Power Balance in the Bulk Plasma and in the Scrape-off Layer during H and L Mode Divertor Discharges in JET

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Introduction – In JET a magnetic separatrix can be formed inside the vacuum vessel at plasma currents up to 3 MA with one ("single null", SN) or two ("double null", DN) stagnation points ("X–point") [1,2]. In SN discharges a transition from L– to H–mode has often been observed with neutral beam (NB) heating in the range 5–10 MW. A significant fraction of the total radiation power loss is dissipated from the the X–point region(s). Using bolometer measurements an attempt is made to estimate the power radiated from the confinement region and the divertor region(s). The radial emissivity profiles of the confined plasma show broad radiation shells during the H–mode. The poloidal distribution of the radiation flux near the X–point is compared with the poloidal distribution of the D_α emission. The power flow to the divertor target tiles is estimated using infrared thermography. The occurence of the H–mode appears to be related to the heating of the plasma edge.

Experimental Setup: The relationship between the JET X–point null, the divertor target tiles and the relevant diagnostics is shown in Fig. 1 in plan view. The eight sets of carbon target tiles were installed as protective tiles for the octant joints.

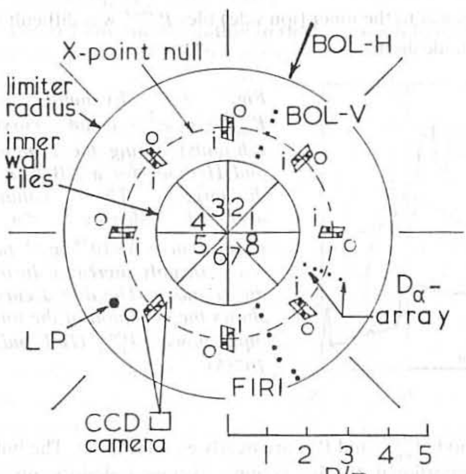

Fig. 1 : Schematic plan-view of the JET vacuum vessel showing the relationship of the diagnostics to the eight sets of divertor target tiles. The scrape-off layer impinges at a glancing angle of 9.5 ° on an outer (o) and an inner (i) location of each set. The horizontal (BOL-H) and vertical (BOL-V) bolometer cameras, the D_α array, the far infrared interferometer (FIRI) and the moveable Langmuir probe (LP) are all located in mid-octant as shown. The CCD camera, mounted midplane, views directly the top target tiles on octant joint 5/6.

The total radiation power is measured by two bolometer camera systems, located in mid-octant, one horizontal the other vertical [3]. Camera chords looking into the X–point regions at the top and/or the bottom of the plasma show enhanced radiation. The detection range of the bolometers is $3 \leq E_{ph}[eV] \leq 9000$, so that all radiation which might contribute substantially to the total power loss is detected. By choosing channels not affected by the X–point radiation and assuming toroidal symmetry one can estimate the radiation P_{rad}^{bulk} from the bulk plasma (confinement region). The radiation from the X–point region P_{rad}^{xp} is defined as $P_{rad}^{xp} = P_{rad}^{tot} - P_{rad}^{bulk}$. Fig 2 shows P_{rad}^{bulk}, P_{rad}^{tot} and P_{rad}^{xp} for a discharge with H–mode.

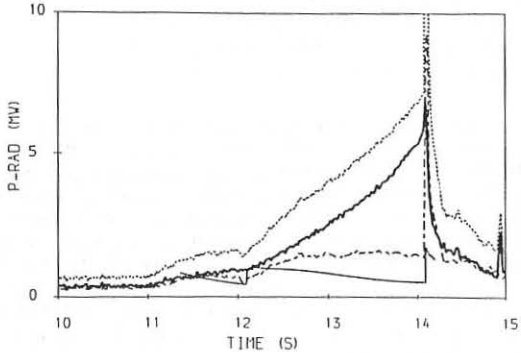

Fig. 2 : Radiation power P_{rad}^{bulk} (bold solid curve), P_{rad}^{xp} (dash-dotted) and P_{rad}^{tot} (dotted) for a SN–discharge with H–mode from 12 to 14.1 s (JET pulse 10755). Also shown is the power flow to the outer divertor target P_t^{outer} (thin solid curve).

One set of target tiles is viewed directly with an infrared CCD camera (Fig.1), filtered to be sensitive from 0.98 – 1.02 μm. For many pulses the camera had insufficient dynamic range to measure the surface temperature of the tiles ($\leq 1800\,^{\circ}C$) throughout the pulse. However it has been possible to estimate both the power flux to the outer (electron side) tiles P_t^{outer} (Fig. 2), and the area of the SOL. The power to the inner (ion side) tiles P_t^{inner} was difficult to estimate but it was $\leq P_t^{outer}/2$ in all H–mode discharges.

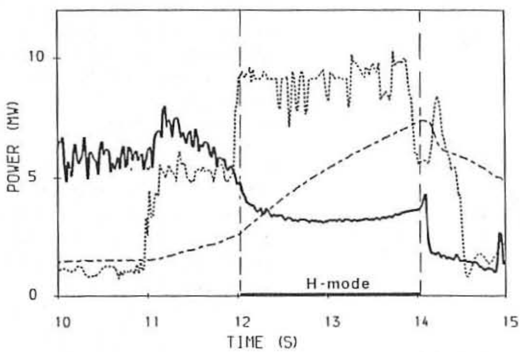

Fig. 3 : Evolution of $P_{rad}^{bulk}/\langle n_e\rangle^2$ (solid curve; arb.units) during the L–mode and H–mode for a NB–heated discharge. The volume averaged density $\langle n_e\rangle$ (dash-dotted; $6\times10^{19}\ m^{-3}$ full scale) steadily increases during the H–mode. The dotted curve shows the evolution of the total input power, P_{heat}^{tot} (JET pulse 10755).

Bulk Radiation Loss: During the L–mode P_{rad}^{bulk} and P_{rad}^{xp} are nearly equal (Fig. 2). The bulk radiation power is about linearly proportional to the volume averaged density up to $\langle n_e\rangle \leq 1.5\times10^{19}\ m^{-3}$, achieved in the L–mode. During the H–mode when $\langle n_e\rangle$ increases steadily up to $\leq 4\times10^{19}\ m^{-3}$ a strong increase in P_{rad}^{bulk} is observed, roughly proportional to $\langle n_e\rangle^2$ in pure NB heated discharges (Fig. 3). Disregarding changes in temperature and in profiles of density and of impurities this implies constant impurity concentration. In the few cases when the H–mode was sustained for some time with the addition of slight RF–heating ($P_{ICRH} \leq 2\ MW$) a more rapid increase of P_{rad}^{bulk} with $\langle n_e\rangle$ was observed.

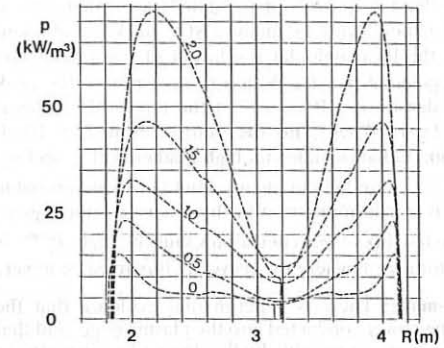

Fig. 4 : Evolution of the radial emissivity profile during the H-mode. Although the main impurity species are carbon and oxygen, very broad radiation shells are observed. The number at each curve gives the time of the profile with respect to the start of the H-mode. Curve 0 shows the profile during the preceding L-mode (JET pulse 10755).

The dominant impurities in purely NB heated discharges are carbon and oxygen; metals are negligible [4]. Radial emissivity profiles derived from the bolometer measurements show a radiation shell much broader than predicted by coronal equilibrium. Furthermore the width of the radiating shell broadens during the H-mode although the plasma density in the outer region grows faster than in the centre. This behaviour is not understood at present. Fig. 4 shows the evolution of radiation emissivity profiles during one of the longest H-modes ($\sim 2.1\ s$) achieved so far in JET.

Power Flow and Radiation in the Scrape-off Layer: The power conducted into the SOL (the heating power of the SOL) is given by

$$P_{heat}^{SOL} = P_{heat}^{tot} - dW_p/dt - P_{rad}^{bulk} - P_{cx}^{bulk}$$

The charge exchange losses P_{cx}^{bulk} are not measured and are neglected thus overestimating P_{heat}^{SOL} which is typically 40 to 60 % of P_{heat}^{tot} and does not vary significantly during the H-mode. The power loss from the SOL is given by

$$P_{loss}^{SOL} = P_{rad}^{xp} + P_t^{inner} + P_t^{outer} + P_{cx}^{SOL} + P_{cx}^{xp} + P^{\lim} .$$

An upper bound for the charge exchange loss may be estimated, using the measured D_α-influx from the walls ($\leq 10^{22}\ s^{-1}$), to be $P_{cx}^{SOL} \leq 0.3\ MW$; P_{cx}^{xp} is estimated to be smaller. Using data from the Langmuir probes the power conducted to the limiters and wall, $P^{\lim}$, is negligible. The largest power losses measured from the SOL are by radiation and conduction to the target tiles, and these are maintained during the H-mode, in contrast to observation in ASDEX [6]. At the onset of the H-mode in JET, P_{rad}^{xp} usually decreases suddenly and then increases with $<n_e>$ until it reaches $\sim 15\%$ of P_{heat}^{tot} and then becomes stationary, although both $<n_e>$ and P_{rad}^{bulk} grow steadily. In contrast P_t^{outer} appears to show an increase to about 15% of P_{heat}^{tot} at the onset of the H-mode and then decreases to $\sim 10\%$ before termination. Immediately after the H-mode is terminated, there is a remarkable increase in P_{rad}^{xp}, P_t^{outer} and P_{heat}^{SOL} (Fig. 2) for ≤ 40 ms. The poloidal distribution of P_{rad}^{xp} shows a maximum at the inner wall side of the X-point in its immediate vicinity (Fig.5). This distribution deviates appreciably from the D_α distribution [5] indicating that Lyman-α emission (to which the bolometers are still sensitive) only partially accounts for the observed emissivity. With carbon target tiles, C is expected to be mainly responsible for the radiation loss in the divertor region. The observed maximum mean emissivities lie between 1 and 5 $MW\ m^{-3}$. An estimate on the basis of coronal equilibrium gives the lower limit of the possible carbon concentration, showing that it must be at least 5 to 10% at (assumed) local densities of $5 \times 10^{19}\ m^{-3}$ to account for the observed radiation levels, assuming a SOL thickness of about 2 cm at the maximum of P_{rad}^{xp}. However the local poloidal resolution of the bolometers ($\sim 0.4\ m$) may lead to a flattening of the poloidal profile. With a steeper profile the peak emissivity may be larger, suggesting local densities $\leqslant 10^{20}\ m^{-3}$ at the target tiles. This is consistent with the observed power flux ($\leqslant 1\ kW\ cm^{-2}$)to the outer tiles if $T_e \leqslant 10\ eV$ locally. The fast poloidal decay of the X-point radiation indicates high gradients of T_e and n_e, as have been observed in other tokamaks [6,7]. These high gradients would be more probable with the higher value of n_e ($10^{20} m^{-3}$). It is worth noting that in the inner divertor region, where P_{rad}^{xp} and D_α radiation are high and so the flux of recycling atoms must be high, P_t^{inner} is low. The opposite is true in the outer divertor region where the recycling flux must be lower.

Triggering and Termination of the H-mode: There is experimental evidence that the H-mode is triggered by increasing the heating power conducted into the plasma edge, and that this can be achieved by increasing the power input, or possibly by the decay of a sawtooth, or alternatively by decreasing the edge radiation loss by reducing local impurity sources. At present it is not quite clear if an increase of P_{heat}^{SOL} triggers the L/H-transition. In many cases an increase of P_{heat}^{SOL} preceded an H-mode but there were also cases observed where the H-mode was achieved at constant P_{heat}^{SOL}. Apart from those cases where the additional heating power was switched off the termination of the H-mode always occured when $P_{rad}^{bulk}/P_{heat}^{tot}$ reached about 60%.

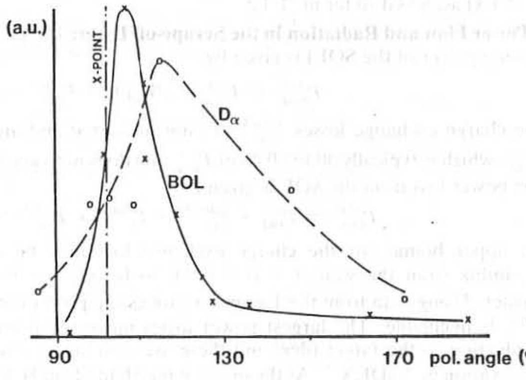

Fig. 5 : Poloidal distribution of P_{rad}^{xp} and of the D_α radiation in the X-point region. The graph covers the upper half of the plasma cross section for a SN discharge (JET pulse 10755) during the H-mode ($\theta = 0$ at the outer midplane).

References

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