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Surface temperature measurements on Tokamak target plates with two types of infra red fibres

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Abstract

Tore Supra has chosen to protect the most heavily solicited and actively cooled target plates by thermography using optical fibres. In consequence to previous experience [J. Nucl. Mater. 290–293 (2001) 701], the prototype periscope for the 2001 experimental campaign was equipped not only with silica fibres but also with a ZrF_4 fibre, transparent up to 4 μm. As then, the measurements in the mid infrared range give lower temperatures than the ones in the near infrared range. The silica fibres are more robust and easier to calibrate, which may justify to use both types side by side using a cross calibration formula. Measurements with an silica fibre embedded in the interior of the target plate exhibited only during discharges with LHCD heating sufficient signal levels to be spectrally analysed. Under these conditions the same kind of additional near infrared radiation as on the silica fibres looking at the exterior of the target plates was observed.

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1. Introduction

During 2001 Tore Supra has run discharges on the first installed quarter of its actively cooled pumped toroidal limiter. The limiter will be surveyed by infrared (IR) viewing systems [2,3], but the leading edges of the target plates below the limiter which channel the scrape off layer particles into the pumping ducts and neutralise them, hence their name 'neutraliser', are outside the view of these systems. These leading edges, actively cooled by hyper-vapatrons [4], may receive the highest localised heat-fluxes altogether, attaining 15 MW/m^2 under full power conditions leading to surface temperatures up to 1000 °C leaving only a small safety margin [5]. Thermography using optical fibre periscopes had been chosen for their surveillance. Pilot projects with silica fibres at Tore Supra had revealed higher than expected signal levels in the near infrared (NIR) range [1]. These findings were interpreted as the sign of dust and flakes on the surface and steep temperature gradients in the semi-transparent surface of the carbonaceous target. Laboratory experiments either did [6] or did not [7] show similar effects depending on the precise measurement conditions. In the mid IR range such problems were assumed to be smaller, even though not necessarily non-existent [8]. During the 2001 campaign these assumptions were meant to be tested further using the prototype of the fibre periscope diagnostic. Here the set-up and some first results will be presented.

2. Description of experimental set-up

The full implementation of neutralisers are 12 cassettes that form a ring below the limiter. For the 2001

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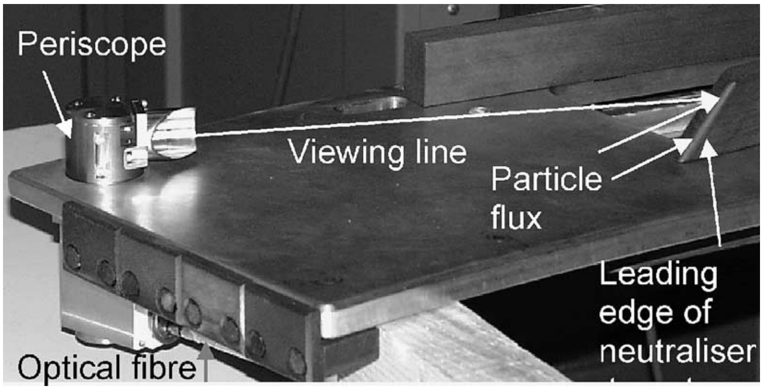

Fig. 1. Photo of the neutraliser cassette before installation with integrated fibre periscope. The height of the neutraliser is 4 cm.

campaign one of these cassettes was mounted, equipped with target plates made of solid carbon fibre reinforced carbon (CFC) and the prototype of the fibre periscopes (Fig. 1). The periscope is a construction using two gold coated mirrors and a sapphire window common to its three viewing lines, each of which is associated with a fibre and an individual collimating optic. Two lines of sight with observation spots of 10 mm diameter (Fig. 2(a)) were oriented to the supposedly hottest upper part of the neutraliser. One of these two viewing lines was equipped with a ZrF_4 fibre of a diameter of 200 μm, transparent from the visible up to 4 μm, the other one with a silica fibre. The third viewing line, also equipped with a silica fibre, provides an integrated view with a 5 cm spot size. Inside the neutraliser itself, a silica fibre was installed to function as a reference measurement independent from the suspected plasma surface interaction effects (Fig. 2(b)). Its front end was facing a small cavity 7 mm below the surface observed by the two fibres with 10 mm spot size. The silica fibres were near infrared (NIR) grade low OH silica fibres transparent from the visible up to 2 μm with 300 μm diameter. All fibres were capable to stand the bake-out temperature of Tore Supra of 210 °C, the front-end part of the internal fibre could sustain 500 °C. The numerical aperture for all fibres was 0.22. The feed-through is for each fibre a 1:1 sapphire lens brazed into a fibre connector (Fig. 3).

The data acquisition for the IR light from the ZrF_4 fibre consisted of a InSb focal plane camera equipped with a band pass filter of 3–5 μm and a dedicated storage system [3,9]. The fibre was imaged onto four pixel of the size 30 μm × 30 μm. The optical throughput was limited to F/5. A wavelength selective beam-splitter separated the NIR part of the radiation off to a separate silica fibre. The three silica fibres signals were optically relayed onto a InGaAs detector array equipped with a high throughput (F/2.9) spectrometer covering the range 0.9–1.6 μm [1] or a filter at 1530 nm (FWHM 50 nm) equipped with the same type of detector. Calibrations with mobile heat sources revealed small variations

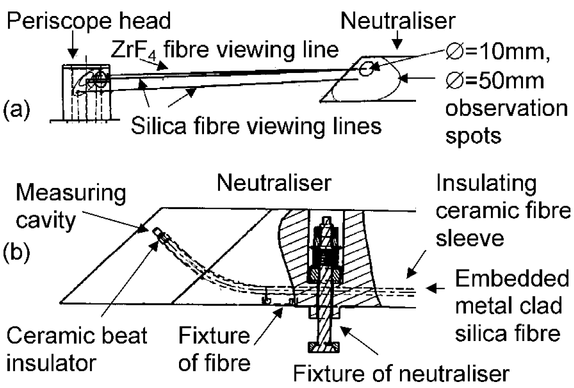

Fig. 2. (a) Lines of sight for the fibres viewing the exterior of the neutraliser. (b) The fibre embedded inside the solid CFC neutraliser.

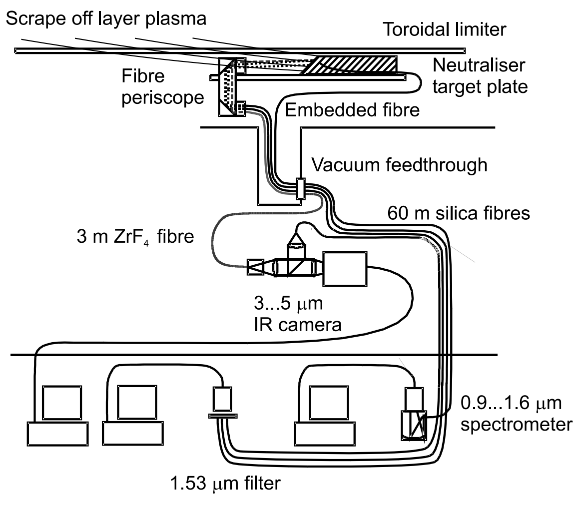

Fig. 3. Overview of experimental set-up used.

during the experiment and good accordance with literature data for the silica fibres (<10%) and more significant variations with ZrF_4 fibres (up to 30%), but also significantly lowered total transmission (50%). Calibrations using the vessel bake out temperature as heat-source gave good agreement with the other calibrations for the internal fibre but 1.8 times higher values for the periscope fibres. The calibration spectra had the form expected for black-body radiators. The post experiment examination revealed no transmission loss of the sapphire window of the periscope. The overall transmission of the periscope assembly itself proved to be low: 30–46%, depending on the line of sight. The low temperature limits of the detection systems (5 Hz for the NIR measurements, 50 Hz for the IR) were found to be 200 °C for the NIR spectrometer, 150 °C for the filter arrangement and 100 °C for the IR measurements.

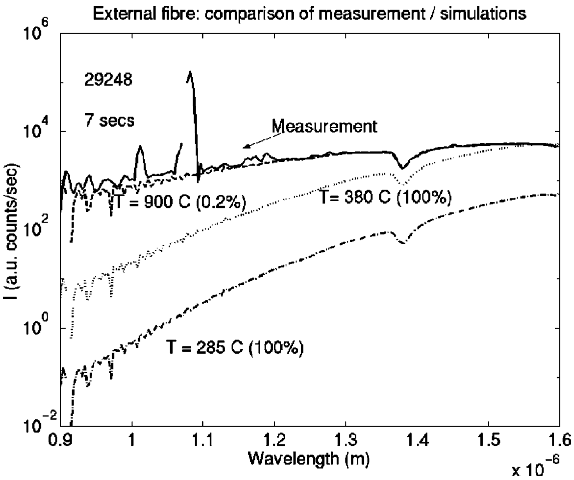

Fig. 5. Infrared spectrum during one time-slice measured with the external silica fibre together with three simulated spectra (1 counts/s ≅ 0.000575 W/sr m^2/m).

3. Measurements

The principal aim of experiments dedicated to the fibre periscope system was to heat up the neutraliser as much as possible. Discharge 29248 is an example of a discharge with a period of lower hybrid current drive (LHCD) and ion cyclotron resonance heating (ICRH) (Fig. 4). The temperature traces shown are derived from the intensities at fixed wavelengths (1.55 and 4 μm) assuming blackbody radiation distribution. During the LHCD phase the plasma current was modulated around the value necessary to connect the rapid electrons created in front of the LHCD antenna directly with the neutraliser. Each passage past the neutraliser was marked by a temperature peak. The temperature traces of the external silica fibre and the ZrF_4 fibre are very similar but the measurement at 4 μm is systematically about 80 °C lower than the one at 1.55 μm. One notes rapid temperature transients on the external observations. The internal fibre reacts slower and only during the LHCD period. It is not well correlated to the exterior observations: during ICRH heating of the exterior surface to the same temperature as by the LHCD heating the internal fibre showed significantly less response (<30 °C), even though the spectral form of the external NIR measurements were the same (Fig. 5). This spectral shape deviated from a blackbody radiation in being too high in particular at the short wavelengths (see Section 4). Also a strong He I line at 1.09 μm was present. In a similar discharge the spectral shape of the light emitted by the internal fibre during the LHCD phase was analysed. Surprisingly the shape of the spectra

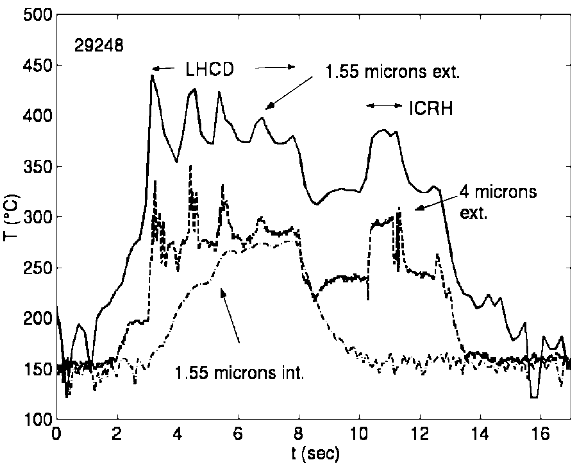

Fig. 4. Temperatures at 1.55 and 4 μm measured with external and internal fibres.

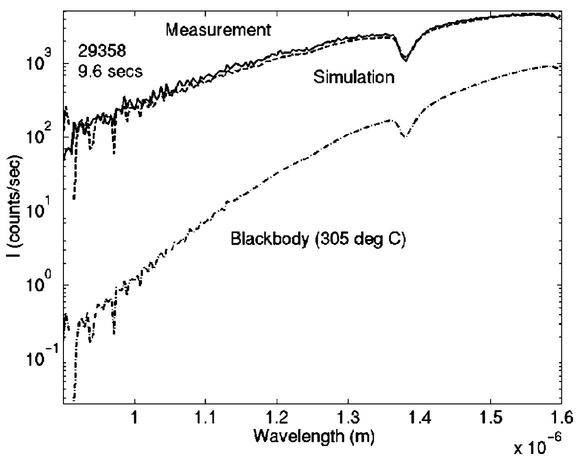

Fig. 6. Measured and simulated spectrum of internal fibre (1 counts/s ≅ 0.00183 W/sr m^2/m).

showed the same kind of deviation from the expected black body distribution as on the exterior fibre, albeit without the spectral line features (Fig. 6).

Concerning the important parameters for the behaviour of the internal fibre it shall be noted that it was possible to change the strength of the signal observed on the internal fibre during LHCD heating considerably by varying the coupling parameters of the antenna while the external fibre observations rested nearly unchanged.

4. Simulation of results

The similarity of the spectral form of the measurements with the exterior and the interior fibres can be described by the following heuristic formula:

$$I_{\mathrm{obs}}(\lambda) = I_{\mathrm{therm}}(\lambda) + I_{\mathrm{therm}}(\lambda) A \exp^{(B/\lambda)}. \quad (1)$$

$I_{\mathrm{obs}}(\lambda)$ is the observed spectral radiation distribution. $I_{\mathrm{therm}}(\lambda)$ is a black body radiation distribution with a temperature 80 °C lower than I_{obs} (1.55 μm) would suggest. The parameter range for the free parameters A and B was $A = 0.005 \pm 0.003$ and $B = 0.0000106 \pm 20\%$. This formula describes well the spectral shapes in the near infrared range for the temperature range from 240 to 440 °C and agrees with the values measured at 4 μm. Examples of the application are given in Figs. 5 and 6 for the external and the internal fibre respectively. The 380 °C curve in Fig. 5 is given for illustration. It is the distribution one would expect if one would know only the intensity at 1.6 μm and one would assume that the observed object has a blackbody radiation characteristic. The black body distribution $I_{\mathrm{therm}}(\lambda)$ relevant for the application of formula (1) is the 285 °C curve. The simulated curve $I_{\mathrm{obs}}(\lambda)$ agrees in this case with a 900 °C blackbody emission distribution, attenuated to 0.2% of its nominal height, which in term agrees with the measurements. Fig. 6 shows the good agreement between measurement and simulation for the internal fibre. Due to the exponential reduction of the additional radiation with the wavelength in formula (1), one does not expect significant additional radiation contribution at 4 μm wavelength, however at 1000 °C the NIR radiation would grow very significantly according to formula (1).

5. Discussion

The observed deviations from the expected technical behaviour can be readily explained. The transmission value of the periscope was low because in the prototype version some light was falling outside the mirrors. This explains also the difference in calibration with the vessel temperature or with external heat sources, since in the first case the periscope acted as emitter as well. The transmission problem of the ZrF_4 fibre is explained by some mechanical imperfections (ellipticity of fibre and eccentricity in the connector) and the higher fragility of this material.

The spectral shape in the NIR range and the difference between NIR and IR measurements seen on the fibres regarding the exterior of the neutraliser had the same general trends as in the pilot projects [1] with an apparent additional broadband NIR radiation on top of a black body radiation distribution. The mathematical descriptions applied are different, but the effect is the same. For the 2001 data, formula (1) seems to be a very good description and since it has the advantage of less independent parameters it seems better suited for future numerical compensation procedures. The temporal responses on the external fibre seem too rapid for normal solid body responses without considering the presence of thin surface films as in the previous experiments [1]. The ZrF_4 fibre gives according to these considerations the better measurement. The silica fibres are more robust and the calibration is more accurate.

The surprising finding that the internal fibre showed the same additional NIR radiation under the conditions of LHCD as the exterior neutraliser surface under plasma impact, and only a weak correlation to the external observations requires further investigations, probably looking for correlation with parameters relevant for the LHCD: distance between antenna and plasma, or the density in front of the antenna.

The experience gained in integrating the periscopes into the neutraliser cassettes may help in the design of similar arrangements planned in the ITER divertor cassettes. Important issues are the radiation hardness, luminescence and probably also fluorescence in the fibres. The ZrF_4 fibre should be tested in material test reactors, as the silica fibres already have been [10], which had revealed a decay of the radio-luminescence with a $1/\lambda^3$ dependence, indicating that this effect is relatively low for the preferred long measuring wavelengths. From the radiation hardness point of view sapphire fibres may be particular interesting.

6. Conclusion

The prototype periscope worked well and proved its usefulness e.g. in the detection of the impact of fast electrons on the neutraliser. The two fibre types tested are seen to be complementary, the ZrF_4 being more accurate and the silica more robust. The best compromise may be to use some ZrF_4 fibres for reference and to develop extrapolation schemes for the measurements with the silica fibres which systematically overestimate the temperature. An example of such an correction term was found in formula (1) that seems to account for the data from the 2001 campaign. The surprising results seen with the internal fibre require further investigation.

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