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Thermography of target plates with near-infrared optical fibres at Tore Supra

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Abstract

First spectroscopic near-infrared thermography measurements in the range 0.9–1.95 μm performed with optical fibres are reported. Two set-ups served as test-beds for physical and technical questions for a security system based on fibre optical thermography. It was found that for the interesting temperature range above 600°C atomic and molecular line emission is negligible in comparison with thermal radiation. The observed near-infrared spectra are however different from simple blackbody radiation curves. They are explained by the coverage of the surface with dust and flakes. The dust particles are identified by their spectral emissivity falling off with the square of the wavelength. On one set-up, flakes were identifiable by fast cool-down times and confirmed by post-experiment inspection. In the absence of flakes, surface temperatures on a ripple protection plate were measured, that allowed to determine the mean energy of ripple trapped ions to be 200–300 keV. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Tore Supra will install for the next experimental campaigns an actively cooled and pumped toroidal limiter. Below the limiter there will be target plates, called neutralisers, that neutralise the incoming ions and channel these particles into the pumping ducts. To avoid damage by overheating (>1000°C), a security system is proposed that reacts on the thermal radiation measured with optical fibres. During the experimental campaign of 1999 two prototype installations using near-infrared fibres were used on Tore Supra to test this concept. The expected problems were transmission loss of the optics, previously seen to amount to a factor 10, and the presence of atomic and molecular lines. The analysis showed that surface conditions as dust and flakes play an important role.

2. Experimental set-ups

Plasma conditions close to future operation scenario were found in the recess behind the pumped mid-plane limiter (Fig. 1). In this recess, an area of 1 cm diameter of the surface was observed from outside the vacuum vessel both by an near-infrared fused silica fibre transparent up to 2 μm and an infrared camera working at 3.9 μm serving as reference measurement. The bulk material of the limiter is pyrolitic graphite of about 3 cm thickness.

In-vessel optics, near-infrared fibres and vacuum feed-throughs were tested in an installation of five sight-lines onto a protection plate in an upper port with spot-sizes of 6 cm diameter. This actively cooled plate intercepts the ripple trapped ions drifting upwards out of the vacuum chamber into the vertical ports. It is covered

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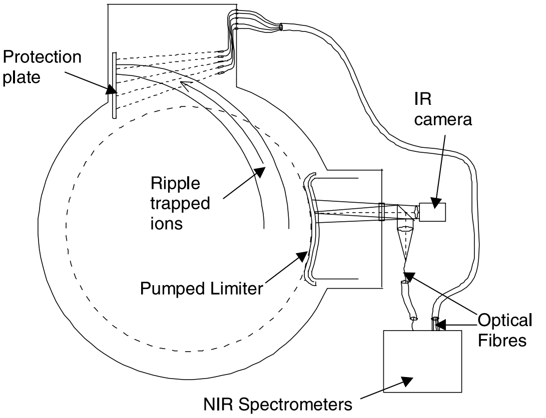

Fig. 1. Experimental set-up.

with 70 μm (±10 μm) of B_4C allowing to convert directly surface temperature into power fluxes [1]. To determine the ion particle flux distribution a segmented ion collector probe in another equivalent upper port was used [2]. The intention was to determine the mean particle energy [3] by a measurement independent from calorimetry which was also performed on this plate and served as reference measurement.

All six fibre measurements were relayed by 60 m of fibres to a low-resolution (3.7 nm resolution) and a high-resolution spectrometer (0.2 nm resolution) both equipped with 256 channel InGaAs detector arrays working between 0.85 and 1.7 μm or to a single channel InGaAs detector at 1.95 μm.

3. Experimental results

In situ calibration of the measuring chain was performed during vacuum vessel bake out at 200°C. The measured emission agrees with the corresponding blackbody radiation spectrum and the transmission measurements of the individual components.

Of the atomic or molecular line emissions in the wavelength range between 0.85 and 1.6 μm only the He I line at 1.09 μm was strong enough to stand out from the thermal spectrum above 600°C. Some other smaller lines seen with the high-resolution spectrometer are negligible in comparison with the thermal radiation. The surprising aspect of all spectra measured with plasma impact on the target plates can be seen in Fig. 2, showing a measurement on the ripple protection plate during a discharge with ion cyclotron resonance heating. The observed spectrum cannot be described by blackbody radiation of a single temperature nor by a weighted sum of several blackbody spectra. Even more pronounced examples of this behaviour were found on the target plates behind the limiter, as Fig. 3 shows, measured during an ohmic discharge. The spectral luminance measured at 200°C – according to the reference measurement at 3.9 μm – has a maximum at 1.1 μm and shows a strong fall-off with the wavelength. At 700°C, the difference between the expected and measured curve behaves similarly. The spectra correspond to a blackbody thermal radiation onto which a broadband extra radiation distribution is added, with a maximum near 1.2 μm and a rapid fall-off towards longer wavelengths. We define a colour temperature as the blackbody temperature one would deduce from the spectral luminance measured at that particular colour. Evaluating a series

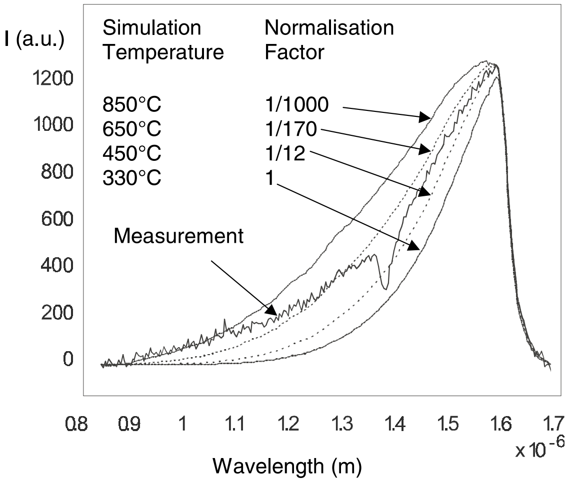

Fig. 2. Raw data (with dip at 1.4 μm due to an absorption in the fibre) from the ripple protection plate and normalised simulations of measurements.

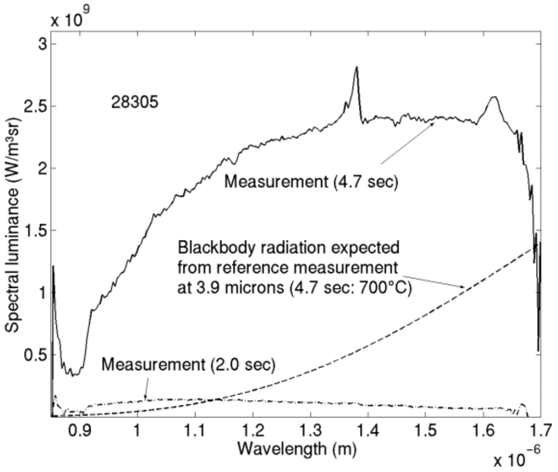

Fig. 3. Measured spectral luminance from behind the limiter at 200°C (2.0 s) and 700°C (4.7 s) together with expected blackbody emission. The calculation for the 200°C case coincides with the zero line.

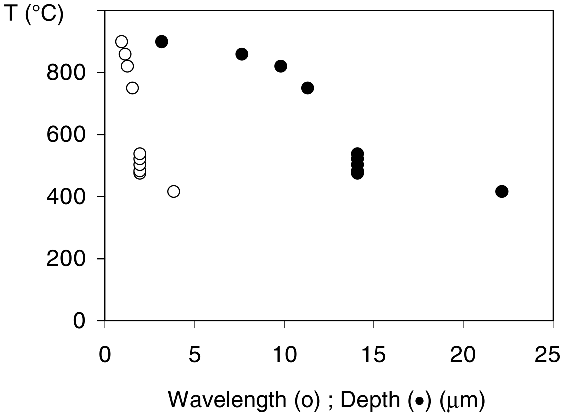

Fig. 4. Colour temperatures from behind the pumped limiter versus their wavelengths and their corresponding viewing depths in amorphous carbon.

of identical discharges with the limiter as target one finds that the colour temperatures decline rapidly in the range 0.9–1.95 μm from whereon they seem to rest stable (Fig. 4, open circles).

All the measurements on the backside of the limiter (including the reference measurement at 3.9 μm) showed cool-down times (visible on Fig. 6) that are significantly faster than a semi-infinite model would allow.

Post-experiment macrophotography of the surfaces revealed that behind the limiter large flakes are formed, which are almost completely detached from the solid covering between 50% and 100% of the viewing area. Their thickness reaches 70 μm. The target area on the ripple protection plate was free from flakes and other large-scale (>5 μm) surface changes, except for a darkening of the zone of impact.

4. Analysis of measurements

The analysis is first concerned with the effects of dust, which is present on both observation areas, than with the flakes only found behind the limiter.

The hypothesis that dust or dust-like small grain structures play an important role in interpreting the data stems from the fact that the emissivity of dust falls rapidly with the wavelength for dust particles that are smaller than the wavelength. For graphite dust, the spectral emissivity is inversely proportional to the square of the wavelength in the range 1–15 μm [4,5]. This seems necessary to explain the rapid fall-off with wavelength of the extra radiation on top of the blackbody radiation. Dust of this size is omnipresent in tokamaks and has recently been analysed in Tore Supra [6]. It has been reported that dust on carbon surfaces hit by neutral beams may heat up to its thermal radiative equilibrium giving significant extra radiation for measurements integrating over the wavelength range from 2 to 5 μm [7]. These facts are used here to explain the existence and the spectral shape of an extra radiation on top of the relatively low temperature blackbody radiation (Figs. 2 and 3). We take the reference measurement at 3.9 μm as the bulk temperature and fit to the low wavelength part of the spectrum a thermal radiation distribution corresponding to dust of a certain size covering a small fraction of the surface. For wavelengths larger than this size the emissivity for the extra-radiation falls inversely proportional to the square of the wavelength. The slope of the measured spectrum below the cut-off wavelength determines the temperature and the coverage of the surface (Fig. 5) by dust. One finds that the dust-size is not too well fixed by this procedure allowing also dust sizes smaller than the smallest wavelengths measured, albeit with higher dust temperatures. The hypothesis of dust with a size of 1.2 μm allows to fit the measured spectra and to reproduce the observed temporal evolution above 600°C (Fig. 6).

The measurements on the ripple protection plate were analysed by ignoring the dust contribution and determining only the colour temperature at 1.6 μm, since the dust contribution is relatively small overall and particularly so at longer wavelengths. The spectrum corresponding to this particular colour temperature is the 330°C curve in Fig. 2. To determine the mean energy of the particles some spatial unfolding was necessary, requiring the knowledge of the deposition profiles. The horizontal profile of the deposition distribution of ripple particles inside the observation area was determined from the visible erosion marks and the spatial distribution of the remaining radioactivity on the plate as being about 3.6 cm wide. The electrical ion flux measurements

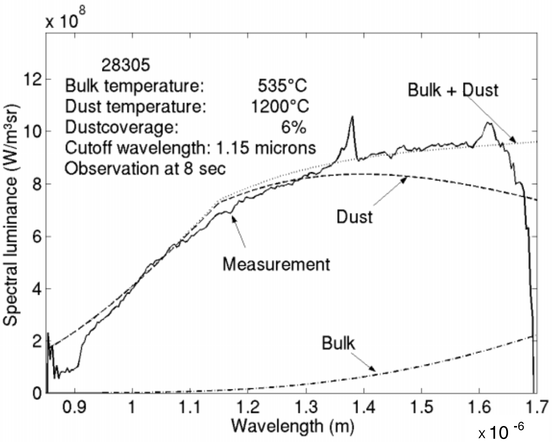

Fig. 5. Spectral luminance from behind the pumped limiter and fit with combined contribution from bulk and dust.

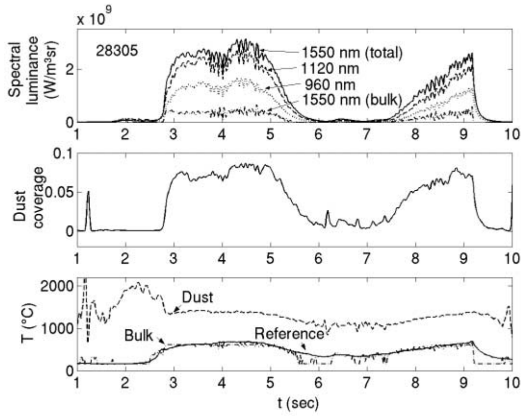

Fig. 6. Temporal evolution of near-infrared radiation and deduced temperature allowing a variation of the dust coverage.

gave the vertical profile and the number of particles involved. With these data and the measured colour temperature, average energies of the ripple ions of 200–300 keV were determined depending on the discharge conditions. These measurements agree within 10–20% with the estimates of the average energies derived from the calorimetry [8]. This indicates that in the absence of flakes and the presence of favourable plasma conditions the measurements at 1.6 μm may be good enough for the determination of the temperature.

The rapid cool-down of the reference temperature observed on the data taken behind the limiter is certainly an indicator for the flakes. Here we try to determine their thickness from the near-infrared spectrum by making use of the wavelength dependence of the absorption coefficient in amorphous carbon, of which flakes are normally made of [9,10]. Firstly a so-called characteristic viewing depth is calculated. This is the depth at which the 1/*e*th part of light of a given wavelength is absorbed. Plotting the colour temperatures from Fig. 4 (open circles) versus the viewing depths of their corresponding wavelength is used as a first indication of a temperature depth profile (Fig. 4, closed circles). The interesting feature is the sharp temperature decline between 10 and 20 μm below the surface. The heat conduction one would calculate from this gradient over this short distance is as small as that of air at ambient condition. This agrees qualitatively with the notion of flakes only loosely attached to the bulk but is less than the 70 μm deduced from the macrophotography.

5. Discussion

Clearly the presence of the flakes affected the temperature measurement at 3.9 μm and the depth profiling attempt indicates in which way the spectrum might be influenced. But for the finer analysis of the near-infrared spectra, the dust hypothesis in the form of a postulated grain size smaller than the wavelength rests indispensable. A possible link between the two might be, that amorphous carbon will re-crystallise into nanocrystals of a size smaller than 20 nm [11,12] when heated up to 600°C, a temperature surely exceeded in our case. In the future one might well try to combine the two ingredients, dust-like addition to the basic spectra and depth profiling of flakes, but this would clearly benefit from additional characterisation experiments outside the tokamak using well-characterised surfaces with dust and flakes.

Bremsstrahlung in the plasma which has a spectral distribution inversely proportional to the wavelength is normally too small to give a significant contribution at high target temperatures, but may help to explain the very steep spectral fall-off seen at a reference temperature of 200°C (Fig. 3).

6. Conclusion

The dust hypothesis can explain the main feature of near-infrared spectra measured on target plates as being composed of two different components: a low temperature blackbody bulk temperature radiation distribution covering almost all of the surface plus a hotter component, the dust, on a small fraction of the surface. The presence of flakes complicates the situation, but there are also indications that near-infrared spectroscopy might allow in situ characterisation of dust and flakes. In the absence of flakes, temperature measurements are possible under favourable plasma conditions and for wavelengths longer than 1.5 μm. From such measurements average ripple ion energies in the range 200–300 keV were deduced. For the future security system based on thermography with fibre optics was found that atomic and molecular line radiation will not pose a problem and that the longest possible wavelength should be used due to the rapid fall of the dust contribution with wavelength, the larger viewing depth into the solid, and for retaining a chance to eliminate the influence of a transmission loss of the optics by using multi-colour pyrometry.

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