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Experimental developments towards an ITER thermography diagnostic

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Abstract

In the course of the development of a concept for a spectrally resolving thermography diagnostic for the ITER divertor using optical fibres experimental development work has been carried out in three different areas. Firstly ZrF_4 fibres and hollow fibres (silica capillaries with internal AG/AgJ coating) were tested in a Co^{60} irradiation facility under γ irradiation up to doses of 5 kGy and 27 kGy, respectively. The ZrF_4 fibres suffered more radiation induced degradation (>1 db/m) then the hollow fibres (0–0.4 db/m). Secondly multi-colour pyroreflectometry is being developed towards tokamak applicability. The emissivity and temperature of tungsten samples were measured in the range of 700–1500 °C. The angular working range for off normal observation of the method was 20–30°. The working distance of the method has been be increased from cm to the m range. Finally, encouraging preliminary results have been obtained concerning the application of pulsed and modulated active thermography.

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Keywords: Optical fibres; IR-thermography; Divertor diagnostic; Tungsten; ITER divertor target

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1. Introduction

For the safe operation of ITER it is necessary to know the power-flux onto the divertor target plates, and their temperature. To respond to this demand a concept study of a thermography diagnostic has

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recently been conducted [1]. It features mirror based front end optics under the divertor dome, optical fibre bundles for the transport through the divertor port, imaging infrared spectrometer, bidimensional focal plane array detectors and lasers. It shall deliver temperature measurements of the surface of one poloidal cross-section of the divertor targets by spatially, spectrally and time-resolved infrared thermography – similar to a diagnostic of the neutraliser target plates of Tore Supra [2]. Measurements at several wavelengths shall help to compensate emissivity variations of the target and to distinguish the thermal emission of the target from parasitic hotspot-emission, strong Bremstrahlung in the divertor and reflections by exploiting the differences in their respective spectral distribution of radiance. The lasers shall illuminate certain points of the target cross-section to overcome remaining ambiguities in the measurements and the calculation of the power-flux. For example, carbon deposits on the target shall be characterised by their thermal response to pulsed or modulated laser light thus enabling power-flux calculations despite their presence. Such photothermal methods (see also: [3,4]) shall also permit unambiguous temperature measurements in case of strong reflections – e.g. from the outer divertor leg onto the inner one. Furthermore, the system features a few lower power lasers for multi-colour pyroreflectometry [5,6] which shall yield absolute temperature measurements in the case of unknown emissivity of the target and transmission of the system. Here we report on the first results of collaborations to advance by experimental research on three key-aspects of this concept. The first aspect is the question of the radiation hardness of optical fibres of interest. The second aspect is the integration of the pyroreflectometric method into the tokamak environment. The third aspect is active thermography i.e. the application of the photothermal method, using pulsed or modulated illumination in such an environment.

2. γ-irradiation test of IR fibres

The question of the irradiation hardness of IR fibres is treated in a collaboration between the CEA and the SCK·CEN. The performance of the proposed diagnostic system was analysed [1] in the range from 1 to 10 μm and sufficient performance is expected in the 2–6 μm window. Silica fibres which are relatively radiation hard in the near infrared (NIR) range are only transparent up to 2 μm. In Tore Supra we have used with success ZrF_4 fibres transparent up to 4 μm [7], but too little was known about the radiation hardness of these fibres. They became therefore, the prime candidate to investigate in our first irradiation tests. We selected ZrF_4 fibres from Reflex analytical of 3.33 m length and two types of fibre from Le Verre Fluore named IR Guide 1 (ZrF_4) and IR Guide 2 (HfF_4) of 2 m length. Hollow fibres which are made of silica capillaries with an internal coating of a metal and a dielectric can be transparent from about 2 μm to beyond 10 μm. This fibre type promised a certain radiation hardness and a particular potential [8] for active thermography measurements. Therefore, two hollow fibres from Polymicro with internal Ag/AgI coating, 750 μm internal diameter of a length of 2 m and 8 m were also selected for the first radiation tests. The total length of a potential fibre path in ITER from the pumping port of the divertor cassette to the bioshield is about 8.6 m. Over this length the dose-rate of neutrons of an energy >0.1 MeV at full power operation decreases exponentially from 10^{17} n/m^{2}s at the port to 0.5×10^{14} n/m^{2}s at the bioshield with a characteristic decay length of 1.6 m [1]. The full lifetime dose of ITER (7600 h of full power operation assumed) at the potential fibre connection point at the cassette is 3×10^{23} n/m^2. The ratio of γ dose rate to neutron (>0.1 MeV) dose-rate in ITER is typically of the order of [9] 1 Gy/s for 10^{15} n/m^{2}s. This means that the full lifetime γ dose is expected to be 300 MGy at the transition from the divertor cassette to the divertor port and 150 kGy at the bioshield. For an initial test of IR fibres we planned γ irradiation in the multi-kGy range with spectrally resolved in situ measurements throughout the irradiation period and the subsequent period of time without irradiation to investigate both the loss and the recovery of transmission. Fig. 1 shows the main elements of the measurement set-up we used. A Globar light source is used to provide broadband spectral illumination. This light is passed through a filterwheel, chopped, spectrally selected by a TRIAX spectrometer, then passed either through a fibre or onto a reference detector to be analysed by synchronous detection. The accessible wavelength range with Peltier-cooled PbSe detectors and a grating of 300 l/mm blazed at 2 μm was from 1 μm to 4.8 μm. We carried out gamma irradiations using the Co^{60} irradiation facility RITA of the SCK·CEN Mol at a maximum dose-rate of 0.42 Gy/s up to a total dose of about 5000 Gy. We observed that the

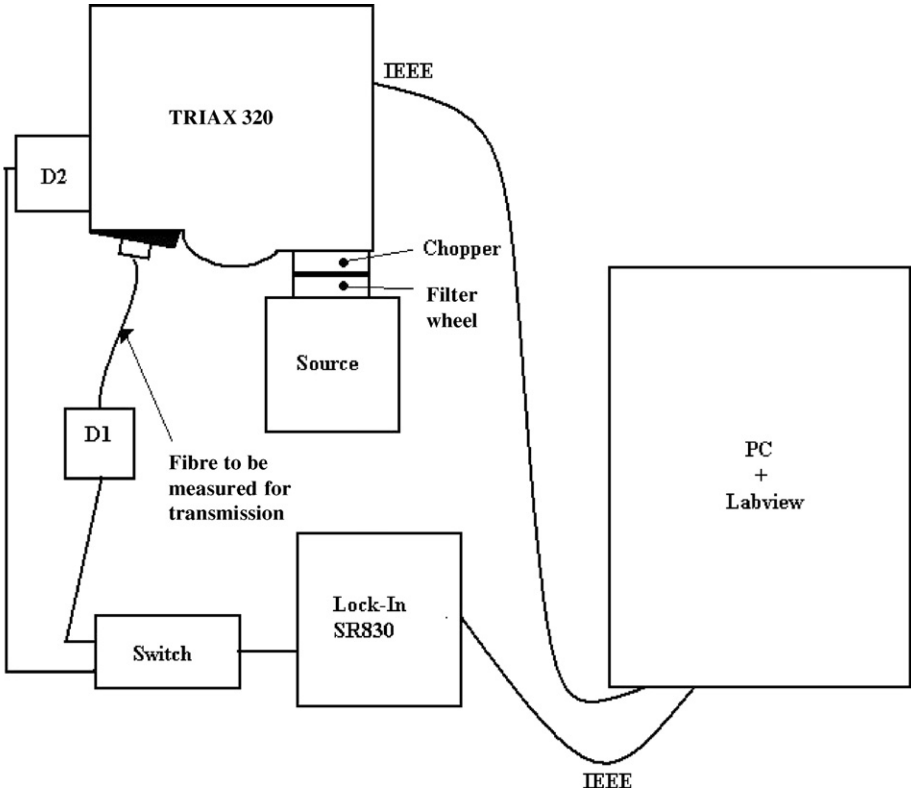

Fig. 1. Schematics for in situ fibre irradiation measurement set-up.

optical transmission of ZrF_4 fibres strongly decreased, primarily for wavelengths below 2 µm (Fig. 2). In this type of fibre typical optical losses can reach 50% at 5 kGy around 3 µm. Nevertheless, the optical transmission can be significantly recovered by thermal annealing at room temperature (Fig. 3) or more rapidly by performing a thermal annealing treatment at a temperature of 100 °C (Fig. 4). These results were independent from the manufacturer of the fibre. The hollow waveguide fibres were irradiated at the same dose-rate but up to 25 kGy. According to the manufacturer the transmission values of these fibres at the moment of production were typically about 1 dB/m but we could only find values around 5 dB/m with our equipment described above comparing the transmission of 2 m and 8 m samples. At a test length of 2 m we did not observe a significant change in the optical transmission due to the irradiation. For a fibre of 8 m length we observed about 50% transmission loss for the same dose. The absolute values of these results have to be regarded as preliminary due to the fact that these measurements could not be performed in the online fashion due to the low overall transmission of the available samples. Nevertheless it can be stated that the hollow fibres are more robust against degradation by γ-radiation than the ZrF_4 fibres. Their high intrinsic absorption and

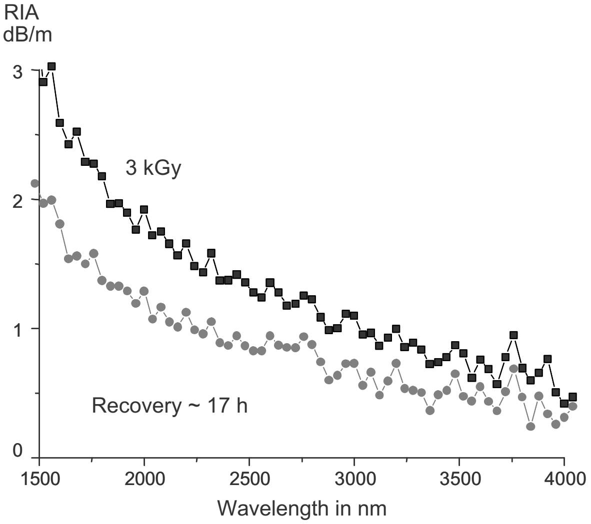

Fig. 2. Spectral distribution of radiation induced attenuation (RIA) on ZrF_4 fibre (Ir Guide 1 from Le Verre Fluoré).

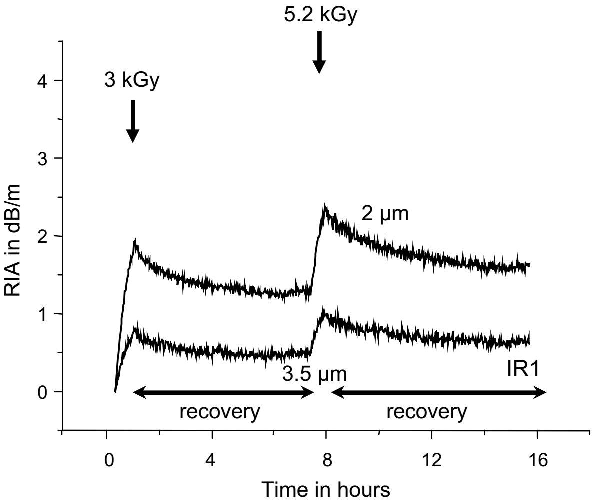

Fig. 3. Evolution of RIA at two wavelength during two irradiation and recovery periods at room-temperature (IR guide 1 from le Verre Fluoré).

strong sensitivity regarding the bending radius remain however a problem. For the time being, we conclude that ZrF_4 fibres could be used in the 3–4 µm region if the radiation flux does not exceed 1 Gy/s and if the fibre is simultaneously heated around 100 °C. For wavelengths above 3 µm, hollow fibres appear to be better candidates but only for short fibre lengths. The doses to which the fibres have been tested so far are much smaller than the full lifetime doses of ITER. The next fibres that shall be tested are sapphire fibres.

3. Multi-colour pyroreflectometry

Multi-colour pyroreflectometry methods that allow to measure temperature under conditions of wavelength dependent emissivities have been developed at the CNRS-PROMES in two colour [5] and three colour versions [6]. With the advent of more reflecting wall surfaces in tokamaks it is of increasing interest to have this possibility also in that environment. To test the use of this technology for tokamaks a collaboration between the CEA and the CNRS-PROMES was started. The principle of the method (explained in detail in [5,6]) is the following: of two parallel optical fibres with largely overlapping viewing areas one serves for the illumination of the target and the other for detection of the thermal and the reflected light from the target. The illumination is provided by pulsed laser diodes working at 1.3 µm and 1.55 µm. It is so weak that it does not heat up noticeably the target. This light is reflected off the target. The reflected light and the intrinsic thermal emission of the target at the two wavelengths are distinguished by synchronous detection tuned into the pulse of the illuminating diodes. From the reflected light the emissivities ε at both wavelengths are determined – as well as the diffusivity factor η which corresponds to the ratio of bidirectional to hemispherical reflection, which is assumed to be constant for the two wavelengths of interest. In installations with three colours this hypothesis can be tested and an eventual error can be quantified [6]. These values known,

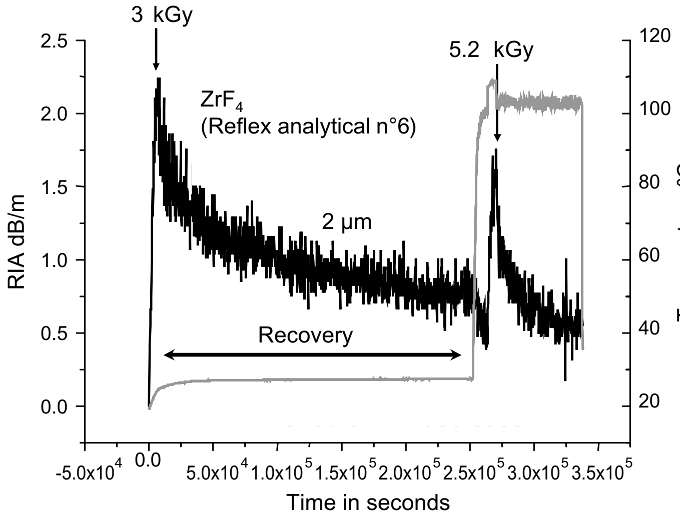

Fig. 4. Effect of thermal treatment at 100 °C on recovery of RIA (Reflex Analytical fibre no. 6).

the absolute temperature of the target can be deduced from the passive measurements. To follow the temperature evolution of these values over a large temperature range the solar furnace and the MEDIASE facility of the CNRS-PROMES were used. We investigated tungsten samples with different surface roughness. Fig. 5 shows a result of these measurements for a clean tungsten target after several heating/cooling cycles when the measurement had become stable. The temperature range from 700 °C to 1500 °C was accessible in this experiment. Between 1000 °C and 1200 °C there is a noticeable change in the emissivity and the diffusivity of the target but the ratio of the reflectivities ρ_r/ρ_b at the two wavelengths (1.55 μm and 1.3 μm) stays rather unaffected. The next question had been under which off-normal angle of illumination the principle still works. Fig. 6 shows the measurement of the reflected signal on two tungsten samples. Depending on the roughness, the useful cone has a width of 20–30°. Recently lenses were introduced in front of the fibres in preparation of a prototype installation in the electron beam test bed FE200 in Le Creusot. With these lenses of 12 mm diameter and 25 mm focal length measurements over a distance of 50 cm are possible. Longer term developments that we consider are the transfer of this technique in the mid-IR range (3–5 μm) and the inclusion of the possibility to move the illumination (and measurements) spot with a scanning mirror system or by using a fibre bundle matrix.

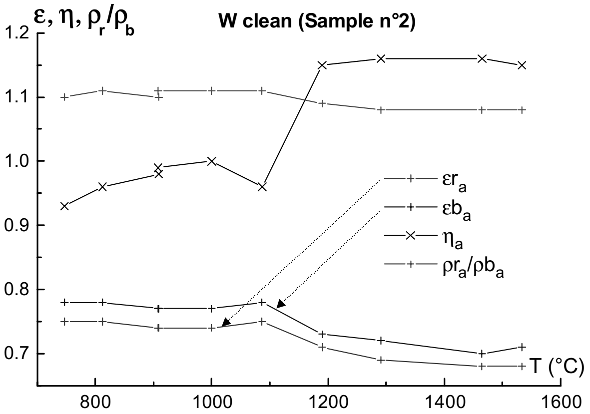

Fig. 5. Result of two colour pyroreflectometry measurement in MEDIASE facility of CNRS-PROMES.

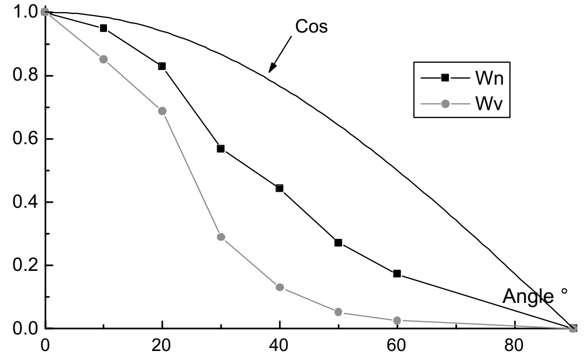

Fig. 6. Angular distribution of reflected light on two tungsten targets with different surface roughnesses for normal illumination.

4. Photothermal characterisation

Two directions are pursued to develop active thermography for the divertor thermography of ITER. The first method uses sinusoidally modulated laser light of which the frequency of modulation is swept in the range of a few Hz to kHz. The primary aim is to characterise eventual deposited layers by their modification of the frequency dependant phase delay between the light impinging on the surface and the thermal response of the target. At the DGA in Odeillo we used a 60 W fibred diode laser (810 nm) to illuminate an unused spare part of the Tore Supra limiter elements. Up to a frequency of 55 Hz the thermal signal was strong enough to be analysed for its phase delay in the first experiments of this kind. We estimate that this should be just sufficient to identify deposits larger than 0.3 mm as encountered on the neutralisers of Tore Supra. The second method used is the flash method using short pulsed laser light illumination. The aim of this experiment, performed at the CNRS IUSTI in Marseille, is to analyse, with an infrared detector (HgCdTe, 2–22 μm), the 1D cooling of a carbon coating on a CFC substrate once it has been uniformly heated (on a few cm^2) by a laser pulse (20 ns, ~100 mJ , 248 nm). Thermal diffusivity and effusivity of the carbon coating and the thermal contact resistance between coating and substrate shall be identified through least squares approximation of the experimental photothermal signal and the response of a corresponding thermal model. The method was successfully tested on a homogeneous graphite disk.

5. Conclusion

The results of the irradiation hardness test of the fibres seem to have ruled out the use of ZrF_4 fibres close to the divertor of ITER. The judgement on the hollow fibres is still reserved and needs further evaluation. We have however-based on the reputation of bulk sapphire [10] – some hope regarding the next tests foreseen with sapphire fibres. The pyroreflectometry method is progressing well towards applicability in tokamaks. After initial testing and installations of proof of principle set-ups for the two photothermal methods of pulsed and modulated illumination we are now looking forward to decisive tests on targets with deposits.

Acknowledgement

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References

[1] R. Reichle et al., in: Proc. 32nd EPS Conf. on Plasma Phys., ECA Vol. 29C P4.083, 2005.
[2] R. Reichle et al., Rev. Sci. Instrum. 75 (10) (2004) 4129.
[3] Th. Loarer et al., J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.01.205.
[4] Ch. Grisolia et al., J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.01.169.
[5] D. Hernandez et al., Rev. Sci. Instrum. 66 (1995) 5548.
[6] D. Hernandez, Rev. Sci. Instrum. 76 (2005) 024904.
[7] R. Reichle et al., J. Nucl. Mater. 313–316 (2003) 711.
[8] J.A. Harington, United States Patent, Number 5,815,627, 29 September 1998.
[9] A.E. Costley et al., Fus. Eng. Des. 55 (2001) 331.
[10] E. Colby et al., IEEE Trans. Nucl. Sci. 49 (2002) 2857.