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Divertor Impurity Sources; Effects of Hot Surfaces and Thin Films on Impurity Production

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEAFusion Energy Conference, Lyon (2002).*

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ABSTRACT

Strong continuum emission has been observed from divertor tiles at visible wavelengths and identified as Planck radiation from surfaces with temperatures of typically ~2600K. Such hot spots (which are not tile edges) are often seen at the inner divertor, and can persist for several seconds. Outer divertor hot spots are much rarer, and were never seen in the MkII GB divertor. Surprisingly, these hot spots do not usually produce significant impurity fluxes. In contrast, ELMs may produce a significant enhancement of impurity fluxes, depending on strike point location and ELM size.

1. INTRODUCTION

Graphite is widely used in present-day tokamaks, and is proposed as part of the ITER divertor [1]. It has good power handling properties, but off-normal events are a concern. This study examines the consequences of overheated graphite (CFC) tiles in the JET divertor. The Central Physics File (CPF) database at JET has been used to identify instances of hot divertor tiles, and look for consequences on impurity fluxes and plasma purity. The method is described below.

2. METHOD

Spectrometers and interference filter/photomultiplier tube combinations are used to monitor bremsstrahlung emission at 523.5nm (±0.5nm), in order to calculate the plasma Z_{eff}. However, if hot tiles are present in the same line-of-sight (l-o-s), then Planck radiation must also be considered. The strong variation of Planck emission with temperature at short wavelengths means that Planck emission at 523.5nm can be neglected for temperatures below about 2000K. Additionally, since the spectrometers are used with a 50ms integration time, emission from very short-lived hot spots (e.g. from ELMs) may not be distinguishable from the usual line, molecular and bremsstrahlung emission.

The CPF database was used to identify the locations of hot spots on JET tiles, using these 523.5nm l-o-s signals. The vertical l-o-s is on a chord that looks close to the plasma centre onto a carbon tile outside the divertor. This tile is essentially a wall tile that receives no significant power loading during a discharge. Consequently, the ratio of divertor/vertical signal is sensitive to the Planck radiation in the divertor l-o-s, and has been used to identify hot spots. This ratio typically has a value of 2-5, depending on divertor conditions. However, when a hot spot is in the l-o-s, the ratio can reach values of > 100.

3. RESULTS

3.1 LOCATION AND FREQUENCY OF HOT SPOTS

The CPF database at JET has been used to look for instances of hot divertor tiles, as described above. Figures 1&2 show some examples of the ratios for the inner and outer MkII SRP divertor. MkII GB data was also examined. It was notable that hot spots in the outer divertor were not observed in the MkII GB configuration and that even in MkII SRP, they are rare. In contrast, a large number of pulses showed enhanced 523nm emission at the inner divertor.

The hot spot positions are quite localised, and co-incident with tile positions identified as areas of redeposition [2]. The outer divertor hot spot (R=2.88m) was mostly observed on one day of operation, and is probably the heating of a temporary redeposition zone. For Pulses 56975-56980, which are discussed later, the strike point history [3] seems to be an important factor; eleven out of the previous thirteen discharges had the outer strike point on the horizontal target at R=2.853 or 2.871m.

3.2 TEMPERATURE MEASUREMENTS

The JET survey spectrometer (420-600nm) records enough wavelength range that the shape of the continuum emission vs. wavelength can be used to derive an 'average' Planck temperature of the hot spot. The spectrometer has an integration time of 50ms, and the best spatial resolution is a 33mm diameter spot, so the measurements are a time and space average and will consequently not indicate the absolute maximum tile temperature (though emission intensity is heavily weighted to high temperatures).

Figure 3 shows three frames of data from this spectrometer, each 100ms apart. Thermal temperatures (T^{vis}) of upto 2630K are derived from the wavelength dependence of the emission. Though the emission in Fig. 3c is 4x larger than in Fig.3b, implying a DT of 350K, the measured temperature is only 150K higher – implying a change in the emission area. Indeed, comparing the absolute divertor emission with a Planck body, then the effective emission area (at the measured temperature) increases form 11% to 20% of the area in the l-o-s (33mm diameter spot). This implies that the 'hot spot' is not a uniform hot layer, but is granular (dust or carbon grains or CFC high-points), consistent with observations by Herrmann [4]. There is IR camera data for this discharge, Fig.4, which shows a broad hotspot at the inner divertor, in agreement with other visible spectroscopy. Consequently, these measurements rule out strong molecular emission (at'mm wavelengths) as an explanation of previous IR observations [5].

At the outer divertor, hot spots have only been observed in the MkII SRP divertor, and mostly at a tile location equivalent to the inner divertor hot spots.

The centre divertor tile, the Septum Replacement Plate (SRP) tile, in the MkII SRP divertor has been observed (at visible wavelengths) to reach high temperatures only twice, in Pulses 54823 and 61248. In Pulse No: 54823, the edges of the tile were determined to have reached a temperature, T^{vis} ~ 2800 (±100)K. The SRP tile was not designed for power loading, unlike all the other divertor target tiles, which were engineered so that tile edges are always hidden from the plasma.

3.3 CONSEQUENCES OF HOT SPOTS

During an L-mode experiment that required a slow sweep (17-23s) of the strike points from the horizontal tiles to close to the top of the vertical tiles, it was noticed that a hot spot was created in the outer divertor at R=2.88m, t=14.65 and 17.83s (Fig.5). The Planck emission from this hot spot was very reproducible (first 3, and last 3 pulses had different gas fuelling, which seems to change the time evolution of the second hot spot), indicating that the high temperatures (T^{vis}~2600K from visible emission; no IR data available) were not modifying the surface conditions (i.e. not removing any films). Figure 5 also illustrates that the hot spot does not significantly increase carbon impurity influxes, or Z_{eff}.

At the inner divertor, where we know that there is significant redeposition of eroded first wall material, hot spots are regularly observed. One example, with high power heating is shown in Fig. 6. The Planck emission is very high during most of the heating phase, though it does drop significantly around 10s, indicating a reduced temperature at this time (EFIT indicates a fixed strike point position, so it is not likely that the strike point is moving out of the observation volume). Measured temperatures are T^{IR} ~ 2075K; T^{vis} ~ 2500(±100)K. The difference is most likely due to the toroidal averaging built into the IR camera analysis, though toroidal asymmetries are possible. The early time evolution (8-10s) of the signals in Fig.6 suggests that there is some thermal release of carbon impurities. However, from 10s onwards, there is no correlation of the carbon impurity emission with the Planck emission. This may indicate that carbon dust, or 'soft' amorphous films, are quickly eroded in the first seconds, to leave a more resilient' 'conditioned' surface.

Although most data indicates that these hot spots do not generate significant impurities, there are exceptions, e.g. Pulse No: 60580, when T^{IR} ~ 2800K (Fig.4), and increases in Z_{eff}, due to enhanced carbon fluxes, are observed.

3.4 ELM POWER LOADING

ELMs have the potential for extreme heating of divertor target tiles: MJ of plasma energy can be incident on the tiles in 0.1 - 1 milliseconds. The ITER requirement is that ELMs must be less than about 1MJ/m^2 in size [1]. Although visible spectroscopy is unlikely to see the Planck emission produced by short-lived ELMs, the JET IR camera system is capable of capturing such fast events.

Figure 7 shows a 2D plot, and inner divertor spectra for a horizontal target ELM-ing discharge in JET, with 0.5MJ ELMs. Planck radiation during ELMs is not evident from the spectra, though the IR camera only measures T^{IR} ~1900K. However, these ELMs generate large influxes of CII and C_2. The average CII and CIII carbon fluxes (assuming constant photon efficiency) are increased by ~50% by these ELMs.

Figure 8 shows similar data for another discharge with 1.0MJ ELMs (i.e. ~1MJ/m^2). In this case the strike points were on the vertical target tiles. The spectra look quite different; although there are large increases in CII and CIII, the increases in C_2 are smaller, and many metal lines (Be, Cr) can be observed. Some spectra show a small amount of Planck emission, but the intensity is too low to properly distinguish it from molecular and bremsstrahlung emission, and derive a thermal temperature. The IR camera measures T^{IR} = 2500-2800K, so the surface is getting much hotter than in the previous case. During the ELMs, Z_{eff} is observed to ratchet upwards (for a total ΔZ_{eff} of 1.0), so core contamination has become an issue.

SUMMARY

Hot spots with temperatures >2400K have been observed in the JET divertor with visible spectroscopy diagnostics. Hot spot locations and temperatures correlate well with the IR camera diagnostic, finally ruling out long wavelength molecular emission as an explanation for the IR camera signals.

Hot spots are found to be most common in the inner divertor, and often last several seconds at typical temperatures ~2600K. They are located on the horizontal target plates (not tile edges) in the divertor corners, on regions identified as areas of plasma redeposition. The hot spots may be extensive, and seem to have a granular structure – they are definitely not a uniformly hot film. This may be due to the CFC surface structure, or soot/dust particles on the surface. Typically, these hot spots do not generate significant extra impurity, though when temperatures rise to 2800K (where thermal sublimation is becoming important), increases in carbon fluxes and Z_{eff} are observed.

On shorter timescales, ELMs may cause short-lived hot spots (~0.1ms) that are not detectable with the JET visible spectrometers. If the ELM's fall onto deposition regions, fluxes of molecular carbon (C_2) can be significantly enhanced – likely due to thermal decomposition of amorphous carbon films. If large ELMs (1MJ) impact the metal-rich vertical target tiles, C_2 emission is not so pronounced, but carbon, beryllium and chromium atom/ion emission is significantly increased. The threshold for thermal ablation of the CFC tiles is expected to be at about this ELM size.

We have demonstrated the first use of an absolutely calibrated survey spectrometer (420-600nm) to measure both the surface temperature (from the intensity variation of the Planck emission with wavelength) and the temperature homogeneity (from the measured emission intensity vs. the expected emission at the measured temperature) of hot spots on divertor CFC tiles.

ACKNOWLEDGEMENTS

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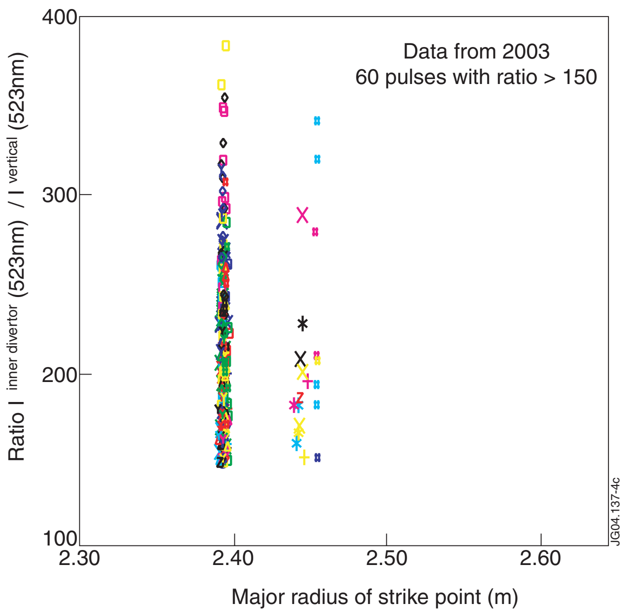

Figure 1: The 523.5nm enhancement vs. strike point position for 2003 MkII SRP inner divertor data.

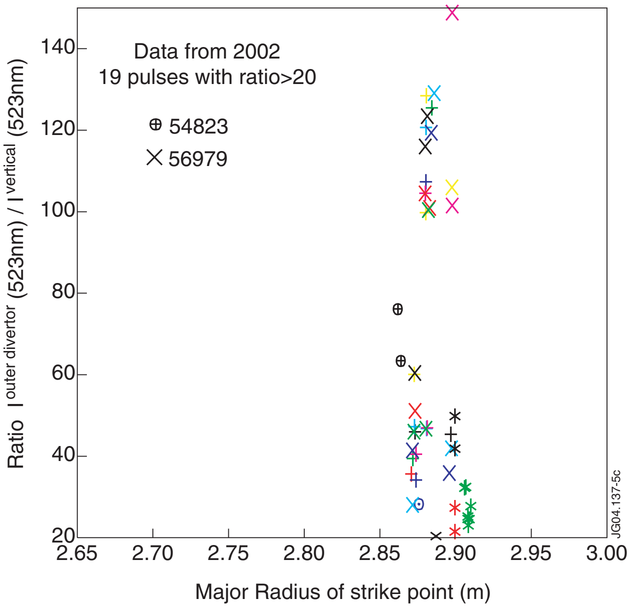

Figure 2: The 523.5nm enhancement vs. strike point position for 2002 MkII SRP outer divertor data.

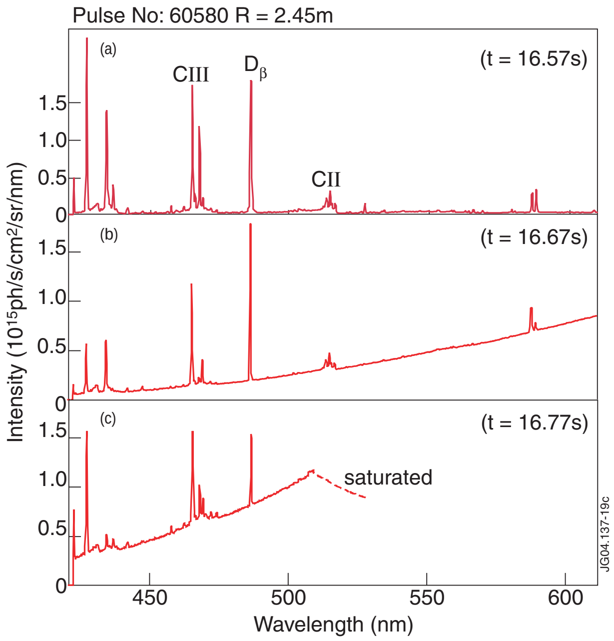

Figure 3: Calibrated spectra for the inner divertor l-o-s at R=2.45m. (a) A 'normal' spectrum at a time (t=16.57s) before the hot spot is evident. (b) Spectrum 100ms later (t=16.67s, T^{vis}~2520K). (c) Spectrum another 100ms later (t=16.77s, T^{vis}~2630K).

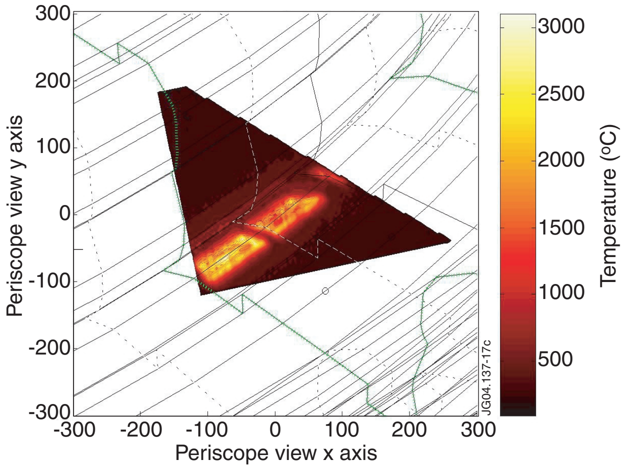

Figure 4: IR camera image (t=16.65s), showing peak temperature of ~2800K. The hot spot is clearly broad and non-uniform.

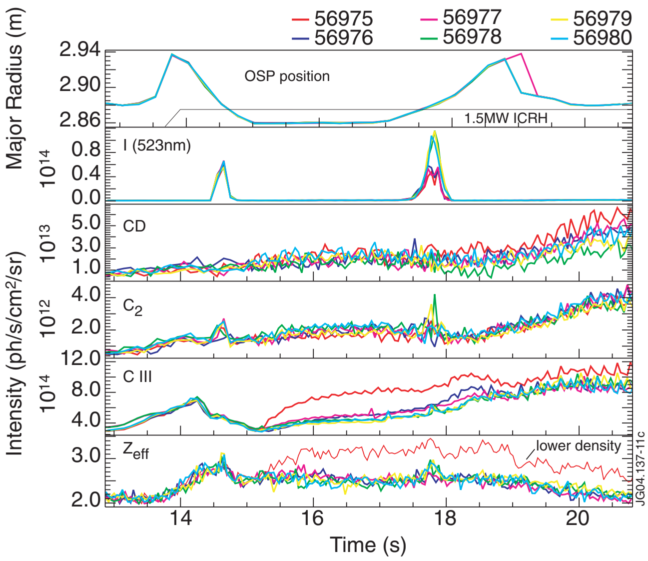

Figure 5: Strike point position and spectroscopy data for the swept strike point pulses, 56975-80. The intensity of emission at 523nm, I(523), is a measure of the hot spot temperature.

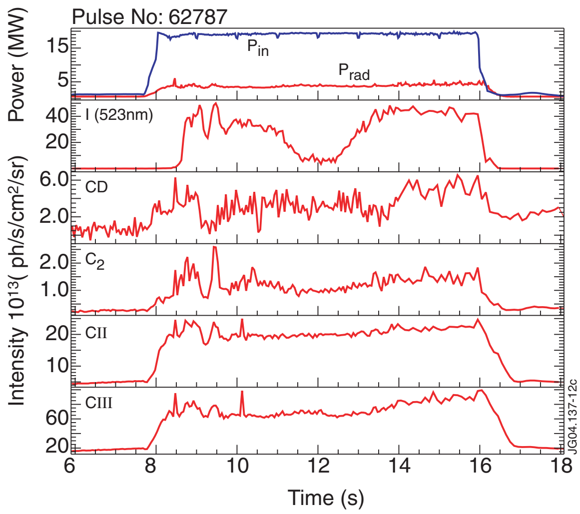

Figure 6: Input power, radiated power and spectroscopy data for the fixed strike point discharge, Pulse No: 62787. The intensity of emission at 523nm, I(523), is a measure of the hot spot temperature.

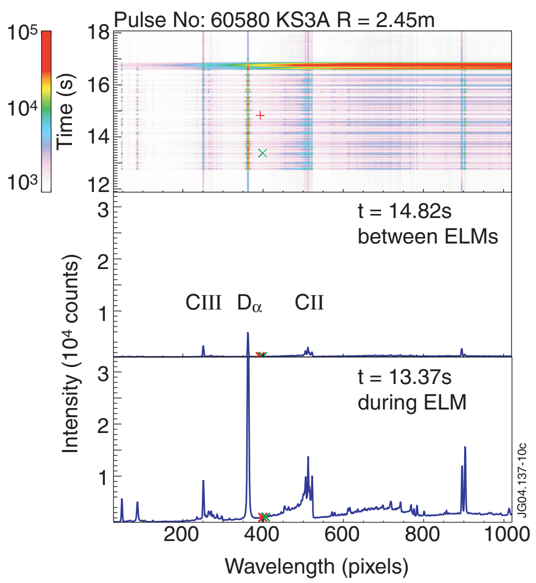

Figure 7: Survey spectrometer data showing enhanced molecular emission during the ELM at t=13.37s.

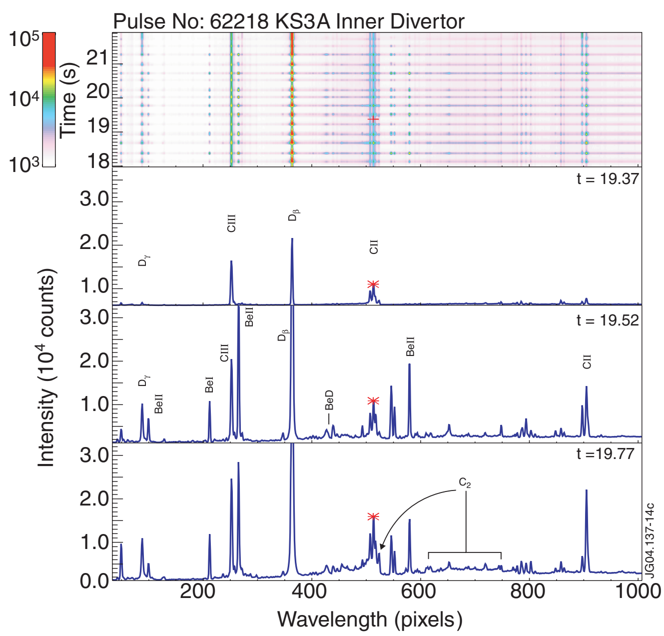

Figure 8: Survey spectrometer data showing strong Be and Cr emission during the ELMs at t=19.52 and 19.77s.