Dependence of the H-mode Threshold on the JET Divertor Geometry

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Introduction

Current designs of the next step device rely on access to the H-mode to provide the confinement improvement necessary to reach ignition. In JET, with the installation of a series of divertors of different geometry, it has been possible to test the dependence on divertor geometry of the power required to attain H-mode conditions. It is found that the H-mode threshold depends on divertor geometry. This dependence is not included in present H-mode scaling laws. Here we report the results of a series of such experiments on the JET Mark I, Mark IIA, Mark IIAP and Mark IIGB divertors.

Characterisation of the H-mode Transition

In JET, the H-mode transition is not always a clear bifurcation from one state to another. For example, at very low density as the power is gradually increased the discharge goes smoothly from a state that is clearly L-mode to one which is clearly H-mode: a gradual increase in the energy and particle confinement and a slow increase in the 'fuzziness' of divertor D_α traces are observed (see the first box in Fig.1). In such cases, it is difficult to identify the transition time, thus introducing additional uncertainty into any study of the H-mode threshold.

Even in cases where the identification of the H-mode transition is clear (for instance from the D_α trace), the choice of the transition time can be complicated by the existence of several transitions as the input power is increased. Such transitions are generally associated with sawtooth heat pulses which temporarily raise the edge temperature above the H-mode threshold. Indeed, the fact that several forward and back transitions are often seen to occur at the same edge temperature is strong evidence that it is this local variable which is controlling the physics of the transition. For the purposes of global threshold power analysis, however, we take the final forward transition which leaves the plasma in H-mode throughout subsequent sawtooth periods (Fig.1).

Variation of the H-mode Threshold Power with Divertor Geometry

The results of our studies of the H-mode power threshold ($P_{LOSS} = P_{IN} - dW/dt$) in the various JET divertor geometries are summarized in Fig.2. In a dedicated study performed at 2 MA and 2 T in the Mark IIAP divertor, the H-mode threshold was found to depend on the divertor target orientation: it is higher for discharges with divertor strike points on the vertical target plates than for horizontal target configurations (the points labelled 'V' and 'H' in Fig.2). This difference in threshold characteristics is also observed in the edge temperature at the transition. For the vertical target pulse shown, the critical edge temperature was 500 eV (at an edge density of 1.4×10^{19} m^{-3}) while the critical temperature for the horizontal target pulse was only 350 eV (1.6×10^{19} m^{-3}).

The study of the dependence of the H-mode threshold power on divertor closure was carried out for horizontal target configurations. Here we define divertor closure by the fraction of divertor neutrals ionised above the height of the X-point. A divertor with a smaller fraction of such ionisations is said to be more closed. We have found that the H-mode threshold power has decreased with increasing divertor closure (Fig.2). This is true both of the comparison between Mark I and Mark IIA, where the increased divertor closure was achieved by reducing the size of the divertor entrance, and of the comparison between Mark IIA and Mark IIAP, where the increased closure was obtained by reducing the conductance of leakage paths from the subdivertor volume (pumping plenum) back to the main plasma chamber. Note, however, that vertical target configurations are more closed than horizontal configurations by our definition and yet have a higher H-mode threshold and thus other factors must also be involved in determining the threshold.

In the Mark IIGB divertor, horizontal target configurations are not topologically possible due to the narrowness of the divertor entrance and to the presence of a septum in the centre of the divertor chamber. An unexpected feature has emerged with this divertor design: as the X-point height is reduced to the surface of the septum and then below it, the H-mode threshold is seen to decrease significantly (Fig.3). In discharges with I_P = 2.5 MA, B_T = 2.4 T (our standard current and field for H-mode studies) we obtain Ohmic H-modes. Thus, in order to measure the loss power at the H-mode transition in configurations limited on the septum we performed an X-point height scan at I_P = 3 MA, B_T = 3.4 T (Fig. 3). Both the global power required for the transition and the critical edge temperature are almost a factor of two lower in configurations limited on the septum. The reason for this is not understood at present.

Dependence of the H-mode Threshold on Plasma Density and Current

In the Mark IIGB divertor, with a vertical target configuration, we have carried out a series of experiments to investigate the dependence of the H-mode threshold on plasma density. At low density the H-mode threshold power is found to be higher (by up to a factor of two) than that predicted by H-mode scaling laws [1]. The critical edge temperature for the transition is seen to increase strongly at low density (Fig.4). This is consistent with a β-dependent H-mode threshold at low collisionality as proposed by Pogutse et al. [2] and is reminiscent of similar results reported by the COMPASS-D Team [3].

At fixed toroidal field (2.4 T) and plasma density ($2x10^{19}$ m^{-3}), the power loss and the critical edge electron temperature at the H-mode transition vary weakly with plasma current (or q_{95}) in a current scan from 2.0 to 3.0 MA (I_P^{α}, $|\alpha|<0.2$).

Type I ELM Threshold

In order to obtain the high confinement usually associated with the H-mode, in JET it is necessary to inject powers significantly above the H-mode threshold power. The best confinement enhancement, relative to L-mode, is found in discharges with the lowest ELM frequency, f_{ELM}, (Fig.5). In a series of steady discharges or discharge phases, the ELM frequency is seen to first decrease (Type III ELMs) and then increase (Type I ELMs) with neutral beam input power (Fig.6, for Mark IIGB discharges). We refer to the power necessary to reach the point where the slope of this dependence changes sign as the Type I ELM threshold power. This power can be as much as a factor of two higher than the H-mode power threshold. The Type I ELM threshold power scales in a similar way to the normal H-mode threshold power. In particular, little dependence on plasma triangularity is found (Fig.6) and the threshold increases with toroidal field and density in such a way that the ratio of the two thresholds remains roughly constant. Since the density in our discharges tends to increase with plasma current, it is necessary to perform specific experiments to distinguish between the two possible dependencies. While this has been done for the normal threshold power (see above) and the dependence confirmed to be on density, our present dataset does not allow a similar distinction for the Type III→I threshold.

Conclusions

In JET the H-mode threshold is found to depend on the orientation of the divertor target: it is lower in discharges with horizontal target configuration than in similar discharges with vertical target configuration. This applies to both the global power loss and the local edge electron temperature at the transition. For discharges on the horizontal target plates the H-mode threshold is found to depend on the divertor geometry: the H-mode threshold has decreased with increasing divertor closure (i.e. from Mark I to Mark IIA and from Mark IIA to Mark IIAP). With the Mark IIGB divertor, discharges with the X-point below the surface of the divertor septum have a lower H-mode threshold by about a factor of two. These studies are of particular importance, given the fact that the dependence of the H-mode threshold on divertor geometry is not included in present scaling laws.

A systematic investigation of the dependence of the H-mode threshold on plasma density has shown that at low density the threshold power required to access the H-mode is more than twice the value predicted by present scaling laws. The edge electron temperature at the H-mode transition increases strongly at low density.

At constant toroidal field and density, the H-mode threshold does not depend on plasma current (or q_{95}).

In JET the best H-mode confinement is obtained only at input powers necessary to produce discharges with Type I ELMs. These powers are substantially above (~2x) the H-mode threshold power.

References

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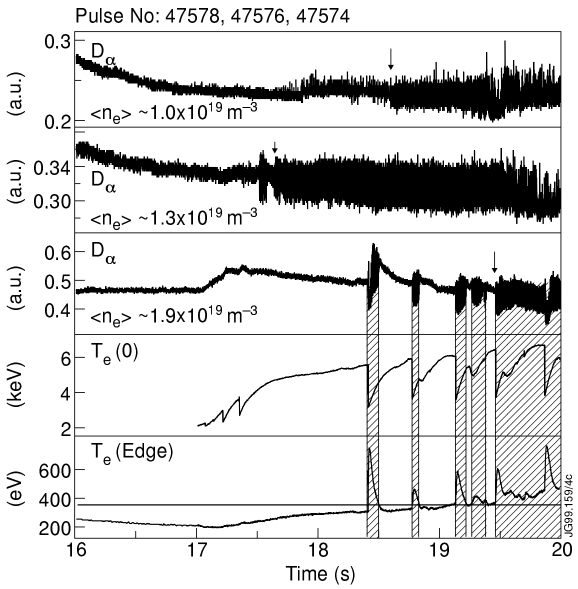

Fig.1: *Examples of H-mode transitions at different central line averaged densities. The transition times selected for global threshold power analysis are marked with arrows. Discharges may make several transitions due to sawtooth heat pulses (third box). In these cases, the forward and back transitions occur at the same edge temperature (fifth box).*

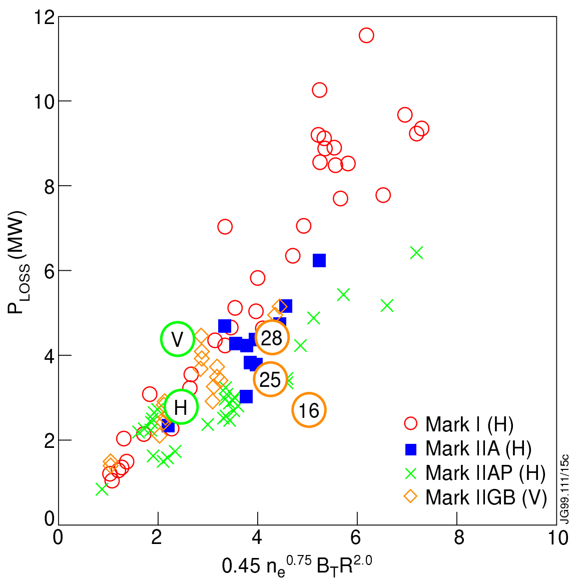

Fig.2: *Loss power necessary to obtain an H-mode transition in the different JET divertors versus a standard scaling law [1]. The points marked 'H' and 'V' are a dedicated horizontal/vertical comparison from the Mark IIAP divertor. The points annotated with numbers are Mark IIGB septum configurations sorted by X-point height, in centimeters, above the divertor floor.*

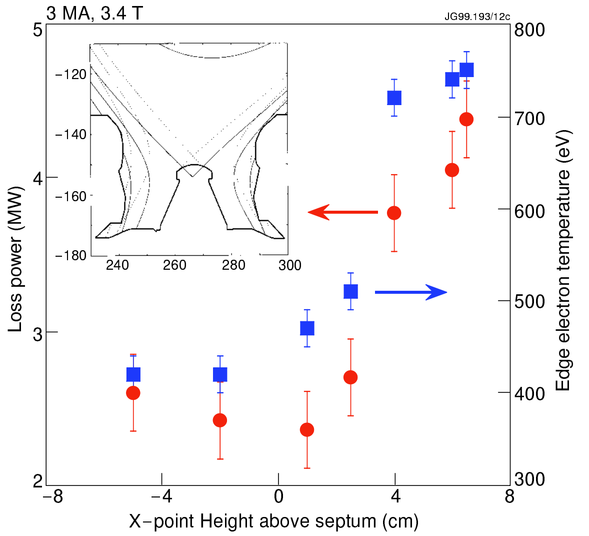

Fig.3: *Dependence of H-mode transition on X-point height in the MarkIIGB divertor.*

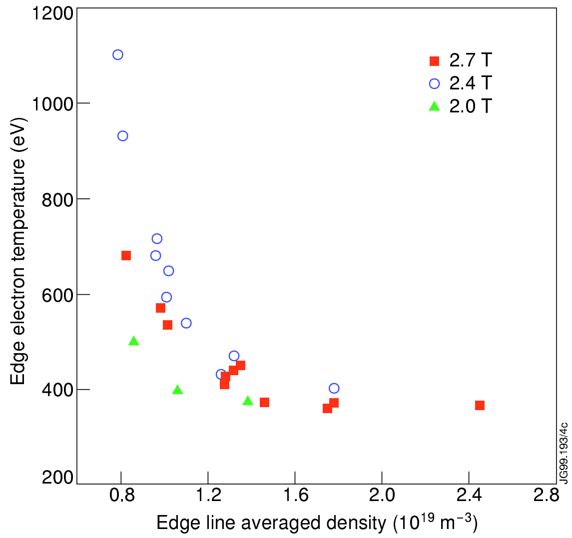

Fig.4: *The dependence of the edge electron temperature on the edge electron density, showing the increased threshold at low density at the time of the H-mode transition in the MarkIIGB divertor.*

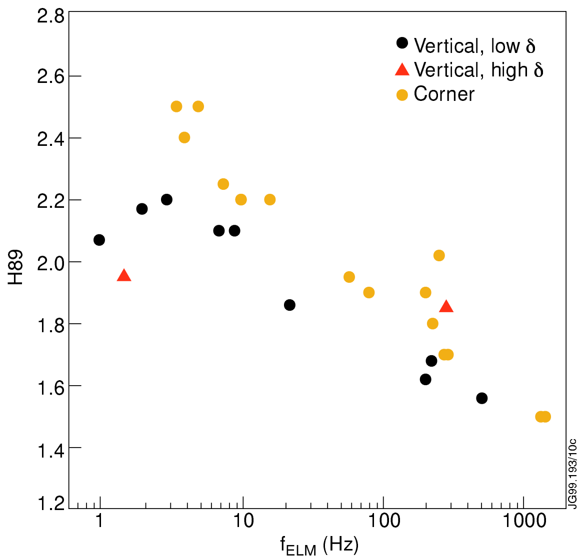

Fig.5: *Confinement enhancement factor as a function of ELM frequency for a series of stationary phases of ELMy discharges in the MarkIIGB divertor.*

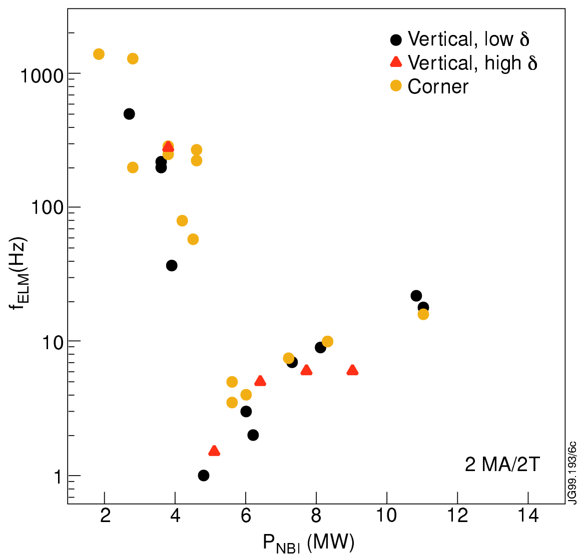

Fig.6: *ELM frequency as a function of neutral beam power for a series of stationary phases of ELMy discharges in the MarkIIGB divertor.*