JET–P(98)63

The JET Team
(presented by K Thomsen)

H-mode Power Theshold and Confinement in JET H, D, D-T and T Plasmas

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Preprint of a Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

January 1999

ABSTRACT.

The isotope dependence of the H-mode power threshold and the energy confinement time have been examined in dedicated experiments on the Joint European Torus (JET) in hydrogen, deuterium and tritium plasmas. The results show that: 1) The H-mode power threshold is inversely proportional to the effective isotopic mass, M, of the plasma. 2) The edge electron pedestal temperature at the L to H-mode transition scales as $M^{-0.5}$. 3) The global thermal energy confinement time, τ_{th}, does not depend strongly on M, ie. in the ohmic, L-mode, ELMy and ELM-free H-mode confinement regimes $\tau_{th} \propto M^{\alpha}$ with $|\alpha| \leq 0.2$, if the engineering parameters such as current, magnetic field, density, power and geometry are kept fixed. 4) In the ELMy H-mode regime the transport in the core and the edge of the plasma scale differently with M, ie. the core transport increases weakly with M whereas the edge transport decreases strongly with M.

1. INTRODUCTION

A plasma composition consisting of about 50% deuterium and 50% tritium is foreseen to be used as the fuel in a future thermonuclear fusion reactor because this mixture gives the highest D-T reaction rate [1]. The energy confinement in a future reactor needs also to be as high as possible in relation to the size of the device. At present the only feasible steady state candidate is the ELMy H-mode confinement regime [2]. It is therefore essential to know how much power is needed to reach the ELMy H-mode regime in a 50:50 D-T plasma and to know what energy confinement to expect in such a plasma in order to be able to design a fusion reactor. Empirical scaling expressions for the H-mode power threshold and the energy confinement time are being used to design future devices due to the lack of well established physics based scalings. In an attempt to decrease the uncertainty of the isotope or mass scaling of especially the empirical multi-machine ITER H-mode power threshold scaling expression P_{IAEA96} [3] and H-mode confinement scaling expressions, ie. $\tau_{ITERH93\text{-}P}$ [4] and $\tau_{EPS97(y)}$ [5], a series of dedicated experiments in hydrogen, deuterium and tritium plasmas have been made on JET [6,7] and in this paper these results will be reviewed.

Although the multi-machine scaling expressions P_{IAEA96}, $\tau_{ITERH93\text{-}P}$, $\tau_{EPS97(y)}$ and $\tau_{ITERL97\text{-}P}$ [8] are empirical in nature they are, however, all dimensionally correct [9]. Especially the confinement scalings have been shown to have a physics basis via the recent dedicated scans in normalised ion Larmor radius, collisionality and plasma pressure as well as the identity experiments on ASDEX Upgrade [10,11], Alcator C-mod [12], DIII-D [13,14] and JET [15,16]. The confinement scalings indicate that L-mode confinement is Bohm-like while H-mode confinement is gyroBohm-like. This means that the scale length of the turbulence responsible for the transport in L-mode scales with the minor radius of the plasma whereas in H-mode it scales with the ion Larmor radius. It is, however, apparent that a positive mass exponent in the confinement scaling expressions is not consistent with pure Bohm or pure gyroBohm type scalings. This was another reason for the recent isotope experiments on JET which can also be viewed as scans in normalised ion Larmor radius. The isotope scaling of confinement has also been studied extensively on other devices [17, 18, 19, 20, 21].

The paper is organised as follows: Brief descriptions of the isotope experiments carried out on JET in 1997-98 and the resulting JET isotope database are given in Section 2 and 3, respectively. The H-mode power threshold dependence on effective isotope mass is examined in terms of global and local parameters in Section 4. The results of the analysis of the H-mode confinement data are reported in Section 5. This analysis includes a comparison of the ELM-free and ELMy H-mode confinement data with existing global scaling laws. For the ELMy H-mode data the core and edge transport have been examined globally as well as locally with the TRANSP code [22]. The conclusions follow in Section 6.

2. THE JET ISOTOPE EXPERIMENTS

The H-mode power threshold and confinement experiments in H, D, D-T and T plasmas have been made with as many parameters fixed as possible in the various scans in order to make it as easy as possible to identify the effects of changing the isotope. The configuration used in all the experiments is close to that foreseen for ITER [23], ie. a single null x-point configuration with the ion ∇B drift towards the x-point at the bottom of the machine with an elongation $\kappa \approx 1.7$ and an average triangularity $\delta \approx 0.2$. In most of the experiments the safety factor is $q_{95} \approx 3.4$ corresponding to a plasma current to magnetic field ratio of $I/B \approx 1$MA/T. A uniform isotopic mixture throughout the plasma can be achieved by carefully controlling the gas loading of the walls of the different isotopes and using appropriate neutral beam fuelling scenarios, ie. H, D, T or both D and T beams. Experiments have been made in pure H, D and 90% T as well as 60% T in D plasmas. Both Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH) have been used to heat the plasmas. The only limitations arising from the use of NBI heating are the available beam power for each isotope and the pulse lengths in D-T due to an imposed neutron fluence allocation. ICRH has only been used when the magnetic field and isotope of the plasma allowed for a heating scheme [24] with large first pass absorption and high heating efficiency, ie. central power deposition. The pulse length of ICRH in D-T plasmas has also been restricted by the neutron fluence allocation. The only other main restriction on the experiments has been the allocated experimental time. Therefore the experiments have been focused on 5 to 7 values of (I,B) ranging from (1MA,1T) to (3.8MA,3.8T). In these experiments strong gas puffing has not been used in order not to mix the isotope effects with any other known effects [25,26]. Finally, the H-mode threshold data have been obtained by slowly increasing either the NBI (modulated) or ICRH power, ie. $dP/dt \approx 1$MW/s, whereas for the confinement data heating pulses with constant power as long as practically possible have been used. Further details of the experiments are given in [6,7].

3. THE JET ISOTOPE DATABASE

Great emphasis has been placed during the isotope experiments to have as many as possible of the JET diagnostics operational; the resulting isotope database is too large to describe it in detail here. Only the main features of the data relevant to this paper will be mentioned. Other details can be found in [6,7].

The parameters used in the global analyses are M, n, I, B, R, ε, κ, P_{loss} , W_{th} and τ_{th}. The effective mass, M, of the plasma is defined as $M=(n_H+2n_D+3n_T)/(n_H+n_D+n_T)$, where n_H, n_D and n_T are the densities of the hydrogenic isotopes. Spectroscopic measurements [27] of the concentrations n_H/n_D and n_T/n_D have been used to estimate M. The line averaged electron density, n, is measured by the Lidar diagnostic [28] . Subscripts 19 and 20 on n will indicate units of 10^{19} m^{-3} and 10^{20} m^{-3}, respectively. Plasma current, I, is in MA and the magnetic field, B (at the geometric centre, R [m], of the plasma) is in Tesla. The values of the size parameters R, inverse aspect ratio, ε, and κ have been determined by EFIT [29]. The loss power, P_{loss} [MW], is defined as $P_{loss}= P_{oh} + P_{NBI} + P_{ICRH} + P_{\alpha} - dW/dt$. P_{oh} is the ohmic power, P_{NBI} is the NBI power corrected for shine through estimated from PENCIL calculations [30], P_{ICRH} is the coupled ICRH power, P_{α} is the α heating power estimated from TRANSP calculations and W [MJ] is the total diamagnetic energy. In the power threshold analyses the loss power may also be corrected for bulk radiation, $P_{RAD,}$ measured by the bolometer diagnostic [31]. Because ion temperature profiles are not available for all shots, the estimates of plasma thermal energy, W_{th} [MJ], used in this paper are calculated from the diamagnetic energy by subtracting estimates of the fast ion energy content. PENCIL estimates, reduced by 20%, have been used for the fast ion energy content due to NBI. The 20% reduction comes from a comparison of PENCIL with TRANSP. An approximate formula established from validated PION calculations [32, 33] has been used to calculate the fast ion energy content due to ICRH. The α particle energy content has been ignored. The estimate of W_{th} calculated this way agrees with the available estimates based on density and temperature profiles. The thermal energy confinement time, τ_{th} [s], is defined as $\tau_{th}=W_{th}/P_{loss}$. In Table I is listed the variation of the main parameters in the JET isotope database.

Parameter	**Range**
Effective mass M	1 - 2.9
Magnetic field B [T]	1 - 4
Plasma current I [MA]	1 - 4.5
Input power P [MW]	25
Line averaged electron density n [10^{19} m^{-3}]	1.8 - 8

Table 1 The variation of the main parameters.

A large amount of profile information is also available. A substantial number of the shots has been analysed with the TRANSP code using electron density, n_e, and temperature, T_e, profiles measured with the Lidar diagnostic as well as ion temperature, T_i, and effective charge, Z_{eff}, profiles measured with the charge exchange diagnostic [34]. The code output provides important information about local transport inside 0.8 r/a of the plasmas. Electron temperature profiles in the edge region are available from the high resolution heterodyne radiometer [35] and are used to define the top of the pedestal in electron temperature, $T_{e,ped}$, and pedestal energy, W_{ped}. The ion temperature in the edge is measured with edge charge exchange diagnostic [36] but only a limited amount of data is available. No detailed edge electron density profiles are available. However, a vertical line of sight at R=3.75m of the FIR interferometer [37] provides an estimate of the line averaged electron density, n_{ea}, near the top of the T_e pedestal observed in H-mode. The pedestal energy used in Section 5 has been calculated as $W_{ped} \approx 3n_{ea}T_{e,ped} \times$ Volume, assuming $T_i \approx T_e$.

4. H-MODE POWER THRESHOLD RESULTS

The transition from L-mode to H-mode (L-H transition) is at present believed to be a bifurcation, which takes place initially, in the edge region of the plasma. If the power flowing through the separatrix surface, ie. P_{loss}, exceeds P_{thr}, then the plasma will bifurcate into the H-mode confinement regime. It may be assumed that the threshold condition for this bifurcation can be expressed in terms of normalised ion Larmor radius $\rho_* \propto M^{1/2}T^{1/2}/LB$, collisionality $\nu_* \propto nL/T^2$ and magnetic pressure $\beta \propto nT/B^2$, ie. $G(\rho_*, \nu_*, \beta, M, \ldots) \geq 1$, where L denotes a length scale. The condition, if expressed as a power law, is equivalent to a dimensionally correct H-mode power threshold scaling of the form $P_{thr} \propto n^X L^Y B^Z \ldots$, if 8X-4Y+5Z=3. The main purpose of the isotope experiments on JET is to determine the mass dependence of P_{thr} but the ultimate goal of determining G is also addressed.

Previous isotope experiments in H and D on ASDEX [38], JFT-2M [39], JET [40] and ASDEX Upgrade [41] have shown a strong mass dependence of the H-mode power threshold, ie. $P_{thr} \propto 1/M$. In the old JET experiments, this was manifested by insufficient hydrogen beam power to access the H-mode regime in hydrogen. The first real attempt to measure the threshold in D-T limiter plasmas has been done on TFTR [42]. But probably due to deuterium loaded walls no difference in threshold was observed between D and D-T. Notice also that operation with limiter is known to increase the threshold. JET is the first tokamak to have accessed the H-mode regime in pure tritium and it will be described below how $P_{thr} \propto 1/M$ is consistent with the results obtained in H, D and T.

Characteristic changes in the intensity of Balmer-α light from the hydrogenic isotopes H, D and T as well as density and energy are used to identify the L-H transition on JET. The global data assembled for the threshold analysis have been taken in the L-mode phase just before the L-H transition in shots where the power was ramped up slowly until the H-mode phase was well established. The L-H transitions in D and T plasmas were in general clearly defined. However, in H plasmas the transitions mostly evolved over a period of time. The transitions in these cases have been identified by the sudden change in the waveform of the floating potential measured by Langmuir probes [43] at the outer divertor target. The uncertainty in the threshold power is thus larger in H than in D or T.

Straightforward comparisons of otherwise identical shots with H, D and T plasmas clearly show that the L-H transition occurs for decreasing values of P_{loss}. The P_{IAEA96} threshold scaling has been established for D plasmas; if this scaling is corrected with a factor 2/M reasonable agreement with all the new isotope data is found, ie. $P_{thr} \approx 2/M \times P_{IAEA96}$. This means that the power threshold is 20% lower in a 50:50 D-T plasma compared to that in a pure D plasma. Only M, n and B (or I because of the fixed q_{95}) have been varied significantly in the experiments. The full isotope dataset also includes data from density scans in H, D and DT as well as magnetic field scans in D. Therefore the M dependence can be examined by regressing the data in different ways, eg. fit to M, n and B; fit to M with n and B dependences as in P_{IAEA96}; fit to M with n and B dependences determined from n and B scans. All these fits show a strong mass scaling, ie. $P_{thr} \propto M^{-0.9 \pm 0.15}$ using P_{loss} as P_{thr} or $P_{thr} \propto M^{-1.0 \pm 0.15}$ using P_{loss} - P_{RAD} as P_{thr}. It is also found that omitting the more uncertain H data does not alter the fits significantly. Finally the isotope data also favour a B scaling that is slightly weaker than $P_{IAEA96} \propto B$ as can be seen from an example of one of the fits, eg. $P_{fit} = 1.1\ n_{20}{}^{1.1}\ B^{0.7}\ R^{2.33}\ M^{-0.9}$, where the exponent on R has been determined from the dimensional constraint.

From the power threshold scaling the threshold condition $G \geq 1$ can be determined if the L-mode confinement scaling is known. As part of the isotope experiments also 2 L-mode scans in M at (3.4MA, 3.4T) and (3.8MA, 3.8T) have been made. The thermal energy confinement time τ_{th} in these L-mode shots and of the data taken in the L-mode phase just before the L-H transition in the threshold experiments agree reasonably well with the recently published L-mode scaling $\tau_{ITERL97\text{-}P} \propto M^{0.2}$. The L-mode scaling also predicts, if $P_{thr} \propto 1/M$ is assumed, that the plasma energy at the L-H transition scales as $W_{thr} \propto M^{-0.07}$, which is in agreement with the weak decrease with M observed experimentally. The $\tau_{ITERL97\text{-}P}$ scaling and the threshold fit given in the previous paragraph suggest that the function G in the threshold condition scales as $G \propto \rho_*{}^{0.75}\ \beta^{1.77}\ \nu_*{}^{-0.72}\ M^{-0.19}$.

A more direct way of obtaining information about the threshold condition is of course to examine the edge parameters. As explained in section 3 the edge data available on JET are limited. However, the electron temperature at the top of the edge pedestal taken just before the L-H transition, $T_{e,ped}$, increases strongly with B ($\propto B^2$ or stronger), decreases with M (roughly as $M^{-0.5}$) and with n_{ea} (roughly as $1/n_{ea}$). The dependencies indicated in brackets correspond to a threshold condition in the edge of the plasma of the form $\beta \geq \text{const.}/M^{0.5}$. The uncertainties though in the exponents leading to this expression are so large at present that a possible additional dependence on either ρ_* and/or ν_*, as the global analyses also indicate, cannot be ruled out.

Finally, the L-H transitions in this paper have been obtained with the plugged MkIIa divertor [44]. The energy confinement after these L-H transitions typically increases steadily with increasing power until the Type I ELMy H-mode regime [45] is reached. The confinement is then as it will be shown in the next section roughly as predicted by the $\tau_{EPS97(y)}$ scaling (Notice this behaviour is different from that after the fast L-H transitions [46] observed in 1991 with the so-called Mk0 divertor arrangement). The power required to reach the Type I ELMy H-mode regime is on average 30% higher than that necessary for the L-H transition but is also found to scale roughly as 1/M.

5. H-MODE CONFINEMENT RESULTS

In this section the isotope scaling of the thermal energy confinement time τ_{th} in the ELMy H-mode (mainly Type I) and ELM-free H-mode regimes on JET will be discussed. The multi-machine H-mode confinement scalings, ie. $\tau_{EPS97(y)}$ (ELMy) and $\tau_{ITERH93\text{-}P}$ (ELM-free), will be used in the analysis of global data. This is necessary because n, I, B and P_{loss} have also been varied in the isotope experiments but not sufficiently to determine how confinement scales with these parameters from the isotope database itself. It is therefore worth recalling the characteristics of the two scalings before presenting the results.

Power law scalings can be written either in terms of physics variables (eg. ω_{ci}, ρ_*, ν_*, β and M etc.) or engineering parameters (eg. n, I, B, P and M etc), $\omega_{ci} \propto B/M$ being the ion gyro frequency. Engineering parameters must be used if ordinary least squares regression is used to determine the exponents in the scaling, otherwise the assumption made on the errors may be violated. The scaling can then be expressed afterwards in terms of physics variables [47]. For example a pure gyroBohm scaling scales as $\omega_{ci}\,\tau_{gyroBohm} \propto M^0\rho_*^{-3}$ in terms of physics variables but as $\tau_{gyroBohm} \propto M^{-0.2}$ in terms of engineering parameters. The change in the M exponent comes from replacing temperature with power. This example shows the importance of specifying which form is being used (physics or engineering) in a discussion of the mass scaling. Here the new results will be presented in terms of engineering variables. As already mentioned in the introduction, the two H-mode scalings are both of the gyroBohm type and both have an additional explicit M dependence, ie. $\tau_{EPS97(y)} \propto M^{1.03}\rho_*^{-2.88}$ corresponding to $\tau_{EPS97(y)} \propto M^{0.20}$ (engineering) and $\tau_{ITERH93\text{-}P} \propto M^{1.61}\rho_*^{-2.81}$ corresponding to $\tau_{ITERH93\text{-}P} \propto M^{0.41}$ (engineering). Finally it should be noted that the data sets, upon which the two scalings are based, indicate that empirically the mass exponent increases with P_{loss}/nVolume [48]. It means that a weak mass scaling is predicted for JET. This effect can also be interpreted that power degradation decreases with M, as it has been done in the analysis of the recent ASDEX Upgrade results [21].

The ELMy H-mode confinement isotope data set examined here contains only steady state data from H, D, D-T and T plasmas with NBI or ICRH heating and the data with strong gas fuelling have been excluded. The comparison of τ_{th} with $\tau_{EPS97(y)}$ for this data set shows that $\tau_{EPS97(y)}$ is a reasonable fit since refitting the M dependence of $\tau_{EPS97(y)}$ results in an insignificant change of the M exponent ($\tau_{fit} \propto M^{0.17}$). It also shows that the NBI and ICRH data are not significantly different. However, a straightforward comparison of 2 pulses with the same NBI input power and density in D and T plasmas shows that the stored energies in the 2 pulses are approximately the same which suggests that the M dependence may be even weaker than that of $\tau_{EPS97(y)}$. It is confirmed by examining a more restricted subset of the data; this subset contains only data from pairs of pulses for which the powers differ by less than 5% and the densities by less than 25% for each pair. A regression fit to that restricted subset gives $\tau_{fit} = 1.03\ \tau_{EPS97(y)}$ $(M/2)^{-0.17} \propto M^{0.03 \pm 0.1}$, ie. the data show practically no mass dependence.

It has been suggested [7] that core and edge transport scale differently with mass in discharges with matched power and density; this observation is based on the following results. Comparisons of approximated edge electron pressure profiles, ie. $P_e \approx n_{ea}T_e$, show the pressure at the top of the pedestal to be increasing significantly with increasing M of the plasma. In steady state the energy W_{ped}, which corresponds to the total pressure at the top of the pedestal (~ W_{ped}/Volume), can be used to estimate the M scaling of the edge transport. A simple regression fit to the available W_{ped} data gives $W_{fit} \propto B^{1.2}M^{0.96}$, which indicates that the edge transport decreases strongly with increasing M. A 'core confinement time' $\tau\chi_{core}$ determined by the core transport can be estimated using $\tau\chi_{core} = (W_{th} - W_{ped})/P_{loss}$. The fit to the $\tau\chi_{core}$ data gives $\tau_{fit} \propto (M/2)^{-0.36}\ \tau_{EPS97(y)} \propto M^{-0.16}$ which is in agreement with a gyroBohm type scaling but without any other explicit M dependence. In addition it has emerged from extensive local transport analyses [49] that the thermal ion diffusivity χ_i in the core region of the plasma is larger in T than in D whereas towards the edge the results indicate the opposite dependence. Fits to the isotope data of effective thermal diffusivity χ_{eff} at the half radius of the plasma also show that the core transport is gyroBohm-like. Hence it can be concluded that the weak positive M exponent in the scaling of global confinement observed in the ELMy H-mode regime on JET is the combination of a gyroBohm-like M scaling (ie. negative M exponent) of the core with a scaling of the edge which has strong positive M exponent.

Finally, the isotope database also contains ELM-free H-mode data but only from D, D-T and T plasmas. When the ELM-free data are compared with the $\tau_{ITERH93\text{-}P}$ scaling it is apparent that the T data are systematically over-predicted compared to the D data. It means that the strong M scaling of $\tau_{ITERH93\text{-}P} \propto M^{0.41}$ is not seen in the JET isotope data. A better fit to the data is τ_{fit} = $1.1\ \tau_{ITERH93\text{-}P}\ (M/2)^{-0.65} \propto M^{-0.25 \pm 0.22}$ which shows that a gyroBohm scaling without any additional mass dependence can easily be supported by the data. The result is also in agreement with that obtained in the hot ion ELM-free H-mode regime [1]. The values of the edge pressure pedestal taken just before the onset of ELMs clearly also increase with M [50, 51]. However, in the ELM-free H-mode phase the pressure pedestal evolves with time, which makes it difficult to assess how the edge transport really scales with M in this regime.

6. CONCLUSION

The JET isotope experiments have demonstrated:

1) The H-mode power threshold decreases strongly with the isotopic mass of the plasma (~ 1/M).
2) The edge temperature at the L-H transition also decreases with mass (~ $1/M^{0.5}$).
3) Overall, the ELMy H-mode isotope confinement data are adequately described by the $\tau_{EPS97(y)}$ scaling expression.
4) The ELM-free H-mode isotope confinement data do not support the strong mass scaling in the $\tau_{ITERH93\text{-}P}$ scaling expression.

In addition a more detailed analysis of the ELMy H-mode data has shown that in this confinement regime the transport in the core and edge regions apparently scale differently with the isotopic mass of the plasma. The mass scaling of the core transport has been found to be in agreement with gyroBohm transport models. In these models it is usually assumed that the turbulence responsible for the transport has a scale-length of the order of the ion Larmor radius and a decorrelation time of the order of the ion diamagnetic drift time. The edge transport on the other hand has been found to decrease strongly with the mass of the plasma; this is believed to be due to the ELMs. It has for example been observed in a subset of pulses that the amount of power lost through the ELMs is decreasing with increasing mass. However, it should be noted that at present the uncertainties on the estimates of W_{ped} are large and with the present data it is not possible to discriminate between different models for the edge.

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