Power deposition studies in the JET Mk I pumped divertor

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1/ INTRODUCTION. The study of divertor performance under steady-state conditions at high power is a central goal of the JET Pumped Divertor programme. Particular care has been taken in the design and installation of the Mk I divertor target so as to optimise its power handling, in particular by avoiding exposure of tile edges, which, in previous JET divertor configurations, limited the range of heating power due to the occurrence of carbon blooms. In addition, the strike points can be swept over the target plates at 4 Hz with an amplitude of up to 20cm so as to increase the effective wetted area of the target. The Mk I JET divertor has shown an excellent power handling capability during the current experimental campaign. In the first part of the experimental campaign, the Mk I divertor target plates consisted of small fibre-reinforced carbon tiles clamped to a cooled support; in March 1995, Be tiles replaced the CFC tiles. The performance of the target has been investigated over a wide range of plasma conditions, at powers of up to 28MW and in steady-state H-modes lasting up to 20s.

2/ EXPERIMENTAL. The surface temperature of the divertor tiles is measured by an infrared thermography system, consisting of a linear array of InGaAs diodes oriented along the radial direction of the divertor and sensitive in the 1.6 μm region. The spatial resolution along the radius is 3 mm; the signal is averaged toroidally over the width of 4 pairs of tiles. In this way, the temperature measured underestimates the maximum temperature in each averaged region, and has to be subsequently corrected for the real wetted area of the tiles. The time resolution of 2ms permits (marginally) the study of fast events such as ELMs. The minimum detectable temperature is 350 to 560°C; the initial temperature of the tiles given by thermocouples imbedded in the tiles. One video camera and 3 spectroscopic CCD cameras (Dα, Be II or C II, and Bremsstrahlung filters) are focused on the same area as the IR camera, and an extra CCD camera coupled with a light source is used between shots to observe the target. The power conducted to the tiles and the corrected temperatures are calculated by a dedicated parallel processor system.

The problems encountered in the interpretation of the IR data arise not only from the 1D toroidal averaging for a very non-symmetrical tile geometry, but also from the contributions of non-thermal emission to the signal, and from thermal radiation emitted by re-deposited layers and loose flakes that have poor thermal contact with the bulk material.

modes: in a typical hot ion mode case (#34230) with a long ELM-free period, P_{cond}=10MW, and 1D power calculation with the corrected temperatures gives P_{inner}=4.5MW, P_{outer}=3.5MW, hence P_{target}=8±2 MW. Langmuir probes however find only ~1MW conducted in the electron channel [4]. This is attributed to the high SOL ion temperature in this regime. In high performance Elm-free H-modes the power sharing between inner and outer strike zones is more balanced than in L-mode in the same configuration.

The effect of giant ELMs is twofold [5]: first, a fast (<1ms) power deposition occurs in the inner divertor, away from the strike zone, with typical energies around 100kJ; then a back-transition to L-mode confinement is often observed, during which energy is deposited at the strike points (already hot); this second phase has caused melting in the Be tiles). The power distribution inner/outer clearly changes between ELMs.

High frequency ELMs are produced in discharges with medium to high gas fuelling. These ELMs also tend to deposit power in the inner divertor target during the fast event, and at the high repetition rates obtained, the net effect is a broad power deposition profile on the target. Combining gas fueling and sweeping, a 20s H-mode has been obtained, at medium injected power (8.5 MW, 120 MJ), where the tile temperature stayed below 550°C. However, high gas fueling at powers near to the H-mode threshold can cause a back-transition into L-mode, where the benefits of the ELMs are lost (fig4).

5/ SUMMARY AND CONCLUSIONS. **a)** The Mk I divertor targets have shown a very good power handling capability both in the CFC and Be versions. In CFC, 140MJ have been injected, of which more than 100MJ were conducted to the horizontal target. For the side plates the values are 85 and 50MJ respectively. The Be target sustained more than 60MJ conducted to the horizontal target, and more than 20MJ on the side plates. With the CFC tiles, in no case has a carbon bloom limited the performance as in the past. The more limited power handling capability of the Be tiles has nevertheless permitted the high current/high power programme to be carried out by using the sweeping capability.

b) Within the uncertainties of the measurements of the IR thermography, a satisfactory global power balance (≈80%) is found in quiescent discharges, both in L- and ELM free H-modes. **c)** Frequent ELMs are extremely effective in alleviating the heat load on the strike zones, by spreading the power over a large surface area of the divertor target, but the penalty is the uncontrolled deposition of power in zones which may have a poor power handling capability. In the case of giant ELMs, the increased power deposition on the strike zone associated with the frequently observed back-transition to L-mode confinement cancels out the benefit of the initial power spreading. **d)** The largest uncertainties in the thermography measurements arise from the existence of loosely bound re-deposited layers on the target surface, that have a poor thermal contact with the bulk material. The

Furthermore, the emissivity of the Be surfaces changes significantly when power is deposited on the tiles. JET Neutral Beam test bed results shows emmisivity changing between 0.2 and 0.8, with a strong dependency on temperature and thermal cycling [1].We attempt to address these problems by using a careful reconstruction of the wetted areas and 3D modelling of the temperatures, measuring the bremsstrahlung profile at the same location, and analyzing the cooling rates to distinguish between bulk material and loosely bound materials. Nevertheless, temperature measurements on the Be tiles have a high uncertainty due to the changing emmissivity and loose flake effects.

3/ POWER HANDLING OF THE CFC TARGET. A quantitative analysis of the power deposition on the Mark I divertor tiles has been carried out with TILO [2], a code that computes the power density on the tile surfaces, taking into account the shadowing patterns, and allows further thermo-mechanical analysis of the tile(s) considered. Four inputs are needed: the magnetic geometry of the plasma, given by the equilibrium code PROTEUS; the power conducted to the divertor tiles, calculated from measured plasma parameters as $P_{cond}=P_{in}-P_{rad}-dW/dt$; the decay length of the power density λ_p, measured with the IR camera; and the geometry of the divertor tiles, which is imported from a CAD system. The resulting power density on the target is then input to ABAQUS and the calculated time evolution of the peak target temperatures at the strike points can be compared with those measured with the infrared thermography [fig2].

A simple case has been chosen: the shot #30909, with I_p=3.2MA, B_t=3.2T, 6MW of NBI heating, L-mode confinement (hence no ELMs) and no sweeping of the strike regions. In this shot, λ_p=1cm at the midplane, and $T_{initial}$ (thermocouples)=40°C.

The results of the simulation are: P_{in}=0.85 (1/2 P_{cond})=0.425 P_{cond}=2.3MW, P_{out}=1.40 (1/2 P_{cond})=0.7 P_{cond}=3.85MW. The calculated conducted power is 112% of the measured conducted power: this is a satisfactory power balance, considering the error of 10-20% in the experimental values, and the uncertainties in the material properties of the tiles. P_{out}/P_{in} differs only by 10% from the value of T_{out}/T_{in}, which means that the tiles behave like a semi-infinite solid to a reasonable approximation, and that the peak temperature values can reasonably be compared to make power imbalance assessments. The result of the TILO simulation shows that the tiles are handling ≈20% more power than predicted from the design parameters [3]. Sweeping the strike regions further enhances the power handling capability of the target. Comparison between two similar shots with and without sweeping show that, for a ratio of λ_p/sweep amplitude=0.44, the effective power seen by the target is $P_{swept}<0.66P_{unswept}$, in agreement with the calculated increase of the wetted area with sweeping [3].

4/ POWER BALANCE AND DISTRIBUTION IN DIFFERENT REGIMES. A good global power balance is found in L mode regime, and also in quiescent ELM-free Hredeposition pattern has been observed to vary on a shot by shot basis [6]. The analysis of the cool down characteristics, coupled with careful modelling, can help to identify the bulk heat transmission processes.

Special thanks are due to Mr. P van Belle.

[1] H Falter et al, to be published.
[2] R. Viola. TILO USER'S MANUAL (JET).
[3] C G Lowry, private communication.
[4] K McCormick et al, these proceedings.
[5] J Lingertat et al, these proceedings.
[6] H Guo et al, these proceedings.

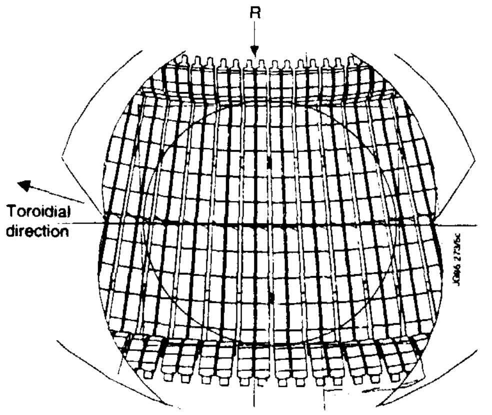

Fig.1. View of the divertor target for the IR camera, and various 1D and 2D CCD cameras, from a vertical port in the JET vessel.

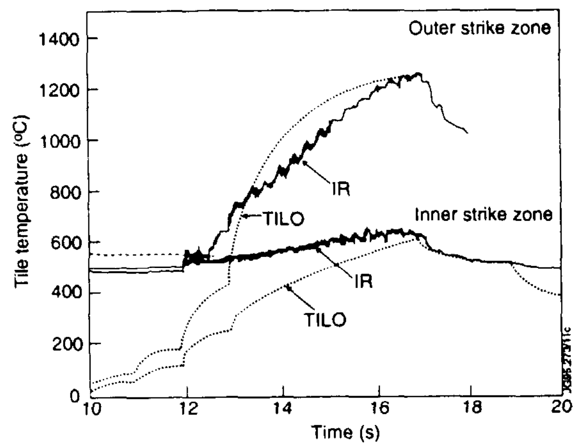

Fig.2. Measured peak temperatures in the strike zones and results of the TILO calculations.

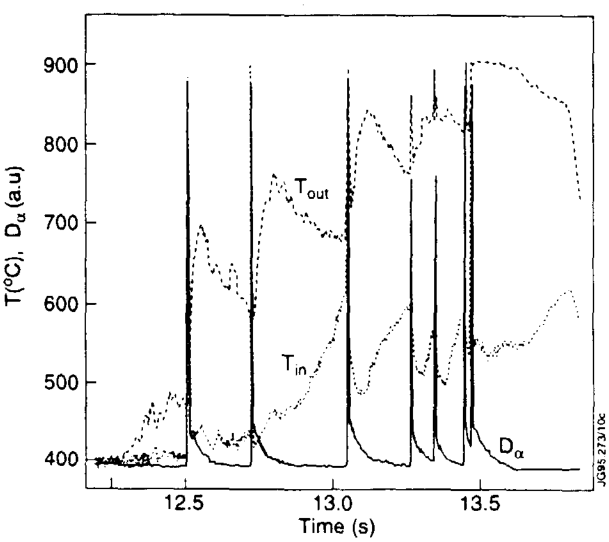

fig 3. Maximum temperatures in each divertor side,and D_α, in shot 34460.

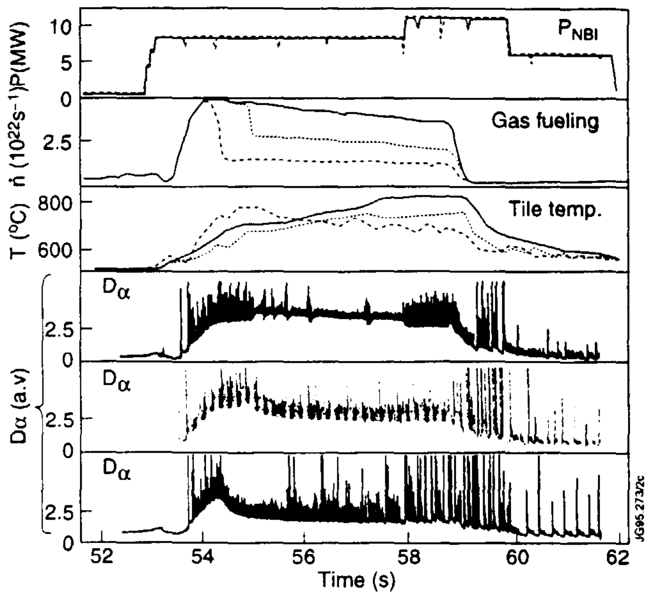

fig.4. Effect of gas fuelling in three similar discharges with different fueling rates (shots #31862 (1), #31863 (3) and #31865 (2)).