Transition to H-mode Regime in JET With and Without Pumped Divertor

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Abstract. In the present paper the JET threshold database from 1990 to 1999 is analysed. Sources of data scatter, which introduce considerable uncertainty in the estimate of the power needed for the H-mode transition in ITER, are identified and eliminated. The influence of divertor geometry and plasma configuration on the power threshold is analysed in detail. In particular, the height of the X-point over the divertor plate (or septum) and the plasma-first wall distance are considered. The data show consistency throughout the ten years of JET operation, and confirm that the power threshold is minimised with decreasing X-point height, while it increases sharply if the plasma is pushed too near the outer wall. Increased threshold due to operation on the vertical target plates can be also explained in terms of X-point height. Although geometry influences the scatter in the database obtained with single divertors, it is found to be negligible if the whole database is considered. More important seems to be the trend towards stronger density dependence with increasing divertor closure. If this trend is taken into account, a significant reduction in the database scatter is obtained and data from different divertors become consistent.

1. Introduction

The nature of the transition to H-mode has been investigated on the JET tokamak during ten years of operation, without Pumped Divertor (Mk0, 1990-1992) and with three different types of pumped divertor: MkI in 1994-95, MkIIa during 1996-1998, and MkIIGB in 1999. The threshold power P_{LH} is found to change with each successive divertor, as shown in Fig.1, where the loss power $P_L = P_{TOT} - dW_{DIA}/dt$ is plotted against the threshold scaling presented at the 1996 IAEA Fusion Conference [1] (IAEA96). Since with any particular divertor the threshold power in JET is highly reproducible, it must be concluded that such difference must be ascribed to changed physical conditions as divertors were installed and changed. The different P_{LH} with different divertors gives rise to a large scatter in the threshold database, which introduces a large uncertainty in the extrapolation of the power threshold values to future fusion devices such as ITER.

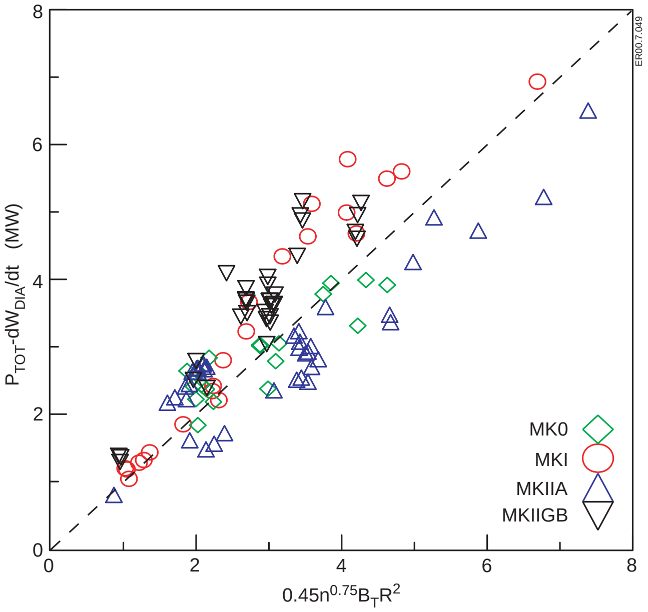

FIG.1. Threshold power with different divertors.

The present paper investigates the nature of the changed threshold conditions, with special emphasis on the effects that geometry has on the conditions for the H-mode transition. In particular the height of the X-point x_p and the plasma-outer wall distance r_{out} are considered. Analysis focuses on both individual divertors and the threshold database in its entirety. It is found that although geometry effects play a role in the scatter of the data within one divertor database, it is negligible if the whole threshold database is considered. However if the different databases are taken separately, P_{LH} shows a stronger density dependence with increasing divertor closure. If this is taken into account the differences within the database are minimised and the data scatter is reduced by 7%.

2. Data Selection

The data used for the present analysis are a fraction of those documented from JET. Starting with MkI (1994) only series of discharges from dedicated experiments to investigate the physical properties of the power threshold are used. Thus the following data are included. MkI: a n_e-B_T scan in an ITER-like configuration. MkIIa: an experiment aimed at taking detailed edge measurements during the L-H transition, the reference discharges for the DTE1 experiment [2] and two series of shots to determine P_{LH} on the vertical target plates. MkIIGB: two n_e-B_T scans and two series of scans of the the X-point height [3]. The data from 1990-92 (Mk0) have been re-validated (see section 3). The databases from the individual divertors (experimental periods) are analysed separately, and the results compared to identify common trends. The different databases are then merged and global conclusions are drawn.

3. Reduction of Data Scatter in the JET Mk0 Database

The biggest source of data scatter is without doubt in the Mk0 database (1990-92). Originally shots in Top, Bottom Single Null X-point and Double Null configurations were included, as well as shots with $P_L \gg P_{LH}$. A selection of this section of the database is therefore now underway, and the database validated so far is used in the present analysis. This contains only shots with Top Single Null X-point with the ion ∇B drift both toward (∇B>0) and away (∇B<0) from the target plates, with the auxiliary heating increased gradually by means of either a staircase of the Neutral Beam Injection (NBI) power or a ramp of the Ion Cyclotron Resonance Frequency (ICRF) power.

4. Influence of the Plasma-Wall Distance on the Threshold Power

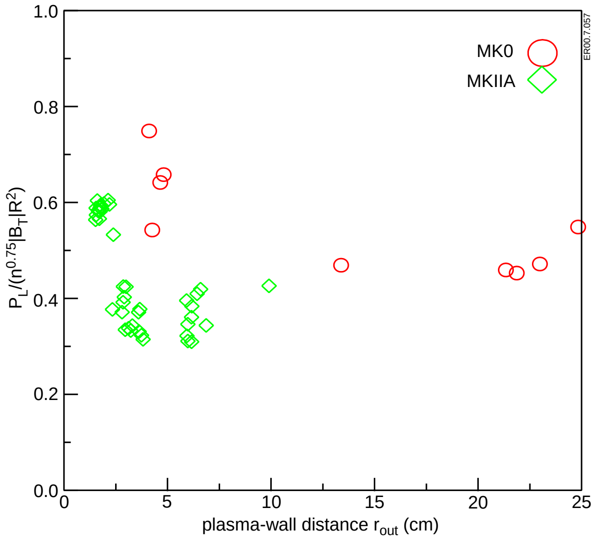

FIG.2. Increased (normalised) P_L with increased proximity of the plasma to the outer wall r_{out}.

Analysis of the databases from single divertors shows that certain groups of data in Mk0 and MkIIa have a substantially higher P_{LH}. Under identical plasma conditions, P_L rises sharply if the plasma-outer wall distance r_{out} goes below 3-4cm (see Fig.2). This is especially true for ICRF heated plasmas, where the separatrix is much closer to the outer wall in order to maximise the coupled power. For the data of Fig.2:

$$P_L \propto r_{out}^{-1.19} + 0.32\,,\quad \text{Mk0} \qquad (1a)$$

$$P_L \propto r_{out}^{-3.32} + 0.28\,,\quad \text{MkIIa} \qquad (1b)$$

The offset seen in Fig.2 is probably due to the forward position of the poloidal limiters and the ICRF antennas and Faraday screens following the installation of the Pumped Divertor. It is very likely that as the threshold database is reprocessed more of these cases will be found. Until this is done though it seems reasonable to assume that, since from 1994 onwards the radial position of the first wall components has not changed, Eq.(1b) is also valid for data from MkI and MkIIGB.

5. Influence of the X-point Height on the Threshold Power

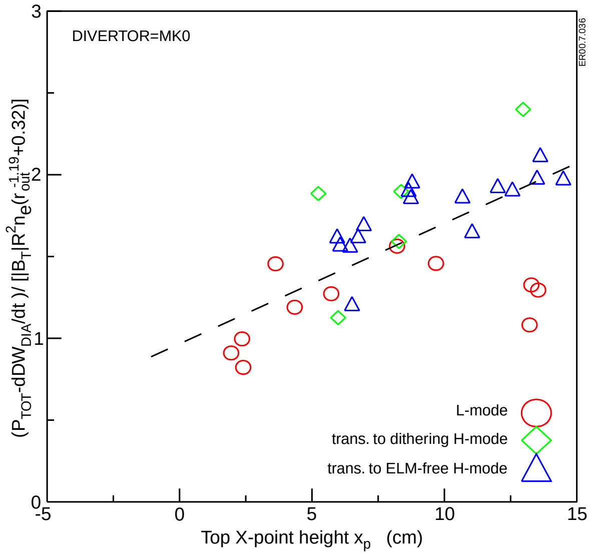

FIG.3. P_L dependence on x_p for the Mk0 data.

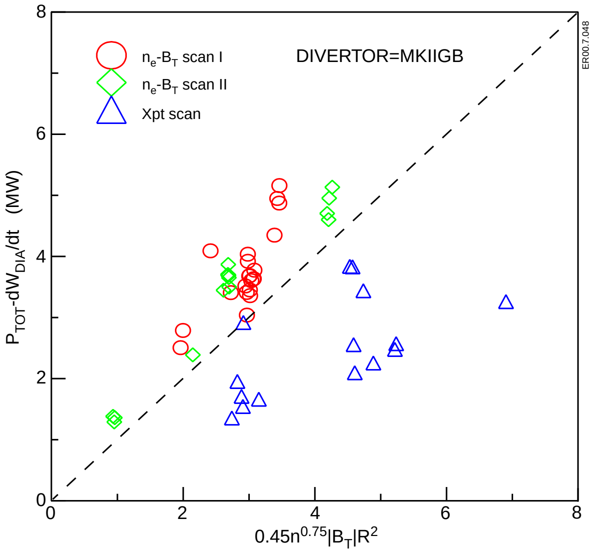

FIG.4. P_L dependence on x_p for the MkIIGB data.

It had been previously noted [4,5] that in the Mk0 database a certain number of discharges with the ion ∇B drift away from the target showed that the threshold power decreased when the X-point height x_p decreased (Fig.3). The same trend was observed when a dedicated threshold scan was carried out in MkIIGB with two different B_T values and decreasing x_p [3] (see also fig.4).

During the MkIIa experimental period two experiments potentially very important for ITER were carried out to compare P_{LH} for a configuration with the strike zones on the horizontal (HT) and vertical (VT) target plates. Both experiments yielded the same result, namely that on the VT P_{LH} was about 20% higher than that on the HT. This result can be explained in terms of the higher x_p in the VT case if the radiated power from both the bulk plasma, P_{RAD}^{bulk}, and that coming from the edge, are also taken into account. For the first experiment in particular it was shown [6] that the edge radiation was responsible for keeping the pedestal T_e to L- mode values and that extra power had to be used for the L-H transition to occur. A dedicated experiment on JET (when the septum is removed) should be carried out to compare P_{LH} on the HT and the VT without changing x_p.

Data from all experimental periods show that the threshold depends on x_p, independently of whether a Pumped Divertor is present and of changes in divertor geometry (Fig.6). If all data available at present are used, then:

$$P_L \propto x_p^{0.32}, \qquad \mathrm{RMSE} = 17\% \qquad (2)$$

This result, together with the threshold dependence on r_{out} of Eqs(1.a-b), can now be applied to the data from single divertors and to the complete database to see if there is a significant reduction in the scatter.

6. Conditions for Access to H-Mode in JET

All the data analysed in the previous sections (including the x_p scan and HT/VT shots) can now be used to assess the role that geometry has in the large (and divertor-dependent) scatter of the JET threshold database. Consider the IAEA96 scaling, $P_L = 0.45n_e^{0.75}B_TR^2$: if to this type of scaling the dependencies on r_{out} and x_p of Eqs.(1,2) are applied, then a reduction of the RMSE of about 8% (from 29.4% to 21.3%) is found. As shown in Fig.7, however, the data remain separated according to different divertor. If the same data of Fig.1 are used (i.e. the x_p scan is excluded, but any r_{out} dependence included in the original database remains) there is no substantial reduction in the data scatter (RMSE=21.3% before and after geometrical corrections). This means that although taking into account geometry effects is helpful to reduce the data scatter for one individual divertor and are of significant importance in the understanding of the physics process leading to the L-H transition, they are not the sole responsible for the dependence of P_{LH} on the divertor used.

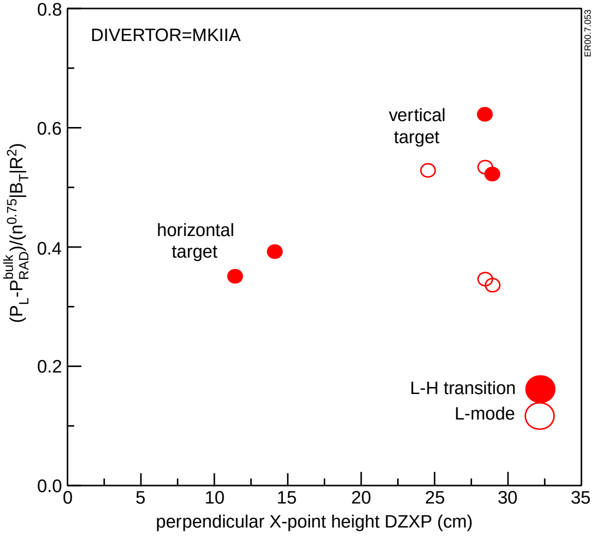

FIG.5. Increase of P_{LH} (corrected for bulk radiation) due to higher x_p for VT. Note that P_{LH} should be corrected for edge radiation [6].

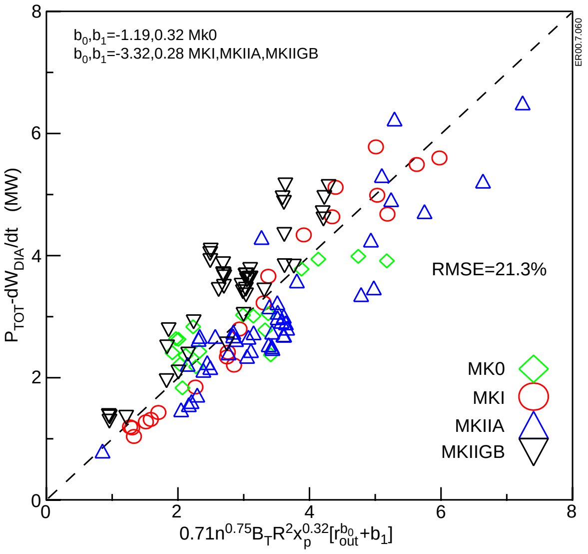

FIG.6. Dependence of P_{LH} on x_p for the 1990-1999 JET operational period.

Consider now the threshold scalings from the individual divertors. The Mk0 database validated so far has not sufficient n_e and B_T variation to allow a regression on these variables, and therefore a IAEA96 type of dependence is assumed:

$$P_L(\mathrm{Mk0}) = 0.71n_e^{0.75}B_TR^2x_p^{0.32}(r_{out}^{-1.19}+0.32)\ , \quad \mathrm{RMSE} = 18.6\%. \tag{4a}$$

For MkI onwards the same r_{out} dependence is assumed (see section 4):

$$P_L(\mathrm{MkI}) = 0.47n_e^{0.71}B_T^{1.07}R^2x_p^{0.32}(r_{out}^{-3.32}+0.28)\ , \quad \mathrm{RMSE} = 12.4\%. \tag{4b}$$

The VT shots are not used for MkIIa (as they need radiation corrections):

$$P_L(\mathrm{MkIIa}) = 0.75n_e^{0.92}B_T^{0.73}R^2x_p^{0.32}(r_{out}^{-3.32}+0.28)\ , \quad \mathrm{RMSE} = 11.8\%. \tag{4c}$$

Lastly, the x_p scan in MkIIGB are included ($x_p \geq 0$):

$$P_L(\mathrm{MkIIGB}) = 1.46n_e^{0.93}B_T^{0.72}R^2x_p^{0.32}(r_{out}^{-3.32}+0.28)\ , \quad \mathrm{RMSE} = 11.7\%. \tag{4d}$$

From Eqs.(4a-d) it seems that P_L tends to depend more strongly on n_e with increasing divertor closure. If this information is used to construct a new form of the threshold power, the RMSE in the JET threshold database reduces from 21.3% (of Fig.7) to 13.5% (of Fig.8). Unfortunately this compound scaling cannot be used to extrapolate to higher n_e, B_T values or to ITER. It is however an indication that the divertor closure changes the physical conditions which determine the acces to the H-mode, and would be in line with results from ASDEX-Upgrade [7].

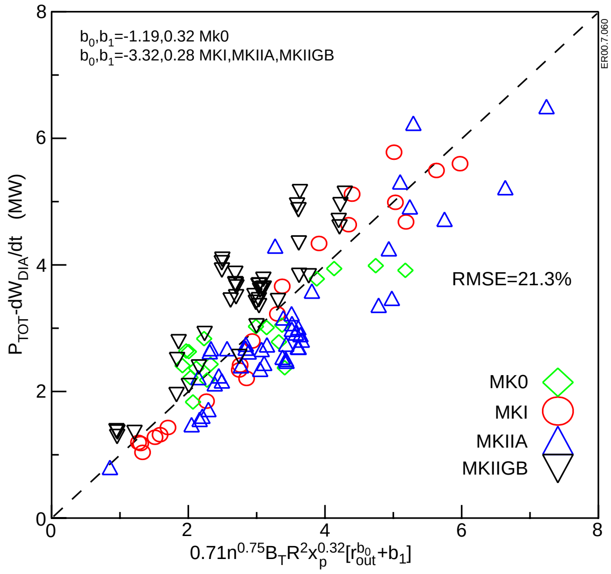

FIG.7. IAEA96-like scaling corrected for geometry.

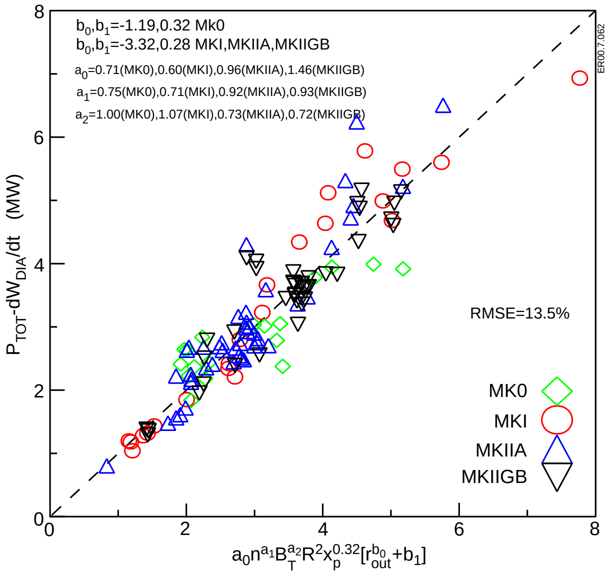

FIG.8. Compound scaling where the different n_e (and B_T) dependences are included.

7. Conclusions

The threshold power in JET changed with changing divertor, leading to increased uncertainty in the extrapolation to the conditions for H-mode access for ITER. Within one operational period, additional sources of uncertainty were found to be due to the dependence of P_{LH} on the plasma-wall distance r_{out} (especially during ICRF heating shots, where smaller r_{out} is needed for better coupling of the launched power) and on the X-point height x_p. In particular the higher P_{LH} in shots with the strike zones on the vertical target plate of the MkIIa divertor, has been shown to be consistent with the increased x_p required to obtain the configuration itself if corrections to P_{LH} due to divertor radiation are included. However if these geometrical corrections are used to derive a new threshold scaling for the whole JET database, no substantial improvement in the overall scatter is obtained, which leads us to conclude that plasma geometry is not the main factor in explaining the data scatter. Threshold scalings derived for different divertors show instead that the density dependence has increased with increased divertor closure. Use of this information leads to a reduction of the data scatter of 7%. Future work will concentrate on the role of increased divertor closure on the physical conditions that determine P_{LH} and how this is linked to the increased n_e dependence.

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