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Thermal effects of surface layers on divertor target plates

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Abstract

Measurement of the heat flux to the divertor by infrared thermography is complicated by processes at the surface leading to excess IR radiation. There are at least two possible causes of the excess radiation: (1) an emission process from the plasma just above the target surface, and (2) a surface layer of low thermal conductivity resulting in higher temperatures for a given heat flux. Understanding these extra processes is important for an accurate temperature measurement and assessment of the heat flux. Comparison of IR emission and visible spectra during very bright events have led us to conclude that the excess IR radiation observed at the JET target plates is genuinely due to blackbody radiation.

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1. Introduction

Handling the power load to the divertor is a major design challenge for ITER [1]. In present experiments, the heat flux to the surface is determined mainly by surface temperature measurement coupled with a calculation of heat diffusion in the wall material. It has been found, however, that extra thermal resistance at the surface must be invoked in the heat conduction model in order to obtain sensible values for the heat flux [2,3].

The need for a more elaborate heat conduction model stems primarily from the observed infrared emission often having the completely wrong magnitude and time dependence to be credible heat flux. In this paper, the presence of a surface layer, and other mechanisms are postulated and confronted with a variety of observations.

Having concluded that the extra IR emission is indeed due to a genuine surface temperature, the effects of the surface reaching these high temperatures is considered.

2. Experiment

In JET, the divertor target surface temperature is measured using a fast 2-d infrared camera. Using a periscope situated at an outer midplane port, two views through the plasma, of the inner and outer divertor target plates, are separately imaged onto two halves of a single 128 × 128 pixel cadmium–mercury–telluride photodiode array. The resulting image has a spatial resolution of 4 and 7 mm for the inner and outer view respectively. From these images, it is clear that excess temperature is not arising from overheated tile edges.

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However, it is not possible to exclude the possibility that the excess temperature arises at many hot spots much less than a few mm in size, e.g. dust specs. The system is sensitive over the wavelength range 3–5 μm. An absolute calibration was obtained by placing a calibrated infrared source in the divertor in the torus during a manned in-vessel intervention.

This camera temperature calibration was also found to be consistent when compared with thermocouple measurements in two different ways. First, a few minutes after the pulse, the heat distribution within a tile can be assumed to be fairly uniform, and so the surface temperature can be compare to that of the thermocouples, located 10 mm below the tile surface. Second, modelling the heat flow in the tiles after the pulse, constrained by the measure bulk temperature, is used to determine the increase in each tile energy as a result of the discharge. This energy increase can be compared to the integrated power determined from the infrared camera.

During the 2001 JET operation there was a campaign of He discharges [4]. This permitted comparison pulses with the same magnetic configuration to be run in D and He. These L-mode pulses had the strike points positioned on the vertical target so as to best suit the camera field of view. Other pulses considered in this paper were internal transport barrier discharges with relatively high heating power. These pulses have the strike points on the horizontal target, close to the pumping gaps which separate vertical and horizontal target.

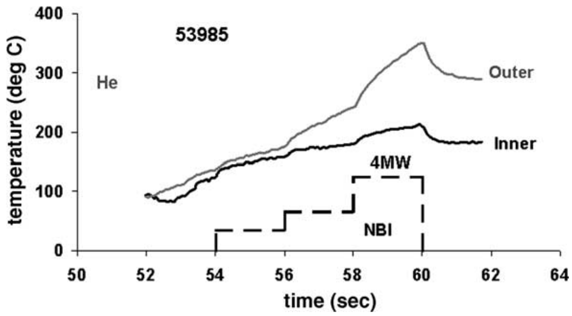

Fig. 1. Helium discharge: temperature evolution at the inner and outer strike points measured by infrared thermography.

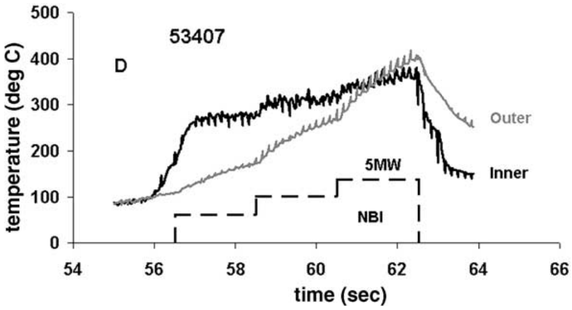

Fig. 2. Deuterium discharge: temperature evolution at the inner and outer strike points measured by infrared thermography.

3. Determining power flux from surface temperature

The power flux to a surface can be determined from a surface temperature measurement if the heat conduction properties of the material are known, i.e. thermal conductivity, heat capacity and density. For example, for a steady heat flux incident on a semi-infinite solid, the temperature rise will be proportional to both the power density and $\sqrt{t}$, where t is the duration of the heat pulse.

Fig. 1 shows the temperature at the inner and outer divertor strike points for a helium plasma where the additional heating is applied in three increasing steps. The temperature responds to each step in power with the classic $\sqrt{t}$ (it takes about 10 s for the heat to diffuse to the back of the tile, so for each step the tile is indeed essentially semi-infinite). The relative temperature rise between the inner and outer divertor is consistent with the total energy increases in the tiles deduced by the tile thermocouples.

Fig. 2 show the same quantities, but for a deuterium pulse. Just as with the helium pulse, about three times as much energy is measured by the thermocouples to be deposited in the outer divertor compared to the inner divertor. The outer divertor temperature evolution and magnitude are also the same as for the helium pulse. However, the inner divertor temperature is much higher than in the helium pulse. It actually exceeds the outer divertor temperature for most of the discharge, and does not follow the stepped $\sqrt{t}$ dependence. If a simple model of diffusion of heat into a solid is applied to the inner temperature evolution, it results in initially an impossibly large power to the inner divertor (i.e. violates an energy balance), and finally a negative heat flux, as this is the only way to account for the rapid rise and fall in temperature.

The impossibly high heat fluxes followed by negative heat fluxes are symptomatic of an excess infrared emission over and above that which would result from the heating of an ideal tile. Specifically this excess emission appears to increase with increasing heating power. To be able to extract correct heat fluxes from the surface temperature measurements, it is necessary to establish the nature of the extra infrared radiation. There are at least two possible explanations for the source of this excess emission.

Firstly, measuring infrared Planck radiation from a solid surface inside a fxusion experiment assumes that the plasma itself is not a significant source in the infrared. Possibly this assumption is incorrect. Indeed any

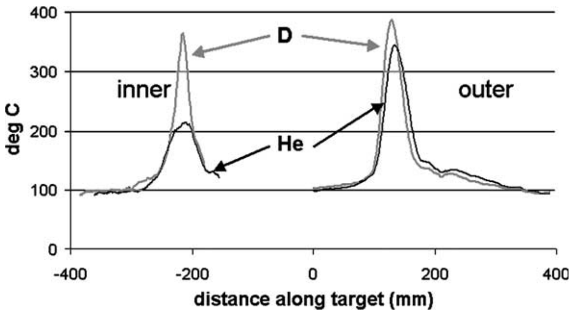

Fig. 3. Poloidal variation of the divertor temperature for helium and deuterium discharges at the end of the additional heating phase.

plasma emission at such long wavelengths would most likely come from the coldest, densest part of the plasma, the inner divertor leg. This is precisely where the excess infrared is most abundant. The observed emission, if due to a plasma emission process, would have to be very close (few cm) to the surface because the infrared image of the inner strike zone is only a few cm wide. Such emission need not be from the deuterium itself. The deuterium plasmas are observed to have a larger intrinsic carbon content and produce more volatile hydrocarbons at the surface.

Secondly, the surface of the tiles may have different thermal conduction properties than the bulk material. Indeed, it is well known that thin layers of deposited impurities cover divertor tiles, predominantly on the inner tile surfaces [5,6], precisely where the excess infrared is seen. It is then possible that the heat incident on the inner leg of the divertor will be incident on surface layers already established from previous pulses. In this case the excess infrared emission would be the result of a genuine excess temperature, the temperature drop across the thermally resistive layer. This temperature drop would in turn be proportional to the incident power.

Another observation from the D and He comparison pulses is that in the spatial profile of the infrared emission from the inner divertor is narrower for the D pulse (Fig. 3). This fits well with the picture of the surface layer. For the ideal surfaces, the heat diffuses laterally, as well as perpendicular to the surface. However, the effect of a surface layer would be to overheat exactly where the power was incident, but there would be no tendency to diffuse laterally because of the layer thinness and poor thermal conductivity.

Finally, although the first infrared measurements were only made several days (D to He) and several pulses (He back to D) after changing the fuelling gas, there was no sign of a gradual change in the surface. Such a prompt change would be expected if a molecular emission process were involved, since the composition of the plasma was observed to change over within a couple of pulses of changing the fuelling gas. If surface layers were the cause of the excess infrared, they would have to be extremely thin to vanish after a few helium pulses and reappear after a few D pulses. This means that the supposed thermally resistant layers cannot simply be the codeposited layers, as the latter are too thick. Instead it would have to be a layer which has a thickness dynamically balanced by, say an impurity influx and outflux, where the use of He instead of D upsets the balance.

4. High temperature surface layer

If there was a measurement not of just the infrared intensity, but the infrared spectrum, it should be simple to distinguish between Planck radiation and molecular emission. Fig. 4 shows theoretical curves for black body radiation, indicating the bands used by the infrared camera and visible spectrometers looking into the divertor. Clearly the surface temperature will have to approach 2000 °C in order to become detectable in the visible spectrum.

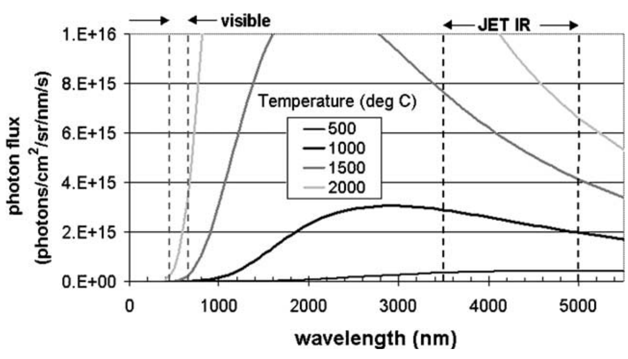

Fig. 4. Theoretical photon flux vs. wavelength for blackbody radiation. Dashed lines indicate the wavelength range of JET infrared camera and divertor spectrometer.

In fact, during some high power discharges, the inner strike point is positioned close to the innermost point of the inner horizontal divertor target plate. These are the regions where the largest amount of deposited films are observed to grow. During such discharges (in deuterium) the apparent temperature measured by the infrared camera does indeed reach 2000–2500 °C. The spectrum from the visible spectrometer viewing such a discharge is shown in Fig. 5. From the shape of the spectrum a peak temperature of 2300–2500 °C is deduced. Since the spectrometer is absolutely calibrated, it is also possible to deduce a temperature from the magnitude of the spectrum; this gives 1800–2000 °C. The fact that the magnitude of the visible spectrum implies a lower temperature than the shape might result from the spectrometer field of view not being completely filled by the bright region on the target, or a bright region which is inhomogeneous, and not completely covering the surface (e.g. dust). Near infrared spectra on other fusion experiments [7] have been interpreted as resulting from overheated dust on the surfaces. Furthermore these authors have noted that the dust particles will not behave like black body sources for wavelengths greater than the particle size.

The above result implies that the excess infrared radiation is indeed the result of an excess temperature, as opposed to molecular radiation. If the heat conduction model is extended to incorporate a surface layer, an extra parameter is introduce, namely $\alpha \equiv k/x$ where k and x are the thermal conductivity and thickness of the layer respectively. In order to have a unique solution for the heat flux for a given temperature, and extra piece of information is needed to constrain the solution. For JET data, two different methods have been used: (1) the subsurface temperature seen by the thermocouples during the pulse or (2) assume that heat flux must be positive and lower α until the heat flux just becomes always positive. Both methods converge to similar values of α of order 3–300 kW/m^2/K, depending on which surface is being modelled; typically much lower values of α are needed on the inner target. This is similar to the values used in ASDEX [3] heat flux analysis, where the criterion of positive heat flux is applied.

Fig. 6 shows the heat flux to the inner target with and without using an additional surface layer. In choosing a value of $\alpha = 3$ kW/m^2/K, it was found that the negative heat fluxes were eliminated, and simultaneously the power was steady for individual steps in the input power staircase. Also shown is the additional heating input power scaled down to give an indication of the input power to the inner target. The scale factor, 0.26, is based on the divertor thermocouple measurement of the in/out asymmetry of the total energy to the target during the pulse.

In the previous section it was argued that if there was a thermally resistant surface layer, it would have to be much thinner than the total codeposited film. This leads to a difficulty since as the layer gets thinner, its thermal resistance decreases. If we take a value of $\alpha = k/x = 3$ kW/m^2/K, and assume that a the thickness is of order 0.1 μm (larger than this could not be conceivably eroded during the switch to helium), one gets extremely low values for thermal conductivity: 3×10^{-4} W/m/K, which is many times smaller than the thermal conductivity of air. This would imply that the hot surface is actually due to dust lying on the surface rather than a uniform layer.

Finally, the motivation for establishing the nature of the anomalously high temperature was to extract the correct heat flux [8]. The heat flux is required to evaluate the survival of components in future machines against melting and erosion. However, while the impossibly large heat fluxes are an artefact of not including a

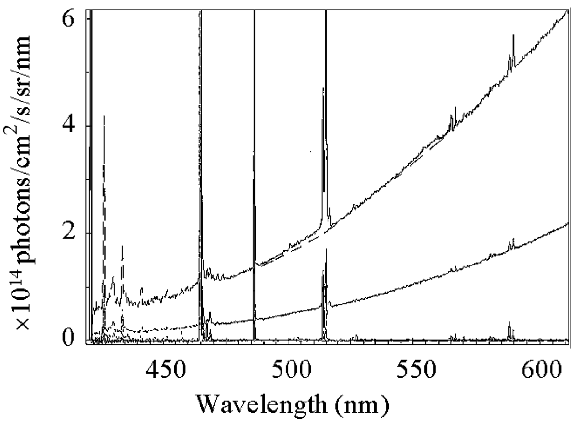

Fig. 5. Visible spectra of inner divertor view for a high power pulse with inner strike point on the horizontal target. As the discharge progresses, the Planck radiation continuum increases.

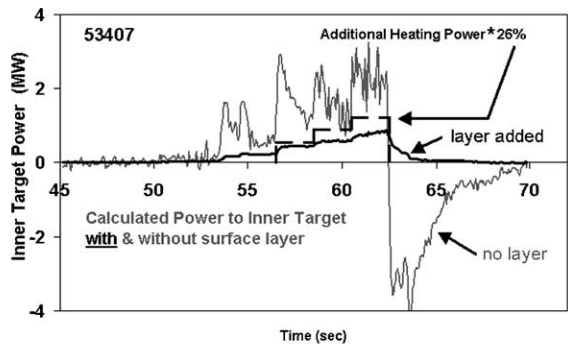

Fig. 6. Heat flux to the inner divertor, derived from the surface temperature measurement for an ideal surface (no layer), and with a added surface layer offering an additional characterised by $\alpha = 3000$ W/m^2 K. Also shown is the additional heating power scaled by the in/out power asymmetry as measured by thermocouples.

surface layer in the heat conduction model, the high temperature is real. Surfaces reaching such high temperatures will be more easily eroded, and this needs to be considered in designing future fusion devices. At first, it might seem that a thin film (or a dusty layer) experiencing high erosion might be expected to disappear. However, the high erosion is balanced by the incoming flux of impurities originating elsewhere (predominantly from the main chamber in the case of JET [5]). The net effect is that impurities transported to this region will experience enhanced re-erosion to be further transported to other regions.

5. Conclusions

Neither a plasma emission process nor a thin uniform surface layer offers an entirely satisfactory explanation of the observed excess infrared emission observed at the inner divertor during deuterium discharges. Visible spectra imply the excess infrared emission is not due to a molecular radiation process, but it due to a genuinely high temperature, probably resulting from poor thermal conductivity at the surface. The regions of the divertor most affected by the supposed thermally resistive layers are also the regions of thick codeposited layers, however, the transient nature of the thermal resistance during a changeover to He pulses suggests that the thermally resistive layer and codeposited layer are not one and the same. Instead, an inhomogeneous layer, such as dust specs on the surface would be consistent with all the observations.

Acknowledgements

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