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ABSTRACT.

Results are presented from a series of dedicated experiments carried out on the Joint European Torus (JET) in tritium, deuterium-tritium, deuterium and hydrogen plasmas to determine the dependence of the H-mode power threshold on the plasma isotopic mass. The $P_{THRES} \propto A_{eff}^{-1}$ scaling is established over the whole isotopic range. This result makes it possible for a fusion reactor with a 50:50 DT mixture to access the H-mode regime with about 20% less power than that needed in DD. Results on the first systematic measurements of the power necessary for the transition of the plasma to the Type I ELM regime, which occurs after the transition to H-mode, are also in agreement with the A_{eff}^{-1} scaling. For a subset of discharges measurements of T_e and T_i at the top of the profile pedestal have been obtained, indicating a weak influence of the isotopic mass on the critical edge temperature thought to be necessary for the H-mode transition.

1. INTRODUCTION

The plasma scenario presently favoured for a fusion reactor like the International Thermonuclear Experimental Reactor (ITER) is the ELMy H-mode with a plasma composition of about 50% deuterium and 50% tritium. Knowledge of the effect of the plasma isotopic composition on the power necessary to obtain and remain in the H-mode regime has important consequences, from both the physics and engineering points of view. The earliest indication of an inverse scaling of the threshold power with the effective isotopic mass, A_{eff}, was found on ASDEX[1], where it was observed that the power necessary for the transition from L-mode to H-mode was increased by roughly a factor of two when going from deuterium to hydrogen plasmas. Similar results were obtained on JFT-2M[2]. The expectation was therefore that with increasing A_{eff}, that is by using a DT plasma, the threshold power would decrease. The first attempt to measure this effect in a DT plasma was carried out in the Tokamak Fusion Test Reactor (TFTR)[3]. Contrary to expectations, no appreciable difference was found between DD and DT plasmas. However TFTR's experiments were critically different in three main aspects from other isotope experiments. First, a limiter configuration was used. Second, current ramps were used to trigger the L-H transition, and third, tritium fuelling relied essentially on the Neutral Beam Injectors, with recycling in the scrape-off layer still dominated by the deuterium released from the wall.

A series of experiments have been carried out on the Joint European Torus (JET) to determine the dependence on A_{eff} of the power necessary for the H-mode transition. A series of DD reference discharges were repeated under identical conditions in tritium and hydrogen plasmas as well as combined DT plasmas. The complete scan with effective isotopic mass was obtained at different values of the toroidal field, B_t. The results of this experiment are consistent with a $1/A_{eff}$ scaling. Critical to these experiments was the gas loading of the wall, to maintain a uniform isotopic mixture throughout the plasma but especially at the plasma edge.

In addition to the transition from L-mode to H-mode, measurements of a possible isotope dependence of the threshold for the transition to Type I ELMs in Neutral Beam Injection (NBI) dominated plasmas were obtained. These measurements showed a power threshold scaling consistent also with a $1/A_{eff}$ dependence.

The influence of the isotope mass on the critical edge temperature, thought to be necessary for the H-mode transition, has also been measured. In agreement with results from ASDEX-Upgrade obtained in hydrogen plasmas[4], the pedestal values of T_e at the L-H transition decrease on average of the order of 20% with increasing A_{eff}, a result consistent with a scaling of the critical edge temperature of the type $T_{e,crit} \propto 1/\sqrt{A_{eff}}$.

The paper is organised as follows. In section 2 the experimental set-up is described, together with the method used to identify the transition to H-mode. In section 3 the isotope scaling of the H-mode power threshold is derived, with and without corrections due to radiation losses from the bulk plasma. In section 4 the transition to type I ELMs is considered, while in section 5 the L-H transition is analysed in terms of local edge variables. Finally, in section 6 the results are summarised and conclusions are drawn.

2. THE EXPERIMENT

The isotope scaling experiment has been carried out in the Single Null X-point configuration, with the ion ∇B drift towards the divertor target plates. The average values of the main geometrical parameters are average triangularity $\delta \cong 0.2$ (at the separatrix), elongation $\kappa \cong 1.69$ and $q_{95} \cong 3.42$. An example of an EFIT equilibrium reconstruction is shown in Fig.1 for one of the discharges used in the experiment. The restriction on the values of q_{95} meant that only certain combinations of plasma current I_p and magnetic field B_t could be used. Complete isotope scans (with tritium, deuterium and hydrogen) were carried out at 1MA/1T, 1.7MA/1.8T, 2.6MA/2.7T. Incomplete isotope scans (hydrogen-deuterium or deuterium-tritium) also exist at 2MA/2T, 3MA/3T, 3.2MA/3.45T and 3.8MA/3.8T. For a fixed I_p/B_t combination the density of the target plasma was in general kept fixed. In all the analysis the central line averaged density n_e (in units of 10^{20} m^{-3}) has been used, measured with the Far InfraRed (FIR) interferometer and validated against LIDAR Thomson scattering. Additional density scans were carried out for all three isotopes to add confidence to the density scaling, and one B_t scan exists from 3T to 1T at almost constant density to

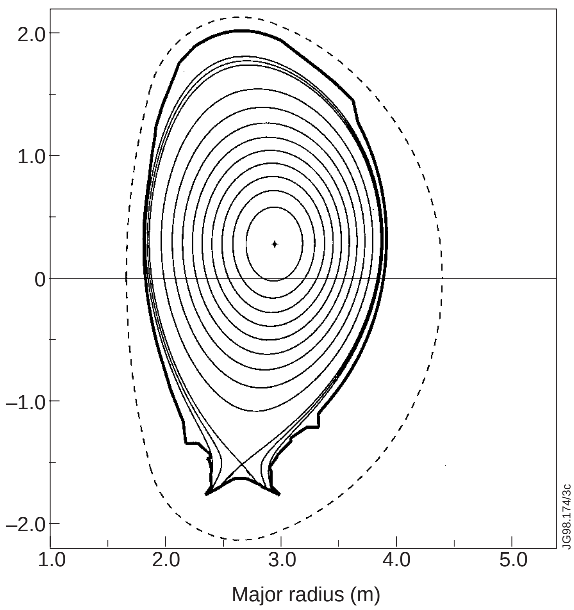

Fig.1: Example of EFIT equilibrium for the discharges used in the experiments.

Table 1. Summary of isotope, density and magnetic field scans

	1MA/1T	**1.8MA/1.8T**	**2MA/2T**	**2.7MA/2.7T**	**3MA/3T**	**3.2MA/3.45T**	**3.8MA/3.8T**
isotope scan	HDT	HDT	HD	HDT	HD	HDT	DT
n_e scan		H		50:50 DT	D		
B_t scan	D				D		

check the magnetic field scaling. Table 1 contains an overview of the isotope, density and magnetic field scans available.

In the experiment the power was increased by means of slow ramps (about $1MWs^{-1}$) from the Ohmic level to a value above the transition to H-mode, using both Ion Cyclotron Resonance Frequency (ICRF) heating and Neutral Beam Injection (NBI). In the case of ICRF heating, only well proven heating schemes with high heating efficiency and strong single pass absorption were chosen. Thus second harmonic hydrogen heating ($\omega=2\omega_{cH}$=52 MHz) was used at 1.8T, while fundamental hydrogen minority heating was used at 2.7T and 3.45T in deuterium and tritium plasmas ($\omega=\omega_{cH}$=42 MHz and 52 MHz, respectively). Heating at the fundamental resonance frequency of deuterium ($\omega=\omega_{cD}$=28 MHz) in a tritium plasma with about 5-10% deuterium was also used with good heating efficiency[5]. Second harmonic tritium heating ($\omega=2\ \omega_{cT}$=34 MHz) was also used in DT mixtures, with no appreciable fast ion losses at the L-H transition[6].

Deuterium neutral beam injection was used at 80 kV and 140 kV into a deuterium plasma, and 80 kV into a tritium plasma. NBI heating of the hydrogen plasmas was instead obtained through H^0 injection with average acceleration voltages of 71 kV and 111 kV. In all cases power ramps with NBI were obtained through fast modulation of the beam ion source with a duty cycle such that the modulation period was much smaller than the fast ion slowing down time. With the exception of the 1MA/1T discharges, the signature of the fast modulation is not visible in the plasma parameters considered for this analysis. The NBI power is corrected for shine-through losses, which are especially important in hydrogen discharges.

A fundamental problem in this type of experiment is how to keep the isotope concentration constant at the plasma edge during the discharge. To this end a series of discharges were used to load the first wall with either tritium or hydrogen to the desired concentration prior to the experiment. For this procedure the in-vessel divertor cryopump was maintained at the temperature of liquid nitrogen instead of liquid helium in order to minimise the consumption of tritium[7] or hydrogen. The isotope concentration was measured spectroscopically through the ratio of the T_α/D_α or H_α/D_α lines close to the outer strike point[8] and used to estimate an effective isotopic mass, A_{eff}, defined as $A_{eff}=(n_H+2n_D+3n_T)/(n_H+n_D+n_T)$. For the present analysis the isotopic balance has been assumed not to vary appreciably at the midplane separatrix, or a few centimetres inside the separatrix near the pedestal of the temperature profile. The experiment was carried out in almost pure (i.e. with isotopic concentration greater than 90%) hydrogen, deuterium, and tritium plasmas as well as 50-60% tritium in deuterium.

All the data used in the present analysis, with the exception of the ion and electron temperatures at the pedestal position, have been taken about 30 ms before the L-H transition, and smoothed over a ±25 ms interval. The pedestal temperature data have been taken as close as possible to the time of the transition to allow for fast temperature rises which can occur when the transition is triggered by a sawtooth crash.

For most of the analysis the threshold power will be defined in the normal way as the loss power though the separatrix, $P_{LOSS}= P_{OHM}+P_{AUX} - dW_{DIA}/dt$, where P_{OHM} is the Ohmic power dissipated in the plasma, P_{AUX} is the power supplied by either ICRF or NBI heating (corrected for fast ion losses and shine-through, respectively) and dW_{DIA}/dt is the rate of change of the diamagnetic energy W_{DIA}. For some analysis the 'conducted' power through the separatrix, $P_{SEP} = P_{LOSS} - P_{RAD}^{bulk}$ has been used, where P_{RAD}^{bulk} is the measured radiation losses from the bulk plasma.

3. ISOTOPE SCALING OF THE H-MODE POWER THRESHOLD

With the experimental set up described in section 2, the dependence of the threshold power for the transition to H-mode on the plasma isotopic composition has been established. A typical isotope scan is shown in Fig.2 for a 2.6MA/2.7T series of discharges. Characteristically, the L-H transition in deuterium and tritium plasmas is clearly defined, with a short dithering phase usually followed by an ELM-free period. On the contrary, the L-H transition in hydrogen plasmas is difficult to identify. Rather than sharp discontinuities in the main plasma parameters, such as the H_{α} light, n_e, and W_{DIA}, the transition evolves over a period of time (Fig. 3). In marginal cases the transition was identified from a discontinuity in the floating potential measured at the outer divertor target by the Langmuir probes. It was verified for clearly identified transitions that the two methods were consistent. Discharges for which the L-H transition was not identifiable within 200 msec have been eliminated from the analysis.

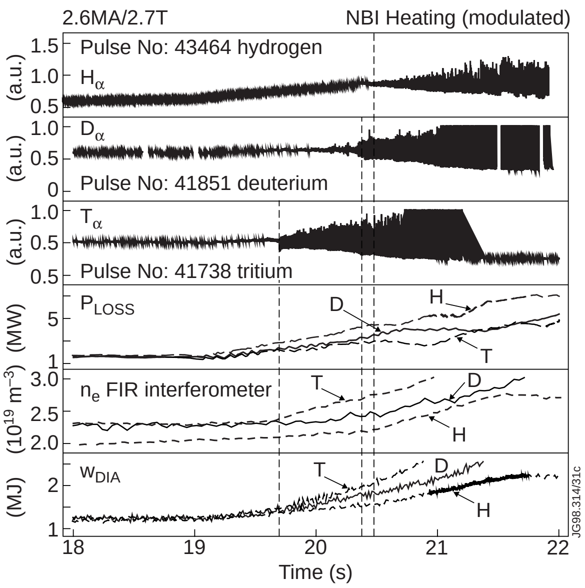

Fig.2: Time evolution of the main plasma parameters for three identical discharges obtained at 2.6MA/2.7T using tritium, deuterium and hydrogen plasmas. In the figure the power used is the loss power P_{LOSS}, for which the isotope scaling is derived in the text. These discharges used a slow power ramp ($1MWs^{-1}$) obtained by fast modulation of the NBI ion source.

The influence that the plasma isotopic composition has on the transition to H-mode is summarised in Fig.4, where the loss power P_{LOSS} is plotted against the scaling obtained using only the deuterium reference discharges. The decrease in P_{LOSS} with increasing A_{eff} is clearly visible at all magnetic fields. A series

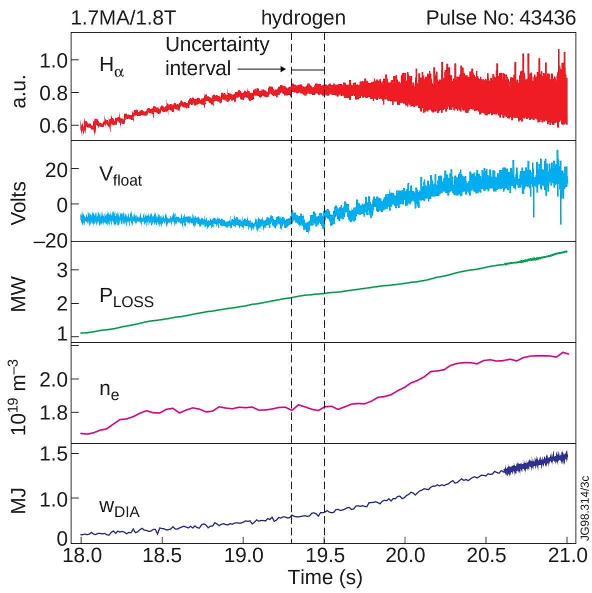

Fig.3: An example of the uncertainty in the determination of the L-H transition in an hydrogen plasma. Instead of a sharp discontinuity in parameters like density, stored energy and H_α light the transition is slow. The floating potential at the outer strike point V_{float} from the Langmuir probes was used to identify the transition.

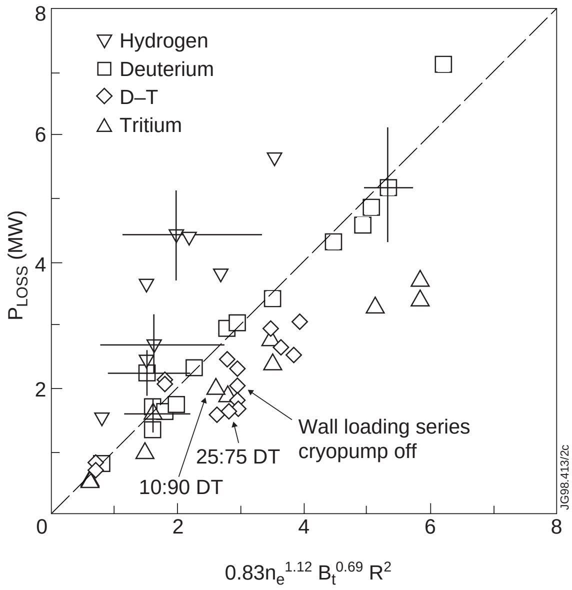

Fig.4: Loss power P_{LOSS}, estimated about 30 ms before the L-H transition, as a function of the scaling of the power threshold derived for the deuterium reference discharges only. The division between the isotopes is quite clear.

of discharges at 2.6MA/2.7T used to load the wall with tritium has also been added. These discharges have been obtained with the cryopump at the temperature of liquid nitrogen (see section 2) and their tritium concentration ranges from about 40-50% to about 75-80% in deuterium. Comparison of these discharges with equivalent ones obtained with the cryopump cooled at the liquid helium temperature shows no difference in the H-mode power threshold. Generally ICRF heating and NBI yielded the same results.

3.1 Derivation of the isotope scaling

For the purpose of determining the isotope scaling of the H-mode threshold power only data obtained with the ‘pure’ plasmas have been used. The scaling can be obtained using several different methods, the results of which are summarised in Table 2 and 3 for P_{LOSS} and P_{SEP}, respectively. They all yield approximately the same result for the isotope scaling, which gives a fair degree of confidence.

The effect of the inclusion of the more uncertain hydrogen data has been assessed by deriving the A_{eff} dependence both with and without its inclusion. The n_e and B_t dependencies of the multi-machine threshold database[9] were taken,

$$P_{LOSS} = b_0 n_e^{0.75} B_t R^2 \times (n_e R^2)^\alpha \qquad -0.25 \le \alpha \le 0.25 \, , \qquad (1)$$

where the central line averaged density n_e is measured in units of 10^{20} m^{-3} and the toroidal field B_t, estimated at the position of the magnetic axis R (in meters), is in Tesla. From Table 2 it can

Table 2. Summary of the isotope scaling analysis for P_{LOSS}

type of analysis	n_e scaling	B_t scaling	A_{eff} scaling
IAEA 1996	0.75	1	-0.93±0.08 with all H-0.83±0.09 w/o H*
n_e and B_t in DD	1.12±0.34	0.69±0.24	-
exp. n_e and B_t	0.997 [0.88,1.07]	0.83	-
A_{eff} scaling using n_e and B_t in DD	1.12	0.69	-0.90±0.07
A_{eff} scaling using exp. n_e and B_t	0.997	0.83	-0.93±0.07
A_{eff} scaling separate for D-T, D-H using n_e and B_t in DD	1.12	0.69	-0.84±0.16 D-T -0.94±0.10 H-D
free regression	1.08±0.20	0.58±0.15	-0.87±0.07

*this value refers to regression using only those H discharges with a clear L-H transition (see section 3).

Table 3. Summary of the isotope scaling analysis for P_{SEP}

type of analysis	n_e scaling	B_t scaling	A_{eff} scaling
IAEA 1996	n/a	n/a	n/a
n_e and B_t in DD	1.17±0.31	0.71±0.22	-
exp. n_e and B_t	0.95 [0.86,1.03]	0.803	-
A_{eff} scaling using n_e and B_t in DD	1.17	0.71	-1.04±0.07
A_{eff} scaling using exp. n_e and B_t	0.95	0.803	-1.03±0.06
A_{eff} scaling separate for D-T, D-H using n_e and B_t in DD	1.17	0.71	-1.08±0.17 D-T -1.03±0.9 H-D
free regression	1.03±0.20	0.68±0.15	-1.01±0.07

be seen that the influence of the uncertain hydrogen transitions is small. Subsequent scalings were performed with the inclusion of the hydrogen data.

Sufficient variation in density and toroidal field are present in the data to allow for an independent determination their dependences. Since there is no appreciable variation of the position of the magnetic axis during the experiments no information on the major radius dependence can be extracted, neither can it influence the other terms in the scaling.

First, the n_e and B_t dependencies were obtained by regression analysis using the deuterium only data. Subsequently these dependencies were kept fixed and the isotope scaling was determined using the full set of data, only the deuterium and tritium data, and only the deuterium and hydrogen data respectively (see tables 2 and 3). The results for the full set of data were,

$$P_{LOSS} = 159 n_e^{1.12\pm0.34} B_t^{0.69\pm0.24} R^2 A_{eff}^{-0.90\pm0.07}, \qquad (2)$$

$$P_{SEP} = 1.61 n_e^{1.17\pm0.31} B_t^{0.71\pm0.22} R^2 A_{eff}^{-1.04\pm0.07} \quad (3)$$

Second, the density and magnetic field dependencies can be derived from the dedicated scans (Fig.5).

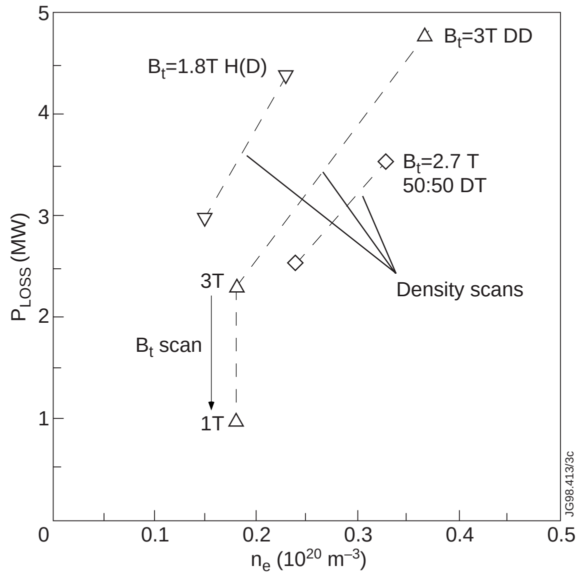

Fig.5: Experimental scans carried out to determine the density and toroidal field dependence of the H-mode power threshold. Three density scans are available in hydrogen, deuterium and 50:50 DT. Only one B_t scan could be obtained, from 3T to 1T in deuterium.

In particular, for each isotopic mass and toroidal field two discharges were obtained at the extremes of density. For each of these scans the density dependence is estimated. Its average value is,

$$P_{LOSS} \propto n_e^{0.997\ [0.88,1.06]}, \qquad P_{SEP} \propto n_e^{0.95\ [0.86,1.13]}, \quad (4)$$

where the numbers in square brackets represent the possible variation in the determination of the coefficient as given by the three distinct scans. With these dependencies, the threshold powers estimated in the toroidal field scan were normalised to determine the toroidal field scaling,

$$P_{LOSS} / n_e^{0.997} \propto B_t^{0.83}, \quad P_{SEP} / n_e^{0.95} \propto B_t^{0.80}. \quad (5)$$

As only one B_t scan was available the variation on the exponent could not be determined. The isotope scaling was derived for the given n_e and B_t dependences using the entire set of data

$$P_{LOSS} = 120 n_e^{0.997} B_t^{0.83} R^2 A_{eff}^{-0.93\pm0.07}, \quad (6)$$

$$P_{SEP} = 1.07 n_e^{0.95} B_t^{0.80} R^2 A_{eff}^{-1.03\pm0.06}, \quad (7)$$

The results from both methods described are consistent with the density and magnetic field dependencies found by analysing the multi-machine threshold database[9],[10],[11].

Finally regression analysis can be carried out on all the variables and the scalings become,

$$P_{LOSS} = 1.60 n_e^{1.08\pm0.20} B_t^{0.58\pm0.15} R^2 A_{eff}^{-0.87\pm0.07}, \quad (8)$$

$$P_{SEP} = 1.31 n_e^{1.03\pm0.20} B_t^{0.68\pm0.15} R^2 A_{eff}^{-1.01\pm0.07}, \quad (9)$$

The previous scalings can be made dimensionally correct by estimating the correct R dependence. This is done by imposing the Kadomtsev constraint[12] on the exponents of the power threshold scalings. With this restriction Eqs.(2)-(3) become,

$$P_{LOSS} = 1.10 n_e^{1.12\pm0.34} B_t^{0.69\pm0.24} R^{2.35} A_{eff}^{-0.90\pm0.07}, \quad (10)$$

$$P_{SEP} = 0.97 n_e^{1.17\pm0.31} B_t^{0.71\pm0.22} R^{2.48} A_{eff}^{-1.04\pm0.07}, \quad (11)$$

Figs.6 and 7 show P_{LOSS} and P_{SEP}, respectively, plotted against these scalings for all the data, including DT.

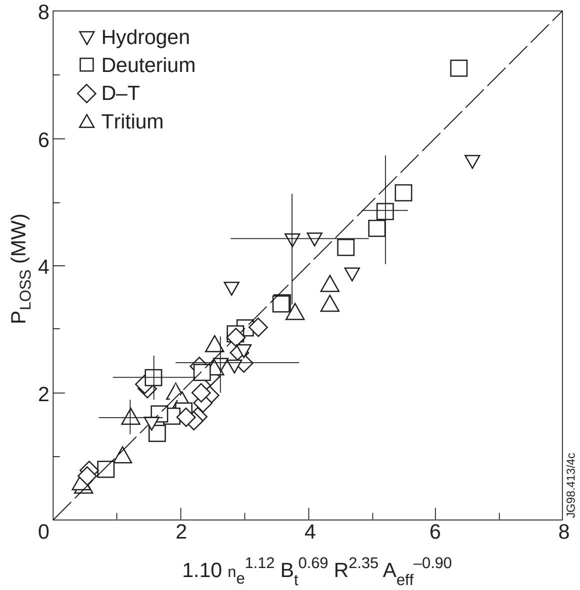

Fig.6: Isotope scaling of the loss power P_{LOSS}. The scaling has been obtained by fixing the density and toroidal field dependencies (see section 3) and deriving the A_{eff} scaling using pure hydrogen deuterium and tritium discharges. The DT discharges have been added to the plot but have not been used to derive the scaling.

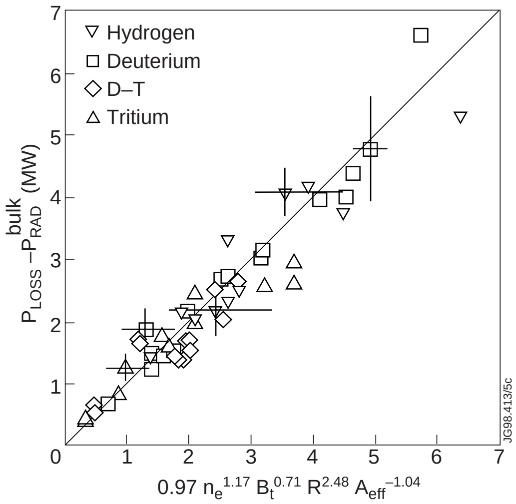

Fig.7: Isotope scaling of the power through the separatrix P_{SEP}, derived from P_{LOSS} with corrections from radiation losses from the bulk plasma. The scaling has been derived in a similar way to that shown in Fig.6.

To summarise, analysis of the threshold data for hydrogen, deuterium and tritium discharges indicates that the H-mode power threshold is approximately proportional to density and toroidal field and approximately inversely proportional to the isotope mass. By averaging all the results obtained above, and taking the largest uncertainty interval determined with one of the methods described the isotope scaling is,

$$P_{LOSS} \propto A_{eff}^{-0.90\pm0.16}, \quad P_{SEP} \propto A_{eff}^{-1.04\pm0.17}. \quad (12)$$

4. ISOTOPE SCALING OF THE TRANSITION TO TYPE I ELMS

The motivation to investigate the transition to Type I ELMs, which occurs after the transition to H-mode, is dictated by the need to know, if possible, how the transition to a reactor relevant type of confinement regime is influenced by the isotopic mass.

Immediately after the transition from L-mode to H-mode, the ELM frequency is about 1-2 kHz. As the input power continues to increase the ELM frequency decreases, until an ELM-free phase occurs, usually followed by Type I ELMs. To investigate this transient behaviour it was necessary to reproduce the various stages under steady state conditions, by means of series of identical discharges at different power levels in excess of the H-mode power threshold. The experiments were carried out in hydrogen, deuterium and tritium plasmas. The ELM frequency was observed to decrease with increasing input power up to a critical level beyond which it started to increase with input power, as shown in Fig.8. The relation between power and ELM frequency has historically been used to classify ELMs into Type I, II and III[13]. Following this definition, it is possible to define a threshold for the transition to Type I ELMs. The importance of the type I threshold is shown in Fig.9, where it can be seen that the energy confinement time remains at the L-mode level for powers just above that necessary for the H-mode transition and

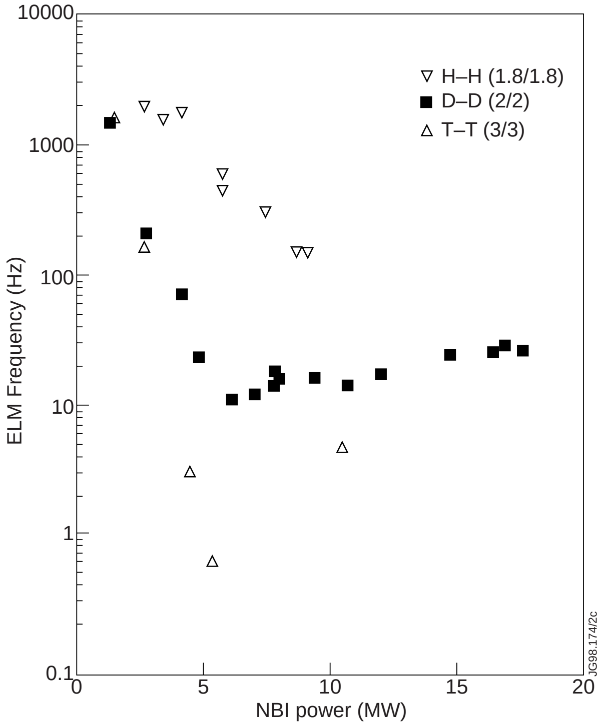

Fig.8: Variation of ELM frequency with increasing NBI power for hydrogen, deuterium and tritium plasmas. The ELM frequency first decreases with increasing power, then at about 6-7 MW it starts to increase. This behaviour is clearly seen in deuterium and tritium, while in hydrogen the type I ELM regime was never accessed due to lack of sufficient NBI power.

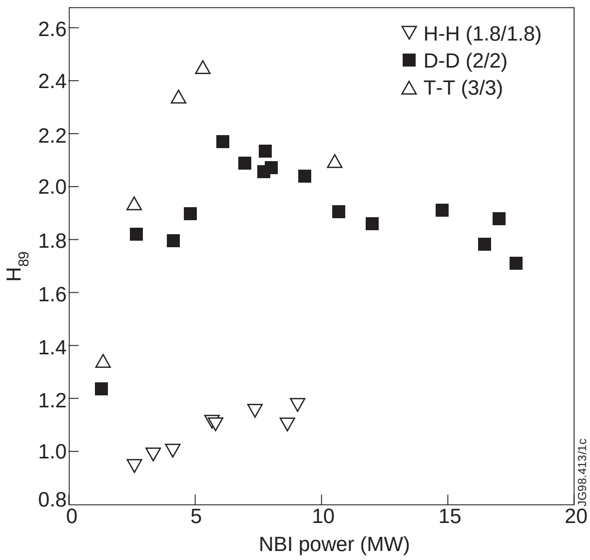

Fig.9: The energy confinement time normalised to the scaling ITERL-89P is shown as a function of the input power for a series of H-mode discharges in tritium, deuterium and hydrogen. The normalised confinement increases with input power for powers just above the H-mode threshold, and reaches a maximum at the onset of type I ELMs. As the power is increased further, the normalised confinement is observed to reduce slowly.

increases steadily until the H-mode has a transition to Type I ELMs. The power required to make a transition to type I ELMs is on average 30% higher than that necessary for the L-H transition, and is consistent with a scaling similar to that obtained for the H-mode power threshold, namely $P \propto A^{-1}$.

5. PEDESTAL ION AND ELECTRON TEMPERATURE

Recent experimental evidence[4],[10],[11] suggests that a necessary condition for the transition to H-mode is that the edge electron temperature exceeds a critical value. This critical value has been found to be rather weakly dependent on the edge density and strongly dependent on the toroidal magnetic field. The electron and ion temperatures at the plasma edge have been measured for as many values of the toroidal field as possible for all three isotopes used in the experiment. The radial profile of the electron temperature is measured using a high resolution 48 channel heterodyne radiometer[14]. The typical spatial resolution is around 10mm in the second harmonic X-mode, while the temporal resolution is better than 10 µs. The T_e profiles are cross-calibrated against an absolutely calibrated Michelson interferometer, giving an absolute T_e error of ±10%. The relative error between individual radial channels however is about ±2%.

In most discharges the edge pedestal in the T_e profile is observed to be a well defined discontinuity in the gradient. The position R_{ped} of the edge temperature pedestal is determined in the fully developed H-mode from the intersection of fitted straight lines to the core and edge gradient zones in the measured profiles. The threshold T_e is then obtained by extrapolating the pedestal position R_{ped} back in time to the L-H transition itself (see Fig.10). For those discharges where the pedestal is identifiable at the L-H transition, R_{ped} is seen not to vary appreciably when the plasma is in H-mode, as in the example of Fig.10. For low values of the toroidal field, however (B_t=1.8T, 2T) the identification of the temperature pedestal position can be compromised by cut-off effects resulting from high edge densities. The temperature near the separatrix is also not always measurable in the H-mode phase itself due contamination from spectral downshifted frequencies from the core region and diminished optical depth in the edge. Discharges where the pedestal is clearly visible are in this case used as a reference position (at the same B_t values) for those where R_{ped} is not readily identifiable. In the analysis both ICRF and NBI heated discharges have been used.

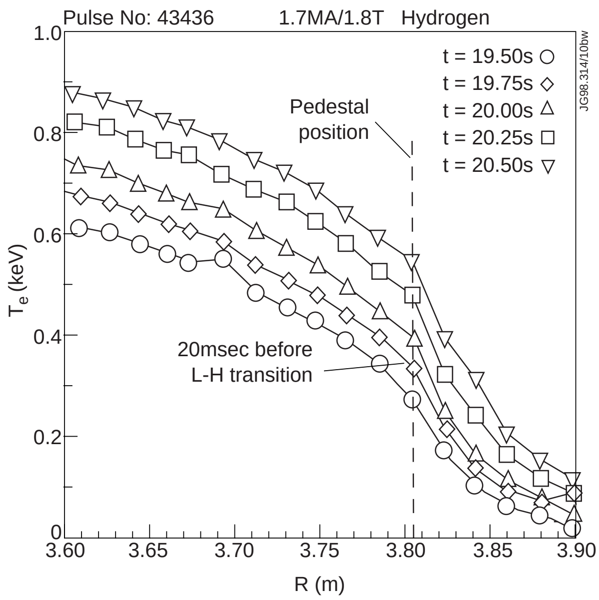

Fig.10: Example of radial profile of the electron temperature in the edge plasma region obtained with the heterodyne radiometer. For the case illustrated the top of the temperature pedestal, where the data for this analysis are taken, is clearly identified around R=3.8m.

The ion temperature is measured at the plasma edge using impurity charge exchange with the heating beams at high spatial resolution[15]. Comparisons of the pedestal position obtained for the ion temperature profile with measurements from the heterodyne radiometer for the available data show agreement better than 3 cm for these discharges.

The results of all the measurements available are summarised in Fig.11 for T_e and Fig.12 for T_i. On average the pedestal T_e at the L-H transition decreases by about 20% with increasing A_{eff} and is compatible with a dependence of the type $T_e \propto 1/\sqrt{A_{eff}}$. The decrease is outside the error bars of the measurements and is seen in both ICRF and NBI heated discharges. Unfortunately the T_i data are not sufficient to draw any conclusions, although they are not inconsistent with the results obtained for T_e.

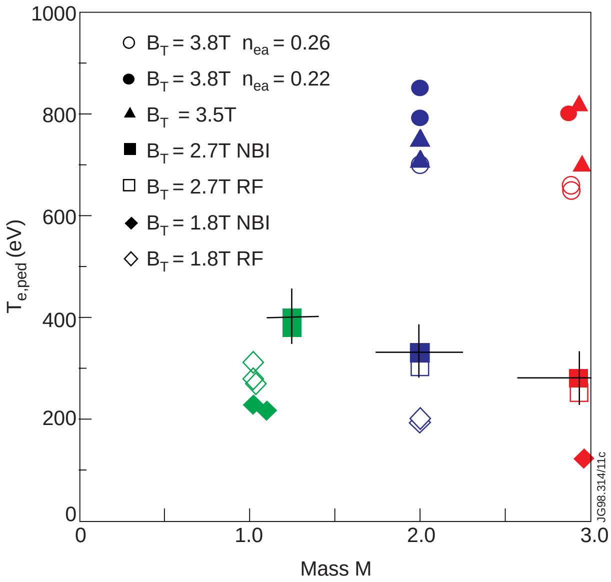

Fig.11: The edge electron temperature at the L-H transition, taken at the top of the temperature pedestal, shows a weak dependence on the plasma isotopic mass. The figure also shows the variations of temperature with increasing toroidal field and edge density.

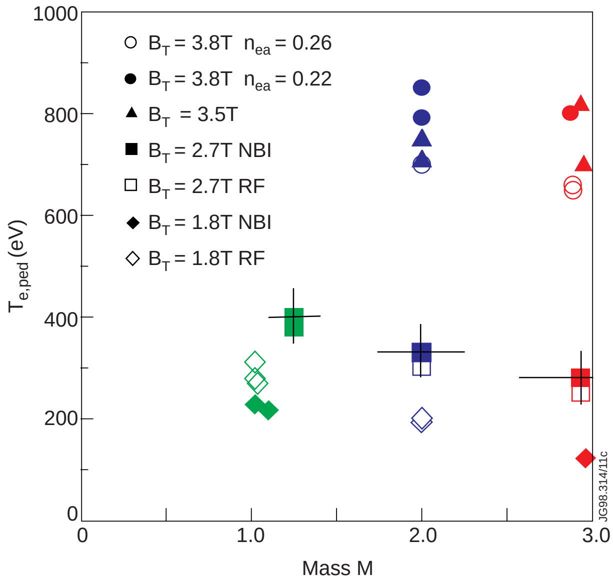

Fig.12: Measurements of pedestal T_i taken with the edge active charge exchange diagnostic. Unfortunately the small number of data available makes it impossible to draw any definite conclusions regarding the isotopic scaling.

Although on JET measurements of the electron density at the pedestal position are not available, it is possible to have an indication of the density dependence of the pedestal T_e by using the line averaged density measured by the FIR interferometer along a vertical line of sight positioned at R=3.75m (about 5cm inside the top of the temperature profile for the cases considered in this analysis). Fig.13 shows the H-mode threshold on the edge operational space diagram constructed from this data. The critical edge temperature decreases with increasing edge density and as already shown increases strongly with the toroidal field.

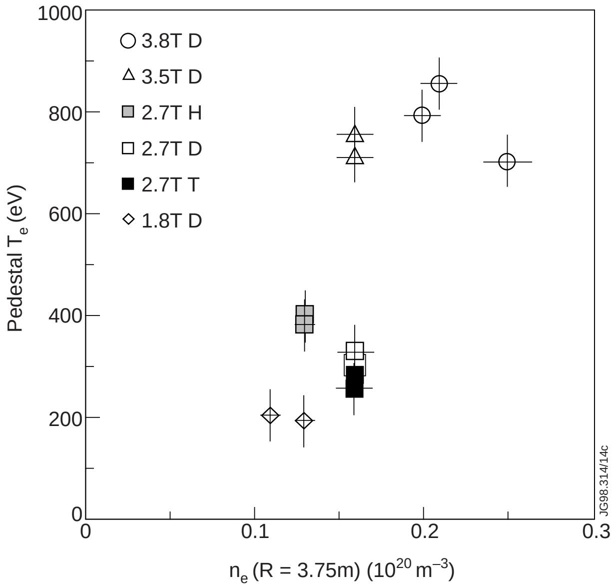

Fig.13: The pedestal electron temperature at the transition shown as a function of the line averaged electron density measured by the FIR interferometer along the vertical chord at the fixed position of R=3.75m. Various isotopes and fields are distinguished by symbol. The scalings qualitatively agree with previous scalings, which indicate a weak decrease of the critical T_e with increasing edge density and a rather strong increase with the toroidal field. The isotopic dependence is small by comparison.

6. SUMMARY AND CONCLUSIONS

A series of dedicated experiments aimed at investigating the isotope scaling of the H-mode power threshold have been successfully carried out on JET. The experiments used hydrogen, deuterium and tritium plasmas, as well as DT mixtures, in a single null X-point divertor configuration with $q_{95} \cong 3$ and at different values of the toroidal field B_t.

The power necessary for the transition to H-mode is seen to decrease linearly with increasing isotopic mass, in line with expectations, $P_{LOSS} \propto A_{eff}^{-0.90}$ or $P_{SEP} \propto A_{eff}^{-1.04}$ if radiation from the bulk plasma is also included. This has important implications for a reactor such as ITER: given the scalings shown in Fig.6 and 7, if for ITER n_e=0.5 10^{20} m^{-3}, B_t=5.68T and R=8.14m then the power needed for the LH transition in a 50:50 DT plasma (A_{eff}=2.5) is P_{LOSS}(ITER)=70MW, P_{SEP}(ITER)=63MW, about 20% less than that needed for a pure deuterium plasma. Measurements of the power needed for the transition to type I ELMs are also consistent with the A_{eff}^{-1} scaling.

The edge electron temperature, measured at the top of the profile pedestal, has been shown to decrease weakly with the isotope mass, and be strongly dependent on the toroidal field. The result is compatible with an scaling of the critical temperature necessary for the L-H transition of the type $T_{e,crit} \propto 1/\sqrt{A_{eff}}$. Although not sufficient to draw any independent conclusions, the pedestal T_i data are not inconsistent with the electron temperature data at the plasma edge.

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