbon fibre reinforced carbon (CFC) employed in the JET divertor are presented.

2. Modelling of ELM heat flux

For the evaluation of the heat flux density q'(t, s) onto the target surface (coordinate s), the 2D heat flux code THEODOR is used. An introduction to the equations and boundary conditions used is given in the literature [10]. This code solves the 2D heat flux equation for a flat target tile.

$$\rho\, c_p\ \partial T / \partial t = \nabla(\lambda\, \nabla T) \qquad (1)$$

Where T is the temperature distribution in the target, λ the heat conductivity, ρ the density and c_p the specific heat capacity. It is assumed that there is no heat transport through the sides of the target. For the top of the tile the following heat transfer boundary condition is applied. For the top, the heat transfer into the bulk is given by

$$q'(t, s) = \alpha_{top}\ [\ T_{IR}(t,s) - T_{surf}(t,s)] \qquad (2)$$

where $T_{IR}(t, s)$ is the measured surface temperature and $T_{surf}(t, s)$ the top bulk temperature calculated from the diffusion equation. The heat transfer coefficient α_{top} represents a virtual surface layer or a coating in thermal equilibrium. Using this boundary condition the influence of surface modifications can be taken into account and the resulting T_{surf} can be used as boundary condition for the solution of the diffusion equation.

$$T_{surf} = T_{IR} - q' / \alpha_{top} \qquad (3)$$

The limit α → ∞ is equivalent to a prescribed surface temperature as boundary condition. For the targets under investigation, the α values used in (2) are $\alpha_{top\ lamella} = \infty$, $\alpha_{top\ 10} \approx 1 \cdot 10^7 W \cdot m^{-2} \cdot K^{-1}$ and $\alpha_{top\ 20} \approx 5 \cdot 10^6 W \cdot m^{-2} \cdot K^{-1}$ for bulk tungsten, 10μm and 20μm thick tungsten coating, respectively.

The influence of the top heat transfer conditions onto the calculated heat flux can be estimated by comparing the thermal response of the layer with that of the bulk.

$$\alpha_{bulk} = \lambda / d_{bulk} \quad (4)$$

with d_{bulk} the diffusion length given by $d_{bulk} = \sqrt{(4D\tau)}$ resulting in

$$\alpha_{Bulk} = \lambda / \sqrt{(4D\tau)} \quad (5)$$

with τ being the sample time of the measurement. The diffusivity D is given by

$$D = \lambda / (\rho\, c_p) \quad (6)$$

Using the bulk properties of W and CFC and the IR sample time of about 10kHz typical values for α_{Bulk} are in the order of $10^6\, W \cdot m^{-2} \cdot K^{-1}$. This has the important consequence that surface modifications or deposited layers imposing corrections being much larger than $10^6\, W \cdot m^{-2} \cdot K^{-1}$ cannot be estimated with this method easily as the effective α_{eff} is the sum of the reciprocal of the bulk material α_{Bulk} and a deposited surface layer or e.g. a coating ($1/\alpha_{eff} = 1/\alpha_{Bulk} + 1/\alpha_{top}$).

The reader should note that in case of thermal changes or surface inhomogeneties, α should be much lower than these values as it was found for e.g. JET Mark II gas box divertor [5, 6]. At this time JET was equipped with CFC target tiles and amorphous hydrocarbon layers were present. Crude estimation of α found numerical values to be in the range of 50,000 – 100,00 $W \cdot m^{-2} \cdot K^{-1}$, hence about 10-20 times lower values clearly indicating significant changes of the thermal properties of the CFC surfaces [11].

3. Experimental

3.1. Introductory remarks

In the frame of the ITER-like Wall project (ILW) at JET [12], a bulk W lamellae design was developed for the outer horizontal target plate [13]. All other divertor components are made of CFC tiles coated with 20µm W on the vertical targets and 10µm for most components with lower heat and particle load [14]. Both types of components were extensively high heat flux tested and investigated during the preparation phase of the manufacturing [15, 16, 17]. The aim of our experiments is to obtain benchmark data of material properties especially for the JET infra red diagnostic [18] under ELM like loading conditions and surface temperatures between 400 and 1200°C.

3.2. Tested samples

Two JET W lamellae type B (overall dimensions 70×40×5.5mm³) [19] were clamped together in a W coated CFC holder. The two other samples, the 10 and 20µm W coated CFC tiles have been manufactured identically to the above mentioned components. Fig. 1 shows the lamellae and one CFC tile after the loading. The measured surface roughness R_a of the W lamellae was 2.4±0.2µm before loading. The surface roughness after loading is given in Tab. 1 for all samples.

3.3. Heat loading in GLADIS

Adiabatic loading in GLADIS was performed with a hydrogen neutral beam. A two-colour pyrometer (∅6mm focus, λ=1.4-1.75µm, t_{95}=20ms, 350-1000°C temperature range [20] was used as reference for the emissivity determination of the fast one-colour pyrometer (∅8mm focus, λ=2.0-2.5µm, t_{95}=20µs, 350-3500°C temperature range) [21].

We started the examination of W lamellae with 12 continuous-wave (cw) pulses of low power at 2.7MW/m² and durations of up to 15s. The surface temperature did not exceed 945°C, however the initial ε=0.2 changed to ε=0.45 after 5 pulses with a total length of 10s. In a second step we increased the applied heat fluxes from 10 to 15MW/m² at 3 and 1.5s cw pulse length, respectively. The beam power can be modulated by fast switching of the extraction voltage U_{ex}. Modulated beams with frequencies between 5 and 250Hz were applied to analyse the thermal response of the different optical instruments and to optimise the test parameters with respect to the energy input, surface temperature increase and respective decrease during the cool down phase. The maximum peak surface temperature reached 1494°C. After 165s total loading the emissivity decreased to ε=0.25.

The 10µm W coating sample was loaded with 10- 26MW/m², 5 to 100Hz beam modulation and 5s pulse length. The loading with 26MW/m², beam modulation 50ms on/ 200ms off (5Hz) resulted in the maximum surface temperature of 1596°C. The same loading resulted in a surface temperature of 1615°C for the 20µm W coating sample. The emissivity ε=0.24 of both samples was nearly constant during the loading.

3.3.1 Beam power measurement

To achieve the results presented in section 4, we applied pulses with 250 modulations at 5ms loading with a repetition time of 20ms resulting in 5s total duration (Fig.2). The average heat flux resulted in 25MW/m² and 120kJ/m² deposited energy. The beam parameters are measured with an accuracy of ±5%. The absorbed heat flux at the target position was measured calorimetrically in cw operation with constant U_{ex} and resulting extraction current I_{ex} according to the reference [9]. For ELM like loading with typical characteristic times in the ms range, we measured U_{ex} and I_{ex} at the power supply of the ion source with 10kHz sample rate (Tektronix TDS-754c) and calculated the corresponding power P. As shown in Fig. 3, after 1.1ms setting time P_{95} is reached. The HV cable capacity of about 100pF/m caused the seeming transient overshooting of I_{ex} at the very beginning. The power supply unit repeats this pulse form with a high accuracy.

4. Results and discussion

We only considered surface temperatures above 400°C for data evaluation. ε was determined separately for each pulse by matching the recorded data of the one- and two-colour pyrometer during the cooling phase after the pulse. Fig. 2 shows the temperature traces of the two pyrometers at the end of the loading cycle of the W lamellae. The summary of the temperature measurements for all samples is given in Table 1.

The above approach of adjusting the one-colour pyrometer to the data acquired with the two-colour pyrometer fully relies on the correctness of the temperatures measured by two-colour pyrometry. In two-colour pyrometry the necessity of knowing the emissivity of the analysed surface is eliminated by using the intensity ratio measured in two different wavelength bands. This is, however, only fully correct for a so-called "grey body", where the emissivity is assumed to be independent of wavelength and temperature. This is surely not the case for tungsten as numerous literature data show, see e.g. [8]. To estimate the error margin of our approach we used emissivity data from reference [8] measured on tungsten at 1200 K surface temperature. For the two central wavelengths of the employed two-colour pyrometer the variation of the emissivity is about 5%. Using the monochromatic correction as described e.g. in reference [22] we obtain a temperature dependent correction for the measured values which increases with increasing temperature. For the ΔT values given in table 1 this procedure results in reductions of about 20%.

To assess the value of α introduced in section 2, the heat flux was calculated using different temperature independent α values. The resulting peak heat fluxes are compared to the reference heat flux. Computations of α during the ELM like heat flux are treated self consistently by taking the actual temperature increase during the pulse into account.

Fig. 3 presents the comparison of computed and applied q' for an individual 5ms pulse at 27MW/m² on the (a) W-lamellae and (b) on the 20µm W coating on CFC. The calculations of the heat fluxes were performed with three different α values to assess the uncertainties of heat flux measurements for typical conditions at JET. Here we like to underline again the closeness of our performed experiments at GLADIS to the real situation at JET in terms of amplitude, temporal shape, temperature range and IR sample time. The three α values are first the derived (and so far used for ELM heat load analysis at JET) value by comparing ELM heat loads in JET on CFC and tungsten coated CFC during actual JET discharges (#74380 and # 74384, I_p = 2MA and B_{tor}=2T), estimated to be around α = 333.000 $W\cdot m^{-2}\cdot K^{-1}$. Secondly the values as described in chapter 2 are used. Finally, we amend the extreme case of α being infinity reflecting $T_{IR} = T_{bulk}$.

For the bulk material and choice of α= ∞ a good match is found that is reflecting the temporal shape of the heat pulse, taking into account the delayed switching on of the beam (see section 3.3.1). The other cases with lower α are smearing out the real pulse shape and result in a strong "virtual" heat flux milliseconds after the end of the pulse. For the target with 20 µm W coating the temporal shape of the heat pulse is well described with $\alpha_{top\ 20} \approx 5 \cdot 10^6\ W \cdot m^{-2} \cdot K^{-1}$. Lower α values result in a pulse shape that is smeared out. A further increase of α has a weak effect on the pulse shape as expected from the discussion in section 2. The thermal response of the bulk is dominating the thermal response of the coating. The absolute value of the heat flux as calculated by the code is too high by about 30%. This might be caused by the thermal parameters used for the calculation or by uncertainties of the temperature measurements due to the wavelength dependent emissivity as discussed above.

However, further improvement and checks will be performed in future work, e.g. extending the studies by making use also of the IR based temperature estimation with an infra red system working in the mid IR region (4.0 - 4.5 µm), as such cameras are used at JET and AUG providing fast sample rates, very good spatial resolution and larger observation regions than pyrometer systems are currently able to provide. For this goal all measurements have been also recorded by the IR system installed otherwise in AUG, but are not yet analysed.

The results from the coated W on CFC substrate are well matched with the predicted values.

5. Summary and conclusions

We have experimentally determined the surface heat transfer coefficient α for W components used as divertor components of the JET ILW-project. The coefficient α was calculated in a temperature range from 400 to 1200°C for the bulk W lamella and for 10 and 20µm W coated CFC tiles according to the IR analysis method used on JET. Based on our experimental results we conclude:

1. The absolute numbers for the W lamellae and the W coated CFC tiles are similar though the results show the necessity to assess the correct heat transmission coefficient for such complex (processed) structures e.g. by the presented GLADIS experiments for further improvements of IR based heat flux data quality. JET will perform experiments on the vertical target plates, which are in contrast to the lamellae not bulk W but W coated CFC. These experiments are vital to understand the power exhaust of the ITER vertical target divertor configuration.
2. The measurements reveal values for α that are larger than the value used in the JET campaign in 2008/2009 before the ILW [2]. However, the largely important ELM energy density is only weakly affected. This is because the ELM energy density is calculated from the time integral (typically 1-5ms) of the ELM heat flux which is in turn only weakly affected [11].

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Tables and Figures:

sample	R_a µm	ε(2.25µm) -	T_{max} surf. °C	ΔT(400°C) K	ΔT(1000°C) K
W-lamellae	2.5±0.4	0.28	1157	106	137
10µm W-coating	2.6±0.5	0.24	1178	114	157
20µm W-coating	3.6±0.5	0.24	1228	139	171

Tab. 1: Pyrometrically measured surface temperatures of the tested samples. T_{max} surf is the end temperature after 5s loading with a modulated beam (5ms on/ 15 ms off) at 27MW/m². ΔT indicates the surface temperature increase during an individual 5ms modulation for starting temperatures of 400°C and 1000°C.

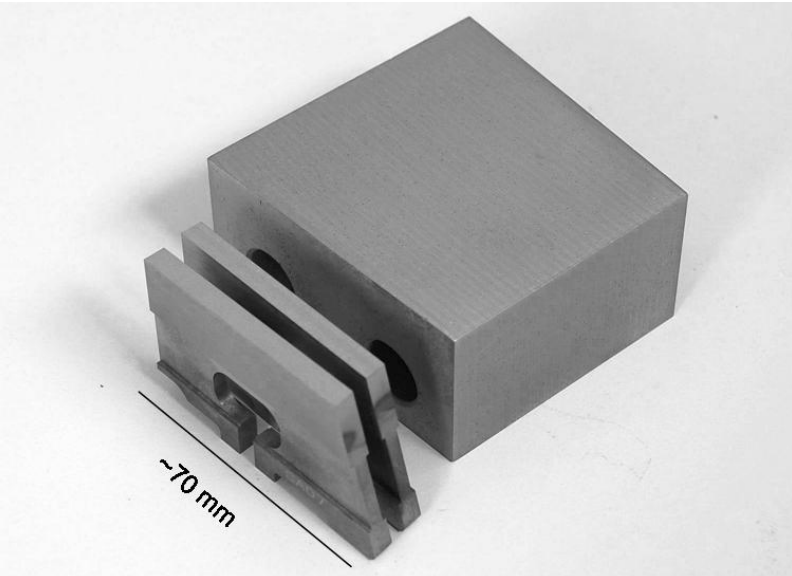

Fig. 1: Samples after loading. The W lamellae are seen in front. The 20 µm W coated CFC tile is placed in the background.

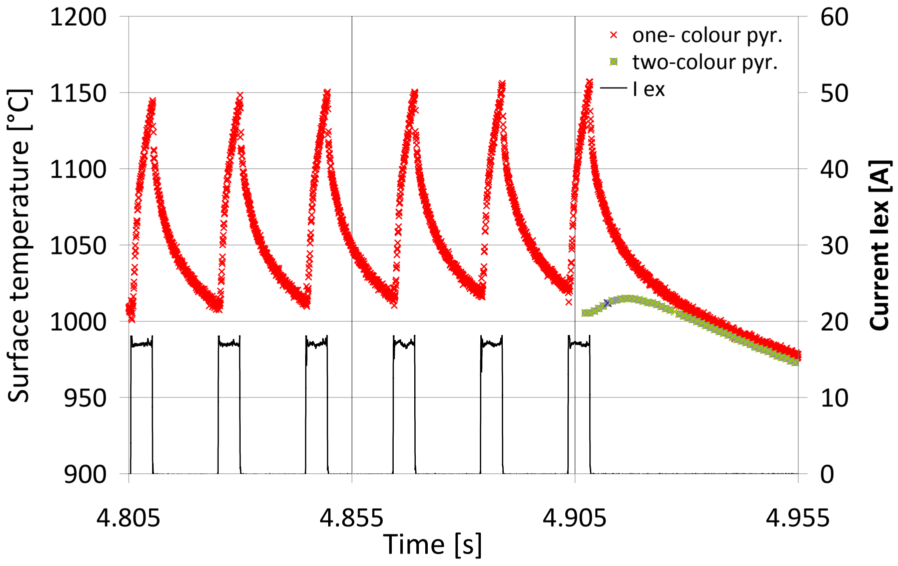

Fig. 2: Surface temperature measurement during modulated heat loading of the W lamellae. A heat flux of 25MW/m² with 5ms on/ 15ms periods off was applied. The extraction current I_{ex} is shown to identify the heat loading periods.

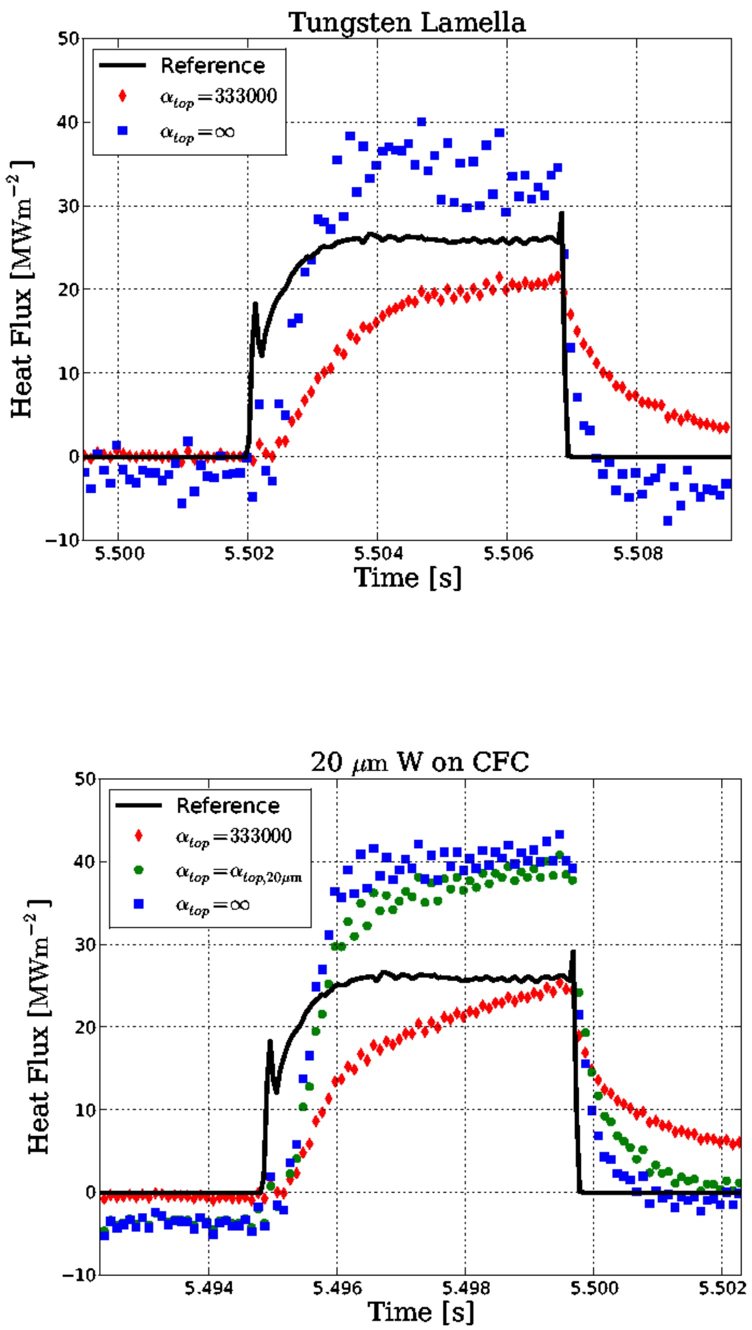

Fig. 3a, b: Comparison between the applied heat pulse (Reference) and heat fluxes calculated for (a) W-lamellae and (b) 20µm W on CFC as example for the vertical target. α is given in $W \cdot m^{-2} \cdot K^{-1}$.