The H-Mode Power Threshold in JET

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1. INTRODUCTION

The JET tokamak is presently equipped with new divertor coils which allow single null configurations to be produced over a wide range in plasma current and with a large flexibility in shape and X-point position. Already H-modes have been produced for plasma currents between 1.5MA and 4MA, for toroidal field values in the range 1.0T to 3.4T and with the ion ∇B drift directed towards the target plates. ELM-free H-modes lasting more than one second are presently being achieved. The power thresholds (P_{th}) for production of H-modes in this new configuration has been analysed and scalings with both toroidal field and the product of density and toroidal field, n_eB_t have been obtained. These results are compared with the data from 1991 and 1992 which show almost exactly the same n_eB_t scaling for carbon X-point tiles and the same ion drift direction. The assembly of the JET 1991/92 H-mode threshold data is almost complete and part of it has been incorporated into the international power threshold database. The important features of the JET database are presented in this paper. It incorporates both double null (DN) and single null (SN) configurations with the ion ∇B drift either towards or away from the X-point in the SN cases. There is evidence for increasing P_{th} with increasing density at constant toroidal field. A unique feature to JET is that the threshold can be studied for different types of heating, namely neutral beam injection (NBI), ion cyclotron resonance (ICRH), combined heating and a few shots with LHCD. The effect of the target tile material (carbon or beryllium) has been investigated as well as the sensitivity of the threshold to plasma current, X-point height and plasma-to-limiter separation.

2. RESULTS OF THE NEW CAMPAIGN.

The longest ELM-free H-mode obtained in the present experimental period lasted for 1.3 sec and is shown in fig.1. The plasma current (I_p) was 2MA, the toroidal field was 2.1T. The H-mode was produced by 6MW of NBI and the energy content increased to almost 5MJ before the first series of ELMs terminated the rise. Thereafter the energy content diminished as the frequency of the ELMs increased. The lowest H-mode threshold achieved so far is with 3MW of NBI in pulse 30071 which was a discharge with $I_p = 1.5$MA and $B_t = 1$T. The initial 0.5 second pulse at 3MW was sufficient to trigger the H-mode which was sustained by only 1.8MW for a further two seconds. At this stage the power was raised to 7MW giving an energy content of 2.1MJ and a poloidal beta (β_p) of 0.8.

In figure 2 the total input power, which was predominately NBI, is plotted against the product of average density and toroidal field. For these cases the most widely varied quantity was the toroidal field with values in the range 1T to 3.4T. The density was also substantially varied by a factor of 2.7 and the plasma current was either 1.5MA, 2MA or 2.5MA. All the relevant parameters for figure 2 and for all the other scaling studies shown in this paper were measured just prior to the H-mode formation. Clearly the power threshold shows a linear dependence on n_eB_t. The threshold is similar to that for the 1991/2 data (fig.2) for similar conditions, namely single null configurations, carbon target tiles and ions drifting towards the target. When 1994 data are plotted against B_t only there is a linear dependence of P_{th} with B_t but the threshold is about a factor of two higher than for the corresponding 1991/92 data and is comparable with that obtained by Ward et al [1] for just 1991 data.

3. THE JET 1991/92 H-MODE DATABASE.

The data are from extensive studies with $1<I_p(MA)<5$, $1<B_t(T)<3.2$, $1<n_e(10^{19}m^{-3})<6$, forward and reversed toroidal fields, NBI, ICRH and LHCD auxiliary power input, X-point heights varying from 0.02m outside the target plates to 0.17m inside the plates, carbon or beryllium target tiles, and up to 0.25m distance (ΔX) between the last closed flux surface and the limiter. In this section the dependencies of P_{th} on B_t, n_e, heating type, ion ∇B drift direction, I_p, ΔX and the target material are discussed.

3.1 Scaling with n_e, B_t and I_p

A plot of power versus the produce n_eB_t for the whole database including an ohmic heating H-mode is shown in fig.3. There is a marked linear dependence of the threshold power on n_eB_t. This is in good agreement with the ASDEX result [2], $P_{th}/S=4.4x10^{-3}n_rB_t$ where S is the surface area and varies between $150m^2$ and $180m^2$ for the JET discharges. The band corresponding to this range of S is shown in fig.3. This scaling gives P_{th} ~300MW for ITER at a density of $10^{20}m^{-3}$. A large fraction of these data was taken at B_t=2.8T which provides an opportunity to check for dependence P_{th} on density. All the data for 2.8T are plotted as P_{tot} versus average density in fig.4. Again a linear relationship appears for the threshold power in agreement with results from other tokamaks [3]. However, some caution should be applied to our present findings. It should be noted that the ICRH data alone show a much weaker scaling with density, NBI shows a much stronger scaling, and combined heating contributes strongly to the linear relationship apparent in fig.4.

The scaling with toroidal field alone was obtained for a density range $1<n_e(10^{20}m^{-3})<2$. The power threshold increases with increasing B_T but at a rate which is a factor of two less than for the 1994 data (fig.2).

The dependence of P_{th} on plasma current was studied at a constant toroidal field of 2.8T and a window in density between $n_e=1.5 \times 10^{19}m^{-3}$ and $n_e=2.5 \times 10^{19}m^{-3}$. The threshold power is almost constant over the five-fold range in I_p except for a few shots at 3MA which have P_{th} as low as 3-4MW. This "optimum" I_p corresponds to a $q_{95}=3$. A similar effect has been found in ASDEX [2].

3.2 Dependence on ion ∇B drift direction.

Single null discharges were produced with the null either at the top of the vessel where the target plates were made of carbon or with the X-point at the bottom of the machine where there were beryllium target tiles. The toroidal field was reversed so that the effect of the ion ∇B draft direction (either towards or away from the tiles) could be explored. A plot of P_{tot} versus $n_e|B|$sig is shown in fig.5 where the value of sig is +1 for ion ∇B drift towards the target and sig= -1 for drift away from the target. The points are identified according to whether the null was at the top or the bottom of the machine. For completeness the new 1994 data are also included. For the shots with the single null at the top, SN(T), the threshold is greater by about a factor of two if the ∇B drift is away from the target as was found by Ward et al [1] for the scaling with B_t only. For the shots with the single null at the bottom of the vessel, SN(B), and the ion drift away from the target, (negative $n_e|B_t|$sig), the threshold is about a factor of two less than that with the null at the top for the same drift direction. It is in fact slightly less than the threshold for the SN(B) discharges with the ions drifting towards the target. This result could be due to the effect of the Be tiles or it could be a result of the different heating systems used. Plasmas with the single null at the bottom and the ion drift away from the target were predominantly heated by ICRH or by combined heating. Perhaps fast ion anisotropy or the combination of a non-fuelling heating system combined with the pumping properties of Be tiles is beneficial for reducing the power threshold.

3.3 Effect of X-point height and plasma position.

The influence of the X-point height above the target plates was studied in 3MA 2.2T single null configurations with reversed toroidal field. The results are shown in fig.6. The X-point position was varied from 0.17m inside the target plates to 0.02m behind the target surface. There is clearly only a very weak dependence of P_{th} on ΔX with a small reduction in the threshold level as the X-point is moved further inside the tokamak. The variation of P_{th} with the distance between the limiter and the last closed flux surface is also weak for distances greater than 2cm but increases rapidly as the separation is reduced below 2cm.

4. SUMMARY.

New H-mode threshold data over a range of toroidal field and density values have been obtained from the present campaign. The scaling with n_eB_t is almost identical with that of the 1991/92 period for the same discharge conditions. The scaling with toroidal field alone gives somewhat higher thresholds than the older data. The 1991/2 database shows a scaling of P_{th} with n_eB_t which is approximately linear and agrees well with that observed on other tokamaks.

For NBI and carbon target tiles the threshold power is a factor of two higher with the ion ∇B drift away from the target compared with the value found with the drift towards the target. The combination of ICRH and beryllium tiles appears to be beneficial for reducing P_{th}. The power threshold is largely insensitive to plasma current, X-point height and distance between the last closed flux surface and the limiter, at least for values greater than 2cm.

ACKNOWLEDGEMENTS.

We wish to thank everyone in the JET Team who have contributed to the present campaign and to the 1991/92 H-mode database.

REFERENCES

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2. F Ryter and the H-mode Database Working Group. Proc. of 19th EPS Conf, Lisbon 1992, Vol. 17c, part 1, p.23.
3. F Ryter et al, Ibid, Vol.17c, part 1, p.15.

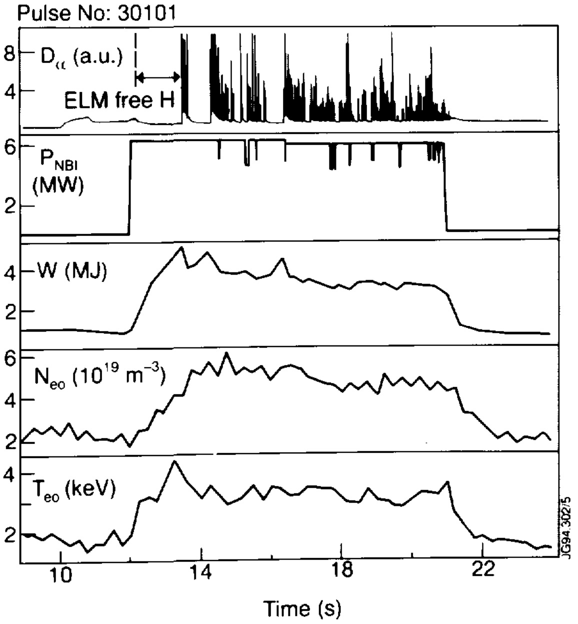

Fig.1 Pulse 30101 with the longest ELM-free period.

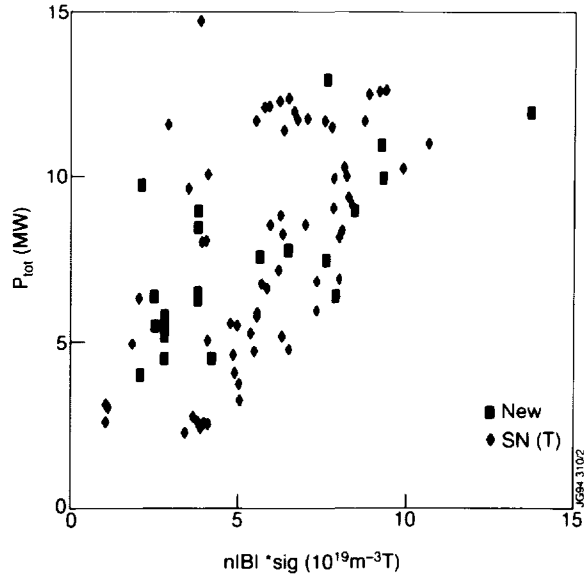

Fig.2: Comparison of 1994 and 1991/2 JET data

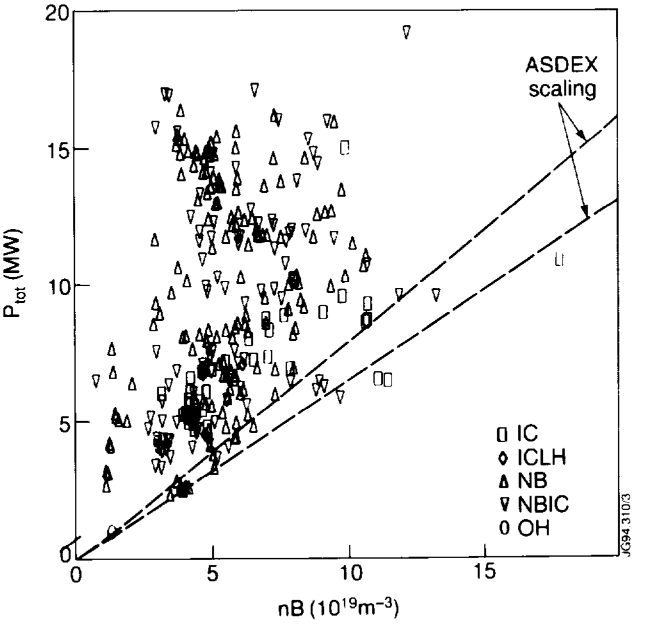

Fig.3: P_{th} versus n_eB_t for the complete 1991/2 database

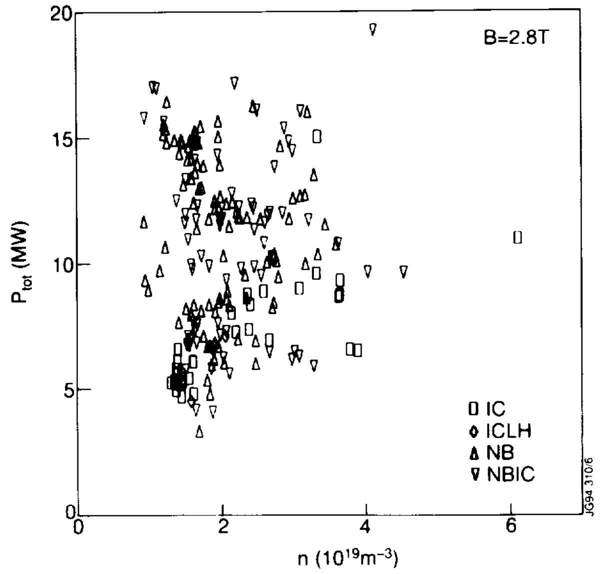

Fig.4: P_{th} versus n_e for B_T = 2.8T

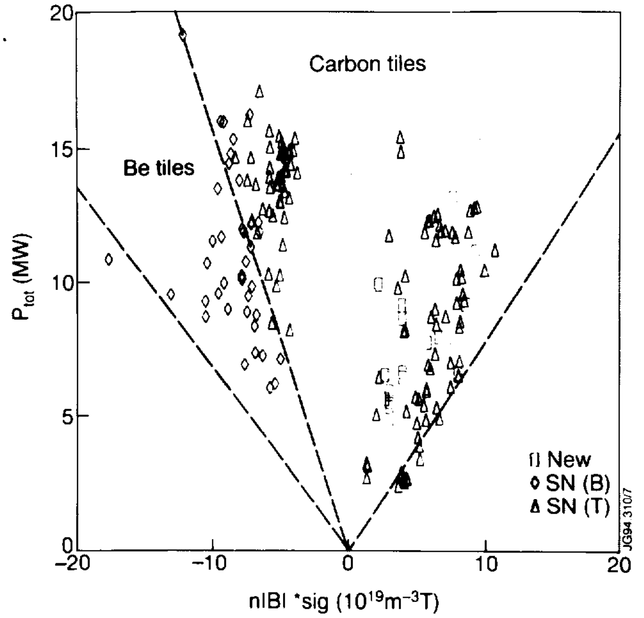

Fig.5: Scaling of P_{th} with n_eB_t for different ion ∇B drift directions in Sn discharges

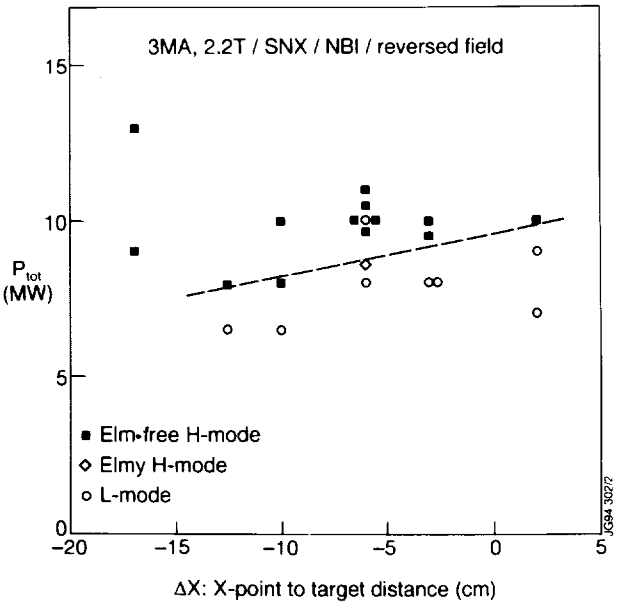

Fig.6: Effect of X- point height on P_{th}