Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Nuclear Materials 337–339 (2005) 1069–1072
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Hot spot effect on infrared spectral luminance emitted by carbon under plasma particles impact

E. Delchambre [a,*], R. Reichle [a], R. Mitteau [a], M. Missirlian [a], P. Roubin [b]

[a] CEA/DSM/DRFC, CE Cadarache, 13108 Saint-Paul-lez-Durance, France
[b] Laboratoire PIIM, Université de Provence, Centre Saint-Jérôme, 13397 Marseille cedex 20, France

Abstract

During the last Tore Supra campaigns, an anomalous deformation in the near infrared spectrum of radiation has been observed on neutraliser underneath the Toroidal Pumped Limiter (TPL) on which we have observed the growth of carbon layer. The consequence is the difficulty to assess the surface temperature of the components and the power loaded. Laboratory experiment has been performed, using an Electron Cyclotron Resonance (ECR) ions source, to reproduce, characterize and explain this phenomenon. The luminance emitted by Carbon Fibre Composite (CFC) and pyrolytic graphite, have been observed under 95 keV of H^+ bombardments. The amplitude of the deformation was found to depend on the type of material used and the power density of the incident power loaded. This paper presents the possible hot spots explanation. The experimental luminance deformation is reproduced and these results are validated using a thermal model of dust in radiative equilibrium.

PACS: 52.40.Hf; 52.70.Kz; 61.16.Bg; 68.55.Jk
Keywords: Tore supra; IR thermography; Power deposition; Carbon-based materials; Dust

1. Introduction

Preventing overheating of Plasma Facing Components (PFCs) during long pulse discharges in tokamaks as Tore Supra (TS) and ITER is important for the future course of magnetic confinement fusion research. This is the reason why an infrared (IR) safety system has been installed in TS in the range 0.9–1.55 μm and optical fibres transparent up to 2 μm. In IR thermography the surface temperature of PFCs is deduced assuming that they radiate according to the Planck law. An anomalous deformation of radiation emission from plasma facing components under plasma particle impact has been observed [1]. The goal of this work was to reproduce this phenomenon in laboratory experiments, characterize it and explain it, so that the measurements of the temperature of plasma facing components can be made with confidence. Laboratory experiments have been performed using an ECR ion source. Here we present the luminance measured on pyrolytic graphite and CFC heated under ions impact. The non-uniform temperature distribution in the field of view of the detector, caused by carbon layer and/or dusts, could be a possible explanation.

* Corresponding author. Address: UKAEA Fusion Association, D3/2.15, Culham Science Centre, Abingdon, Oxon, OX1 3DB, UK.
E-mail address: elise.delchambre@ukaea.org.uk (E. Delchambre).

0022-3115/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2004.10.015

2. Experimental set up

The ECR High Intensity Light Ion Source (SILHI) produces proton beams of 8 mA at 95 keV. The Gaussian beam had a standard deviation of about 10 mm. Pyrolytic graphite and CFC were exposed at power densities of 1–3 MW/m^2. The pyrolytic graphite, an orthotrope material, has been tested with incident flux parallel and perpendicular to the high conductive plans. The standard size of the targets was $30 \times 50 \times 35$ mm. Thermocouples were inserted in each target as reference temperature measurement, to eliminate the uncertainty of the emissivity (ε) measurements. A viewing area of 1 cm of diameter was observed from outside the vacuum vessel by a near-infrared fused silica fibre (Oxford Electronics) transparent up to 2 μm. This fibre is connected to a near IR spectrometer (Jobin-Yvon CP200) with a linear detector array of 256 pixels (Lot-Oriel) in a measuring range of 0.9–1.55 μm. The absolute calibration of the measurement chain was performed using a blackbody radiator at 400 °C with an emissivity of 0.85 ± 0.15 and a focal plane array infrared camera (AGEMA 515) with a narrow transmission range around 3.9 μm observing the entire solid.

3. Experimental results

An emissivity calculation was made at 0.9–1.55 μm and at 3.9 μm when considering transmission of optical chain and temperature reference of thermocouples after heating, when the temperature is equilibrated in the solid around 700–800 °C. The emissivity at 0.9–1.55 μm is 0.92, 0.94, 0.99 ± 15% respectively for CFC, pyrolytic perpendicular and parallel to high conductive plans. The emissivity at 3.9 μm is 0.66, 0.64, 0.96 ± 0.01 respectively for CFC, pyrolytic perpendicular and parallel to high conductive plans. An increase of emissivity after a few hours of bombardment has been observed at 3.9 μm for the area directly under ion impact with 0.72 and 0.88 for CFC and pyrolytic. This is probably due to the surface roughnening which has been observed on the ion impact area after irradiation.

As with previous experiments on Tore-Supra, the observed near-infrared spectra are different from black body radiation curves. For all samples, the temperature distribution is non-uniform due to Gaussian shape of the beam and hot spots which were observed in visible light on the ion impact area. To quantify the amplitude of the luminance deformation we can calculate the extra luminance in subtracting the Planck simulation from the measured luminance. To follow in time the deformation of the spectra during heating, we can display the extra luminance at 1.3 μm versus the surface temperature of the sample for different power densities. In Fig. 1, we notice that the amplitude of the deformation increases with

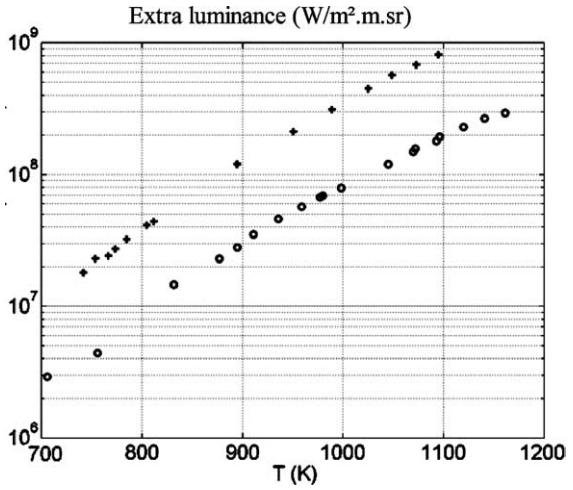

Fig. 1. Extra luminance at 1.3 μm emitted by pyrolitic for different power density. +: $P = 4.5$ MW/m^2; o: $P = 1-2.5$ MW/m^2).

the surface temperature and the incident power density. Fig. 2 displays the extra luminance versus the surface temperature for CFC and pyrolytic. The thermal conductivity is 1.1, 90–140 and 340 W/m.K, respectively for the lower pyrolytic conductivity, the CFC and the higher pyrolytic conductivity. For a same surface temperature, the extra luminance is higher when the thermal conductivity is low. During the 2002 experimental campaign, the surface temperature of the leading edge of the TPL neutraliser was seen to increase for the same plasma conditions. This is attributed to the growth of a carbon layer at the surface of the neutraliser. Target plates have been cleaned and carbon layers were sampled for

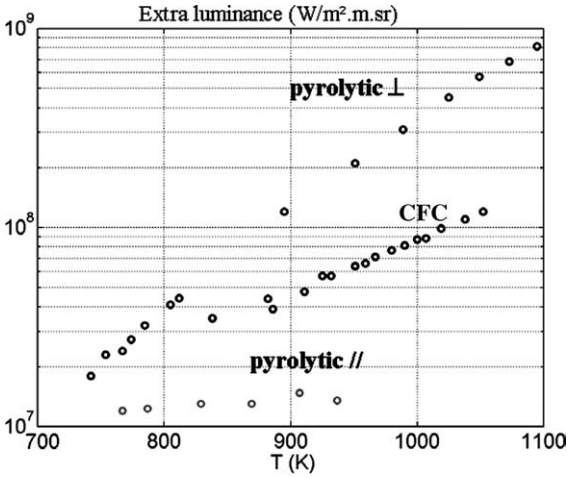

Fig. 2. Extra luminance for CFC, pyrolitic graphite with flux perpendicular to high conductive plan and flux parallel to high conductive plan.

Scanning Electronic Microscopy (SEM) study. SEM micrographs have shown ovoidals and columnar structures and a sub-structure in stratified layers (Figs. 3 and 4). These analyses have allowed us to identify ballistic deposition as the fractal growth mechanism. The columns follow a direction of growth, which seems to be parallel to the magnetic field lines underneath the TPL [2]. A correlation with the evolution of the infrared emission spectra has been made, outlining the sequence of layer growth and the corresponding spectral deformation characteristics. At the beginning of the campaign, when the CFC neutraliser is brand-new, the luminance is in disagreement with the Planck law. In the second stage, granular structures recover non-uniformly the leading edge and the spectra are still deformed. In the third stage a thin carbon layer is visible on the surface neutraliser. The thickness is about 10–20 μm and the measured luminance still shows a disagreement with the Planck law. Finally, the thickness is now of about 180 μm and the layer is partly detached from the neutraliser. The spectra are now in perfect agreement with the blackbody law. The spectral luminance stays in agreement with the Planck law until the end of the campaign with a thickness layer of about 800 μm [2]. The temperature calculation of the surface temperature of the layer is made but not the TPL surface temperature as expected. This problem can be resolved with a layer model partly detached from the surface [3,4]. Nowadays only for thick and loosely attached films a black body radiation curve is observed [5].

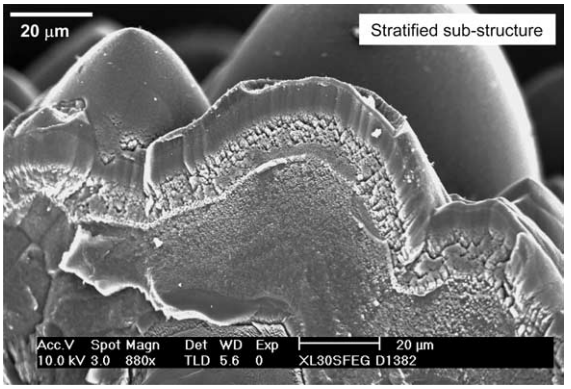

Fig. 3. SEM micrograph of carbon deposited layer sampled from leading edge neutraliser.

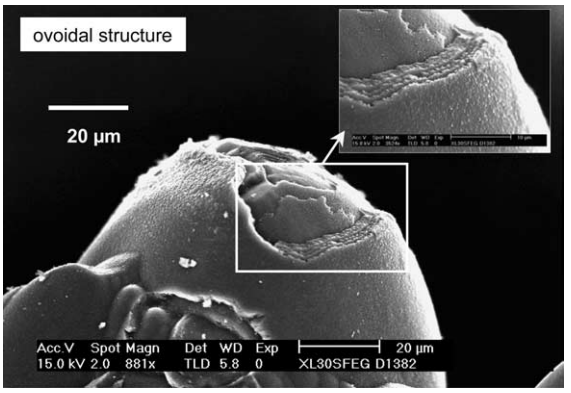

Fig. 4. SEM micrograph of ovoidal structure observed on carbon deposited layer sampled from leading edge neutraliser.

4. Hot spot hypotheses

A systematic consideration and evaluation of explanations for the observed spectral deformation have been made and a number of them has been considered [6] and discarded as e.g. Bremsstrahlung radiation. The possible partial transparency of the material has also been considered at some length, but finally discarded because the low thermal conductivity of the graphite materials under consideration does not permit a strong enough temperature gradient to cause the observed deformation. The presence of other heat source can modify the luminance received by the IR detector. The case of 10% of reflection coefficient (the standard carbon coefficient) has been studied. The spectral luminance can be deformed and the temperature deduced can be overestimated if an external high temperature thermal source is reflected from the observed target but this is not the case for the laboratory experiments. The possible explanation is reduced to the non-uniform surface temperature. The spatial structures measured with SEM have smaller dimensions than the typical area observed with optical fibres, with the consequence, that the luminance measured is from different zones of different temperatures. If we consider a temperature profile, we can calculate the luminance, $L_{TOT,}$ integrated on the length dx (Eq. (1)).

$$L_{TOT} = \int_T (dx/d)\varepsilon L_\lambda(T)dT. \quad (1)$$

In Fig. 5, the luminance L_{TOT} is simulated up to 12 μm for a uniform temperature profile and for a Gaussian profile with a standard deviation of 50 μm to simulate a hot spot. The luminance is integrated for dx = 10 mm, the standard diameter of the viewing area. The surface temperature, T_S, is 500 K, the temperature hot spot, T_H, is 2000 K. The deformation depends on the temperature gradient ($T_H - T_S$) and the hot spot coverage, γ. The deformation is clearly higher for lower wavelength.

For CFC under 1.5 MW/m^2, the experimental spectral luminance, L_{TOT}, can be well simulated according to the hot spot hypothesis (Eq. (2)).

$$L_{TOT} = (1-\gamma)\cdot L(T_S) + \gamma \cdot L(T_H). \quad (2)$$

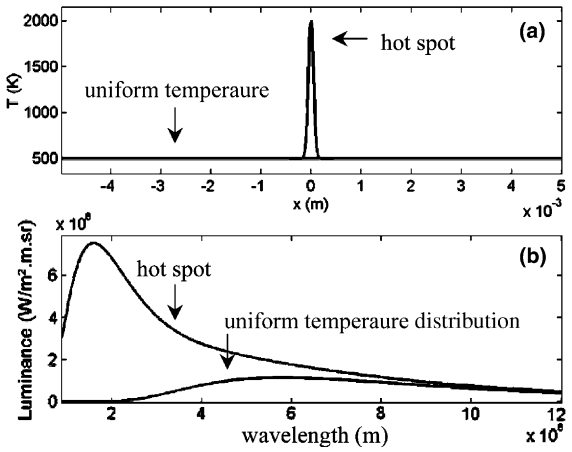

Fig. 5. (a) uniform temperature profile $T = 500\,\mathrm{K}$, Hot spot profile temperature $T_{max} = 2000\,\mathrm{K}$, $T_{min} = 500\,\mathrm{K}$ and (b) Luminance simulated in the range 0.9–12 μm for a uniform profile temperature and for the hot spot profile.

Emissivity of the bulk and hot spot are not taken into account to avoid four free parameters (hot spot temperature, surface temperature, fractional surface coverage and emissivity). The hot spot coverage, γ, has to be in the range 1–5% for a good experimental luminance simulation. To reproduce experimental spectra, the temperature gradient between the surface temperature and hot spot temperature has to be superior to 500°. We notice that the hot spot temperature increase quicker than the surface temperature and the hot spot temperature deduced stabilize around 1250 °C. For CFC, the time resolution data was 1 s. This resolution does not allow seeing the beginning of hot spot heating and we can assess a time constant of hot spot <1 s. For pyrolitic graphite the time resolution of acquisition data was 40 ms. Even in that case the beginning of hot spot heating is not seen and we deduce a time constant $\tau < 40$ ms. A model of dust in radiate equilibrium on the surface has been tested, in order to explain the thermal behaviour of the hot spot (Eq. (3), see Ref. [3]).

$$e.\rho.Cp.\mathrm{d}T(t)/\mathrm{d}t = \varphi i - 6.\sigma.\left(T(t)^4 - T_{sur}^4\right), \tag{3}$$

e = dust size; ρ = density; Cp = thermal capacity (thermal capacity of CFC); T = dust temperature; T_{sur} = surrouding temperature; σ = Stephan radiation constant.

The temperature of equilibrium obtained depends on the incident flux, φi. The density, ρ, has been previously measured on deposited materials from Tore Supra ($\rho = 1\,\mathrm{g/cm^3}$) [7]. To obtain a stabilized temperature of 1250 °C, $Cp = 4000\,\mathrm{J/kg}$ and $\varphi i = 1.8\,\mathrm{MW/m^2}$. The time constant, τ, depends on e, the dust size. For $e = 40\,\mu\mathrm{m}$, the time constant $\tau = 40$ ms. This thermal model allows to deduce an average size of the dust < 40 μm. These results are consistent by the laser heating experiment's on CFC of A. Hermann et al. [8] in which it is inferred that the size of hot spots are down to 30 μm, the spatial resolution of the camera.

5. Conclusions

Spectral luminance deformation has been reproduced in laboratory experiments under ions bombardment. The phenomenon appears on surface under plasma particles impact and the intensity depends on the incident power density and the material thermal properties. The possible explanation is the non-uniform temperature distribution due to surface state, which is modified during Tore Supra campaign. The presence of CFC fibers of a few tenth of micrometer, granular structures and dusts in bad thermal contact or thin carbon layer loosely attached on the surface can be responsible of a non-uniform temperature distribution. When the layer is thick (around 200 μm) and homogeny, the temperature gradient between the hot spots and the surface layer temperature is probably not enough (<500 °C) to produce a deformation. In that case the measured luminance is in agreement with the Planck law and the temperature extrapolated is the average of the temperatures distribution. For non-blackbody spectra, the hot spot hypothesis allows assessing simultaneously the dust and surface temperature by simulating the measured luminance. A dust thermal model allows deducing a dust size down to 40 μm, which is consistent with the pictures of the rough surface of the deposits neutralisers showing about 20 μm feature size.

References

[1] R. Reichle et al., 10th Carbon Workshop Juelich, Germany, 16–19 September 2003, Phys. Scr. T 111 (2004) 107.
[2] E. Delchambre et al., in: Proceeding 30th EPS Control. Fus. Plasma Physics, ECA 27A, P1.068, St. Petersburg, Russia, 7–11 July 2003.
[3] R. Mitteau et al., 10th Carbon workshop Juelich, Germany, 16–19 September 2003.
[4] J.C. Vallet et al., in: Proceeding 30th EPS Control. Fus. Plasma Physics, ECA 27A, P1.137, St. Petersburg, Russia, 7–11 July 2003.
[5] R. Reichle et al., in: Proceeding 16th PSI conference, Portland Maine, USA, 24–28 May 2004.
[6] E. Delchambre et al., in: Proceeding 30th EPS Control. Fus. Plasma Physics, ECA 27A, P3.169, St. Petersburg, Russia, 7–11 July 2003.
[7] P. Roubin et al., in: Proceeding 30th EPS Control. Fus. Plasma Physics, ECA 27A, P1.158, St. Petersburg, Russia, 7–11 July 2003.
[8] A. Hermann et al., 10th Carbon Workshop Juelich, Germany, 16–19 September 2003, Phys. Scr. T 111 (2004) 98.