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ABSTRACT

The paper reviews present understanding of H-mode physics by summarising relevant experimental observations and discussing possible interpretation. The most important features of the H-mode are a minimum threshold edge temperature (threshold input power) required to achieve the H-mode; the bifurcation nature of the H-transition with instantaneous changes at the plasma edge; and the formation of a transport barrier at the plasma edge leading to pedestals in the density and temperature profiles. Global energy confinement times, τ_E, are typically 2x to 3x longer in H- than in L-mode plasmas, reaching, for example, almost 1s in 3MA JET X-point discharges. τ_E is found to increase linearly with plasma current. Results of the variation of τ_E with input power are somewhat contradictory: no power dependence is found in ASDEX and DIII-D, whereas a degradation with power is indicated in JET and in JFT-2M limiter H-modes. Correspondingly, predictions for full power (40MW) 6MA X-point discharges in JET range from 0.6s to > 1s, depending upon which scaling is adopted. Two main theoretical models have been proposed to explain the H-mode with its heat barrier at the plasma edge. Such a barrier is predicted by the stability properties of ballooning modes close to a magnetic separatrix, corresponding to the transition to a second stable region above a certain threshold power. It could also arise from a critical temperature gradient model based on self-consistent stochasticity.

KEYWORDS

Tokamak, energy confinement, H-mode, scaling laws.

INTRODUCTION

One of the main challenges in tokamak research is to understand the observed anomalously high plasma transport losses and to find ways of reducing them. When high power auxiliary heating became available at around 1980 all tokamak experiments showed a deterioration of energy confinement with heating power, now referred to as Low- or L-mode confinement. In 1982 a new confinement regime was discovered in the ASDEX divertor experiment /1/: This High- or H-mode is characterised by a confinement time 2 to 3 times longer than that in the L-mode and no apparent confinement degradation with heating power. In the following years H-mode discharges were also observed in other tokamak experiments with closed (PDX /2/) and open (DIII /3,4/) divertor geometries. A major step forward was achieved in the second half of 1986 when it was demonstrated that H-mode confinement could also be obtained in large tokamak experiments with a magnetic separatrix and X-points rather close to the vessel walls (JET /5,6/ and DIII-D /7/) and even under conditions where the plasma is bound by an inboard limiter (JFT-2M /8,9/).

This paper reviews our present understanding of H-mode physics in closed/open divertor and limiter configurations and places it into perspective with possible performance extrapolations for JET. Following a short recapitulation of the characteristic features of H-mode discharges (Section 2), the paper concentrates on the operational requirements for achieving an H-mode (Section 3) and the observed improvement and scaling of energy confinement times in the H-regime (Section 4). After discussing some theoretical ideas which provide a tentative explanation of the essential features of the H-mode (Section 5) the paper concludes with a summary of achievements and open questions (Section 6).

CHARACTERISTIC FEATURES OF H-MODE DISCHARGES

The characteristic features of H-mode discharges may be exemplified with the help of Fig. 1 which shows results from ASDEX (a) and JET (b). Most obvious is the spontaneous character of the transition from L- to H-regime as manifested by the sudden increase in plasma density and energy (not shown) and the sharp drop in D_α emission. The H-transition is therefore a bifurcation phenomenon, with small changes in the plasma parameters - in particular the edge electron temperature - leading to large changes in the overall plasma performance: a steepening of density and temperature profiles at the plasma edge and a substantial improvement of global particle and energy confinement.

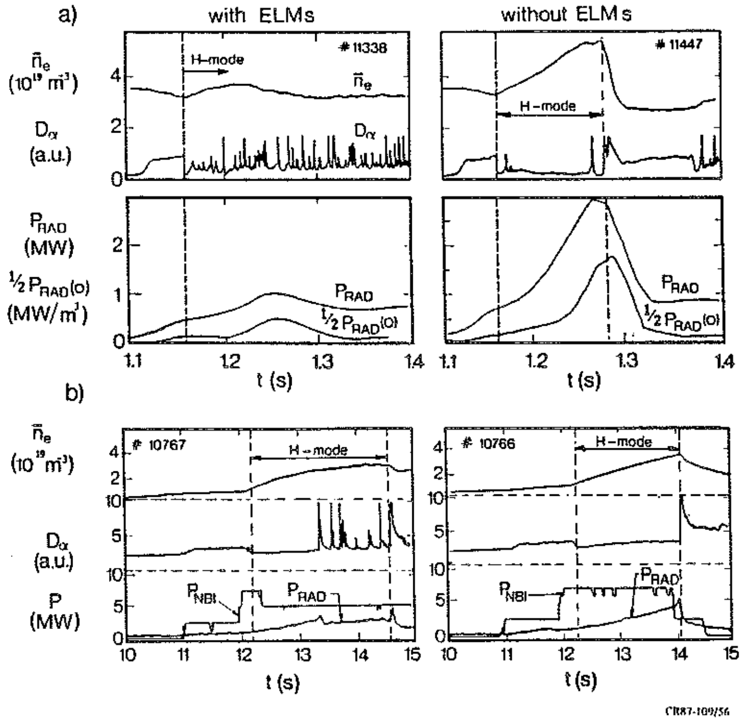

Fig. 1. Characteristic features of H-mode discharges in (a) ASDEX and (b) JET.

Another characteristic feature of H-mode discharges are the spikes exhibited by some of the D_α signals. These bursts in D_α emission are related to a repetitive expulsion of particles and energy from the plasma periphery caused, probably, by some kind of MHD instability at the plasma edge and have therefore been called ELMs (edge localised modes). ELMs periodically degrade the particle and energy confinement in the outer parts of the plasma thereby limiting the rise in plasma density and energy and reducing the accumulation of impurities in the plasma interior.

Among the H-mode discharges so far observed on different tokamaks and under various experimental conditions one can distinguish H-modes with and without ELMs. As pointed out before, H-discharges with ELMs - which are the usual case, for example, on ASDEX /10/ (Fig. 1a, left) - facilitate reaching quasi-stationary conditions and long H-mode periods but at the expense of somewhat degraded H-mode confinement. H-modes without ELMs, on the other hand, - typical for example, of JET (Fig. 1b, right) and DIII-D - which have better confinement, are characterised by a continuous rise in plasma density and a concomitant increase in bulk plasma radiation which finally terminates the H-mode when the radiation losses exceed some fraction of the input power. In JET, with its carbon limiters and inner wall protection tiles, radiation from oxygen and carbon impurities causes a thermal collapse in the plasma boundary /11,12/, whereas in ELM-free ASDEX H-mode discharges accumulation of metal impurities leads to a thermal collapse in the plasma centre /10/ (Fig. 1a, right).

In general the tendency for the occurrence of high frequency ELMs is stronger in experiments with a larger separation between X-point and target plates (like in ASDEX and PDX, but not in JET, DIII-D and JFT-2M, c.f. Fig. 2) and with heating powers close to the threshold power needed for an H-transition. Possible implications of this fact for the observed difference in the power dependences of the energy confinement time between ASDEX/DIII-D and JET/JFT-2M respectively are being discussed in Section 4.

OPERATIONAL REQUIREMENTS FOR ATTAINING AN H-MODE

In this section the various operational requirements for attaining an H-mode are discussed. As will be seen, most of these requirements are related to the need to exceed a certain threshold electron temperature at the plasma edge.

Magnetic Configuration

Until recently, H-mode discharges had only been obtained in experiments with a divertor (c.f. Fig. 2), either of the "closed" type, ie, employing a separate divertor chamber with small conductance to the main chamber (ASDEX /1/, PDX with closed-off outer bypasses between divertor and main chamber /2/) or an "open" one with X-points inside the vacuum chamber but no specific baffling between X-point and target plates (DIII /3/, PBX /13/, JFT-2M /9/, DIII-D /7/, JET /5/). It was therefore the prevailing opinion that a magnetic configuration with a separatrix, ie, with high shear at the plasma edge, was a prerequisite for this high confinement regime. The recent results on JFT-2M /8,9,14/, which show H-mode-like behaviour even under conditions where the plasma is bound by limiters on the inside of the torus, challenge this supposition and may suggest that the role of the separatrix is only indirect, perhaps facilitating the achievement of high edge temperatures.

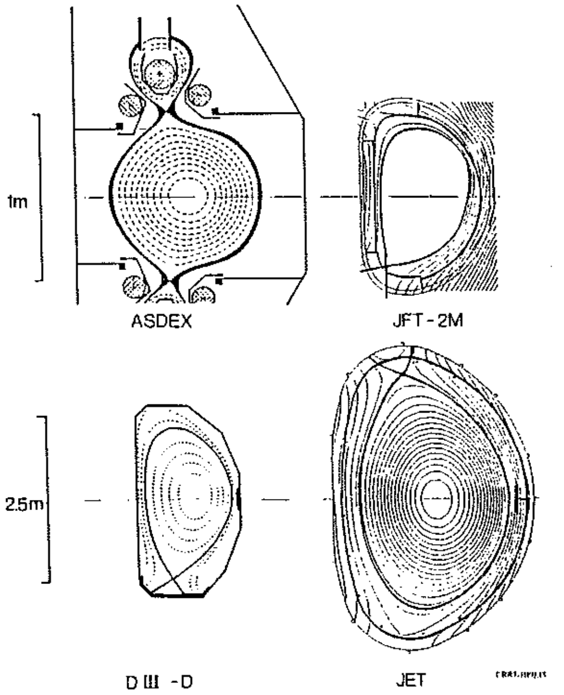

Fig. 2. Magnetic configuration in a poloidal plane for ASDEX, JFT-2M, DIII-D and JET.

	ASDEX	JFT-2M	DIII-D	JET
Magnetic	Closed	← Open Divertor →		
Configuration	Divertor	I.W. Limiter		
R (m)	1.65	1.31	1.67	3.0
a (m)	0.4	0.26	0.67	1.1
K	1.0	1.7	1.8	1.65
B_T (T)	2.7	1.4	2.2	3.5
I (MA)	0.5	0.3	2.5	5.0
P_{ICRH} (MW)	3	1.4	2 (20)	8 (25)
P_{NBI} (MW)	4	0.9	12	10 (20)
E_o (keV)	40	34	75	80
Species	H^o (D^o)	H^o	H^o	D^o (H^o)

TABLE 1 Machine Parameters of Tokamaks in which H-modes Occur

In the subsequent discussion ASDEX, DIII-D, JET and JFT-2M will be used as representative examples of the various configurations (closed/open divertor, limiter) in which H-mode behaviour has been observed. The most important parameters of these four experiments are summarised in Table 1 and their actual magnetic configurations are sketched in Fig. 2.

In addition to the general significance of a separatrix for achieving an H-mode, the poloidal location of the X-points may also be of importance. So far H-mode behaviour has only been observed in experiments with X-points at the top/bottom or inside of the torus. In reference /36/ it is suggested that for an X-point at the outside of the torus ideal interchange modes should be unstable making the attainment of an H-mode more difficult or even impossible. This may be reflected by the difficulty of obtaining H-mode operation in JT-60 which uses such a separatrix configuration.

Power Threshold

The most obvious prerequisite for obtaining an H-mode is that the available heating power must exceed some threshold power, P^{th}. Physically more important, however, is that the edge electron temperature exceeds a certain threshold value T_e^{th} and P^{th} is the power needed to raise the edge temperature to this value. This is shown clearly in Figs. 3 and 4. Figure 3, from ASDEX /15/, displays the electron temperature measured at a plasma radius r = 0.8a, $T_e(0.8a)$, versus total heating power P for discharges with NI or with ICRH (+NI) heating and for conditions with and without wall carbonisation. In all cases the threshold temperature for transition to the H-regime is 0.6-0.8keV (perhaps slightly higher for ICRH- than for NI-heated plasmas), but with ICRH (and with carbonisation in case of NI) more heating power is required to achieve this temperature (both ICRH-heating and wall carbonisation were affected adversely by increased edge radiation).

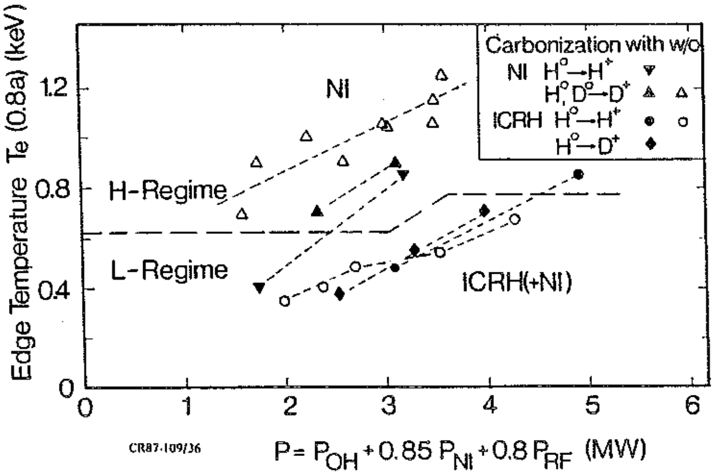

Fig.3.

The edge electron temperature as a function of the total input power for L- and H-regimes in ASDEX with either NI alone or together with ICRH. The effect of wall carbonisation is also shown.

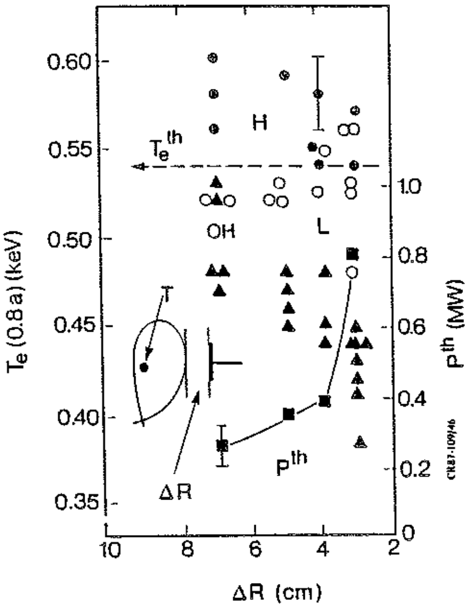

Fig. 4.

The edge electron temperature (symbols ▲, O and ●, respectively, for OH-,L-and H-phases) and the threshold power needed for H-mode operation (■) in JFT-2M as a function of the separation of the separatrix and the limiter.

Similar observations were made on JFT-2M /16/ where in a series of discharges a limiter was brought progressively closer to the plasma edge on the outside of the torus (Fig. 4). Again the threshold temperature remained almost unchanged at ~0.55keV whereas, as the limiter approached the separatrix, more power was required to surmount the difference between this threshold and the lower edge temperature of the ohmic target plasma.

For practical purposes it is important to have some idea about the scaling of the threshold power with parameters such as plasma dimensions. Table 2 lists the threshold powers P^{th} measured in the four representative single null X-point experiments together with the corresponding power fluxes P^{th}/S through the plasma surface $S = 4\pi^2 Ra\sqrt{\kappa}$ ($\kappa = b/a$ is the plasma elongation). One finds that P^{th} is roughly twice as large for hydrogen as for deuterium plasmas, a fact that is probably related to the mass dependence of the energy confinement time (see Section 4). Also, the threshold power fluxes are of the same order of magnitude in the four machines. This could suggest that P^{th} scales either with the plasma surface or with $S' = 2\pi R\cdot\Delta$, Δ being the width of the scrape-off layer.

	P^{th} (MW)		P^{th}/S (MW/m²)	P^{th}/P^{HR}
	D^+	H^+		
ASDEX /17/	1.2	2.5	4.6×10^{-2}	1.2
JFT-2M /18/	.2	.5	1.2×10^{-2}	.5
DIII-D /7/	2.8		4.7×10^{-2}	6.4
JET /6/	4.7		2.8×10^{-2}	4.3

TABLE 2 Threshold Power P^{th} for Single Null X-point Experiments

It is also interesting to note that all these P^{th}-values seem to be close to or to exceed the minimum power required for achieving high recycling in front of the target plates, P^{HR}. As suggested by Neuhauser /19/, an estimate of P^{HR} can be obtained by considering the power to the target plates (index t for target)

$$P = \nu \cdot 2\pi R \Delta_t \cdot n_t c_s (B_p/B_t)_t \cdot (\delta k T_t + \varepsilon).$$

Here ν is the number of target plates, n_t, T_t and $c_s = (8kT_t/3m)^{1/2}$ are respectively the plasma density, temperature and sound speed, B_p and B_t the poloidal and toroidal field components, δ the effective secondary electron coefficient and ε the energy loss per ionisation. Taking $n_t \Delta_t$ to be the minimum optical thickness for localised recycling one gets

$$P^{HR} \simeq \nu \cdot 2\pi R (B_p/B_t)_t \cdot g(T)/m$$

where g(T) is a function of temperature only and has a minimum around $T \simeq 10$ev.

For $\nu = 1$, deuterium, $kT_t = 10$eV, $\delta = 8$ and $\varepsilon = 40$eV, and taking B_p/B_t from equilibrium magnetic field plots of the different machines, the values of P^{th}/P^{HR} listed in the last column of Table 2 are obtained. The result shows, that in all these experiments the H-mode power requirements simultaneously fulfil (except perhaps, for the marginal case of JFT-2M) the conditions for high recycling in front of the target plates, a fact that may be important for attaining the high edge temperatures required for the H-mode.

Minimum Separation between Separatrix/X-point and Limiter/Target Plates

In addition to a minimum heating power minimum separations of the separatrix from limiters or the wall, ΔL, and of the X-point from the target plates, ΔX, respectively, are required for the H-mode.

For limiters at the outside of the torus the minimum clearance ΔL ranges from 2 to 5cm in the different experiments, roughly equivalent to twice the e-folding length of the power flow in the scrape-off layer. The required separation is smaller for limiters at the top or bottom of the machine and can even become zero for limiters on the inside of the torus as demonstrated by the recent JFT-2M limiter H-mode results. A tentative explanation for this strong poloidal variation of the required clearance would be the following: Particle and energy transport are maximum at the plasma outside (eg, in double-null divertor experiments on ASDEX the power flow to the outer target plates was roughly four times that to the inner ones /20/) giving maximum thermal insulation from the contact point for limiters on the inside. (Elongation of the plasma cross-section increases the connection length and therefore further improves the thermal insulation!)

The minimum acceptable separation of the X-point from the target plates in the poloidal plane, ΔX, is usually smaller than ΔL. This may be explained by the fact that in case of a limiter the recycling neutrals have high kinetic energies thereby penetrating deep inside the separatrix and cooling the plasma edge whereas for the case of high recycling in front of the target plates the back flow of recycling neutrals into the main plasma is small (see also discussion of target plate recycling in previous paragraph).

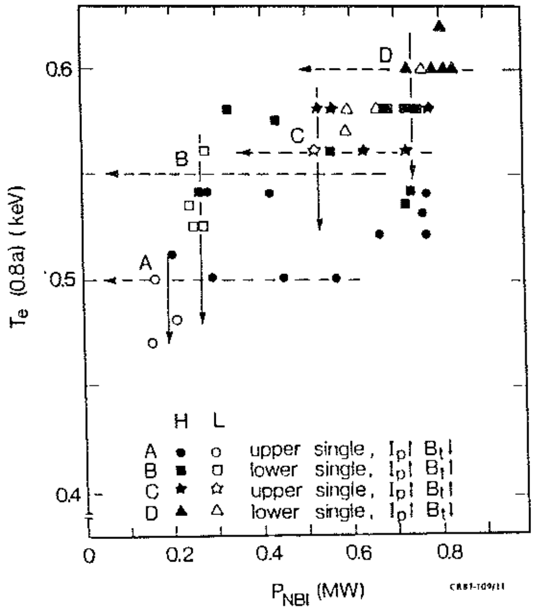

Fig. 5.

The edge electron temperature and the corresponding power threshold for H-mode operation in JFT-2M for four combinations of X-point location and ion drift direction.

Importance of Ion Drift Direction

As first found on ASDEX /21/ and later on JFT-2M/16/ and DIII-D/26/ the heating power required to get into the H-regime is lower if the ion grad B-drift direction points towards the X-point. The most detailed study of this general observation has recently been carried out on JFT-2M where, for all four combinations of X-point locations and ion drift directions, the power and edge electron temperature required for an H-transition were measured simultaneously. As shown in Fig. 5, in these experiments P^{th} was as low as 0.2-0.3MW when the ion drift was in the "good" direction (cases A and B) and was 0.55-0.75MW (almost three times larger) when it was away from the X-point (cases C and D). Despite this large difference in threshold power the edge temperature required for transition to the H-regime again changed only very little.

Hinton /22/ has proposed an explanation for this observation: proper orientation of the ion drift direction reduces neoclassical ion transport. Under marginal conditions this might have a critical effect on whether or not to get into the H-regime.

Operational Range

There seem to be no severe constraints on either the heating method or the parameter range suitable for getting into the H-regime. In fact, H-mode discharges have been obtained with various heating methods (NBI, ICRH /9,15,23) and heating scenarios (co- and counter-injection; low- and high-field-side antennae, minority heating, mode conversion; with current-drive being dominant). The observed differences and difficulties seem to be only secondary effects related to differences, for example, in power deposition (primarily to electrons/ions, profiles) or impurity production associated with a particular heating method. The same is true for differences in wall conditions (eg, with or without carbonisation /15/) and fuelling/pumping techniques (gas puffing, beam or pellet fuelling, with or without gettering). The requirements for a transition to the H-mode are not changed fundamentally, but the power threshold, for example, might be affected.

H-modes have also been obtained over a wide range of plasma parameters and there seems to be no serious restriction in the parameter space typical of tokamak operation. In particular, there is no obvious restriction on low q ($q_s \geq 2.0$) /24/ or high currents. The observed lower density limit has no practical consequences, whereas the upper density limit seems to be a power limit and can be improved by pellet fuelling /24/.

ABSOLUTE VALUES AND SCALING OF H-MODE ENERGY CONFINEMENT TIMES

Absolute Values of H-Mode Energy Confinement Times

H-mode energy confinement times are typically a factor of 2 to 3 longer than those in the L-mode and can equal those observed in ohmically heated plasmas (ASDEX /25/, DIII-D /26/, JET /5,27/). As

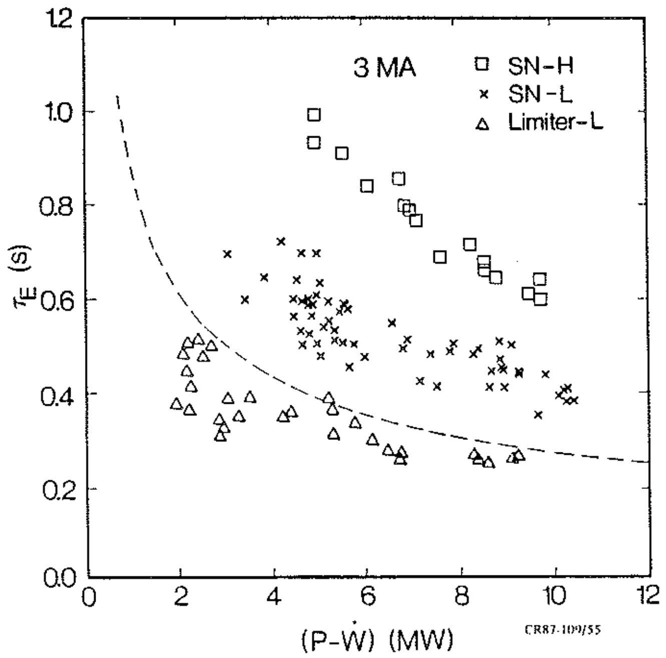

Fig.6.
The global energy confinement time as a function of net input power into 3MA JET discharges in Limiter and Single Null X-point configurations. The dashed line corresponds to Goldston L-mode scaling.

an example Fig. 6 shows the global energy confinement time $\tau_E = W/(P-dW/dt)$ versus total input power (NBI + Ohmic), P, for 3MA Limiter-L, SN (single null)-L and SN-H discharges in JET. It should be noted that confinement times of almost 1s are achieved in the H-mode phase with modest heating powers, the confinement time degrades with power for both L- and H-mode discharges and τ_E-values for SN-L are already about 50% above those for Limiter-L discharges.

For comparison, the dashed line in Fig. 6 corresponds to the L-mode scaling proposed by Goldston /28/, namely

$$\tau_E(s) = 3.7 \times 10^{-2}\, I_p\, P^{-1/2}\, R^{1.75}\, a^{-0.37}\, \kappa^{1/2},$$

showing clearly that H-mode confinement is more than a factor of two higher.

Plasma Profiles and Local Transport

Local transport analysis using measured profiles has been carried out, eg, for discharges on PDX /2/, ASDEX /29,30/ and JET /27/. These analyses show for the H-mode a reduction in local electron thermal diffusivity by a factor of around 5 at the plasma edge and of about 2 in the plasma interior.

There is strong experimental evidence that at the H-transition a transport barrier is formed instantaneously at the plasma edge (evidence comes, for example, from heat pulse propagation measurements on ASDEX where the heat pulses associated with sawteeth were used /31/) resulting in pedestals in the electron temperature (T_e) and density (n_e) profiles. Such profiles are depicted in Fig. 7 for L- and H-mode plasmas in PDX /2/ and ASDEX /25/. Worth noting are the steep gradients in edge electron temperature of ~0.3keV/m typical of the H-phase and the fact that these strong edge gradients lie just inside the separatrix (although admittedly the experimental uncertainty in determining the separatrix position is between 1 and 2cm as indicated by the shaded area in Fig. 7a).

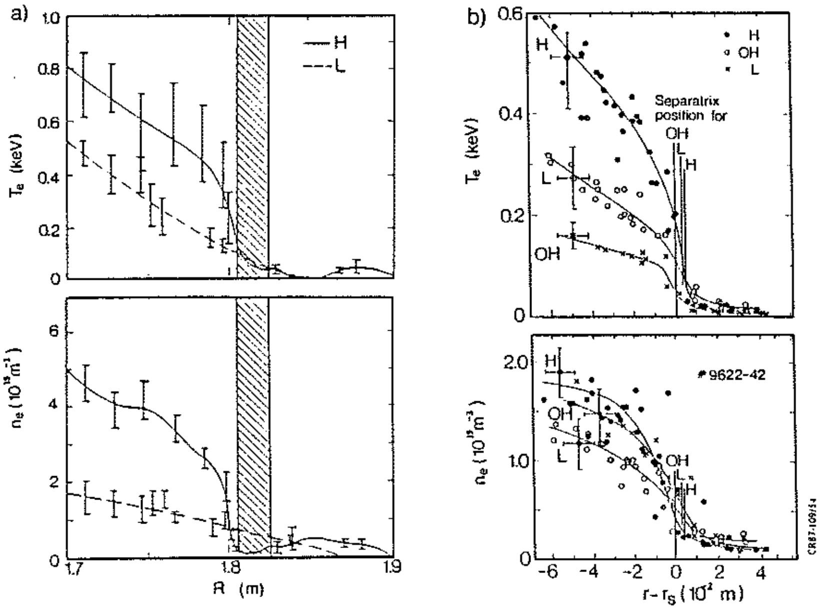

Fig. 7. Electron temperature and density profiles in the vicinity of the separatrix in (a) PDX and (b) ASDEX.

Scaling of Global Energy Confinement Times

Empirical scaling laws for the energy confinement time remain the only means of comparing future machines (like CIT or NET) on the basis of their expected performance. To establish such laws is therefore of paramount importance for any new confinement regime such as the H-mode. In particular, the dependence of confinement on size, input power, density, current, magnetic field etc, has to be determined. We will now discuss the present status of these matters for the H-mode.

Evidence from ASDEX /32/, JFT-2M /18/ and DIII-D /26/ indicates that the global energy confinement time τ_E is independent of toroidal magnetic field B_T for both L- and H-mode (c.f. Goldston's scaling law). Also there seems to be agreement that for stationary H-mode discharges (ASDEX /25/, DIII-D /26/) τ_E does not depend on the line (or volume) averaged plasma density $\bar{n}_e$, whereas in non-stationary H-mode discharges τ_E increases with the continuously rising density (ASDEX without ELMs /10,25/, JET /5,27/, JFT-2M limiter /14/). With respect to a mass dependence, ASDEX (c.f. Fig. 11) shows τ_E to increase more or less proportional to $\sqrt{A_b \cdot A_p}$ /32/, A_b and A_p being the relative masses $m_{b,p}/m_{proton}$ of the beam and plasma species, respectively. In JFT-2M, on the other hand, no mass dependence was found when H°-beams were injected into H^+, D^+ or He^{++} plasmas /18/ (Fig. 12).

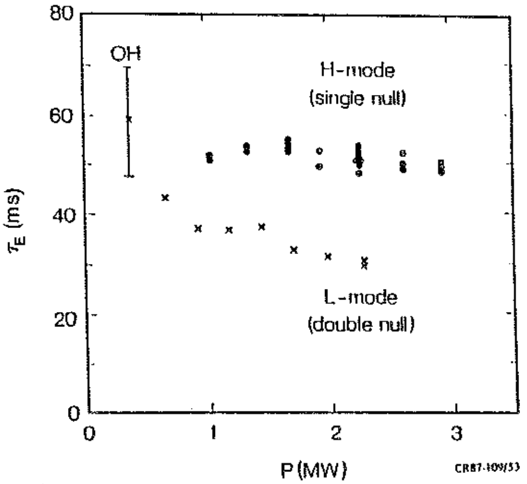

Fig. 8.
The global energy confinement time as a function of total input power in ASDEX double null L-mode and single null H-mode discharges.

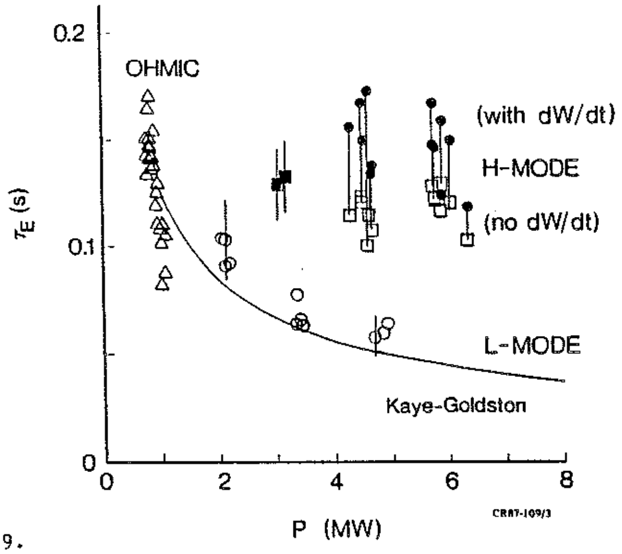

Fig. 9.
The global energy confinement time as a function of total input power in DIII-D ohmic, L-mode and H-mode discharges. Corrections for dW/dt are made for the H-mode discharges. The Kaye-Goldston scaling is also shown.

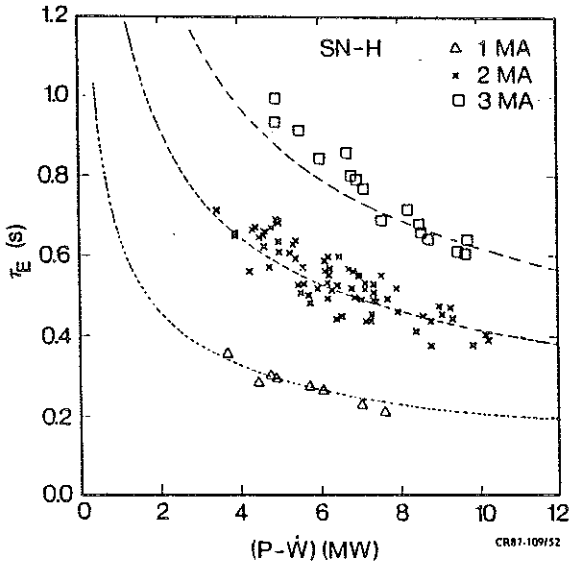

Fig. 10.
The global energy confinement time as a function of the net input power for 1, 2 and 3MA single null, H-mode discharges in JET.

The important scaling of τ_E with heating power P has not yet been established fully. The original H-mode results on ASDEX show no deterioration of τ_E with P as demonstrated for example by the power scan depicted in Fig. 8 /25/. The single null divertor configuration was used to increase the range for the H-regime. This result seems to be confirmed by recent experiments on DIII-D /26/ (Fig. 9) where, however, the power could only be varied over a range of about a factor of 2. In JET, on the other hand, H-mode confinement times degrade with power more or less in the same way as in the L-regime /5,6,27/ (see Figs. 6 and 10). This can be explained at least partly by the fact that in JET H-mode discharges higher heating powers allow access to higher plasma densities before the H-mode reverts to an L-mode (c.f. Fig. 1b). These high densities, however, cause the neutral beam power deposition to shift from a central to an outward peaked distribution. At the same time the plasma radiation increases strongly (- $\bar{n}_e^2$) in the outer half of the plasma. Correcting for these effects considerably reduces, but not completely eliminates the observed degradation of τ_E with power /27/.

With respect to the scaling of τ_E with plasma current I_p, all experiments show τ_E to increase linearly with I_p. This is exemplified for ASDEX and JFT-2M, respectively, by the current scans displayed in Figs. 11 /25/ and 12 /18/, and can also be inferred for JET from the power scans at three different currents /27/ (Fig. 10).

The dependence of τ_E on the elongation, κ, of the plasma cross-section is shown in Fig. 13 for JFT-2M /14/. In these experiments the plasma was moved towards a limiter on the inside of the

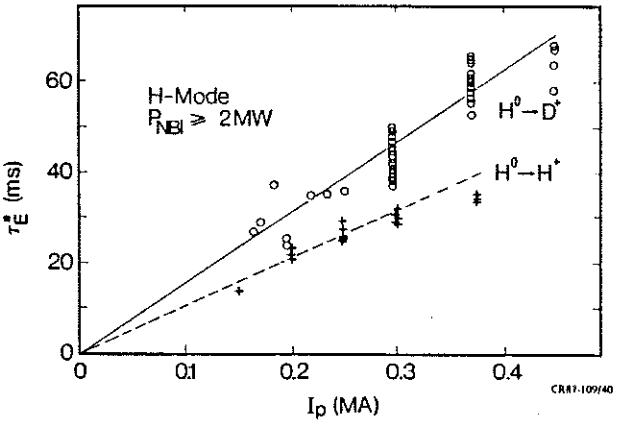

Fig. 11.
The dependence of the global energy confinement time on the plasma current for neutral beam input powers in excess of 2MW in ASDEX H-mode discharges.

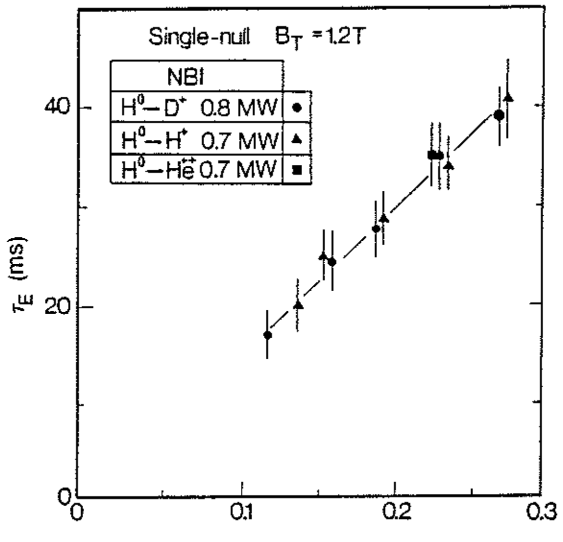

Fig. 12.
The dependence of the global energy confinement time on the plasma current for neutral beam injection into JFT-2M H-mode discharges.

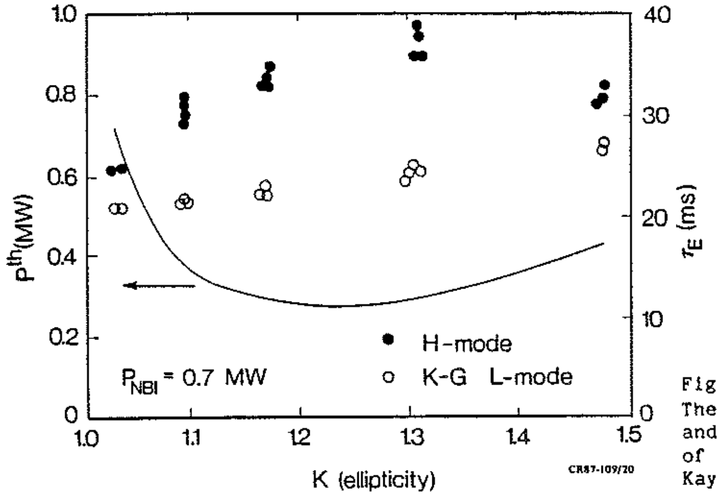

Fig.13.
The dependence of the global energy confinement time and the threshold power of H-modes on the ellipticity of the plasma in JFT-2M limiter discharges. The Kaye-Golston scaling is also shown.

torus, a configuration which is supposed to facilitate the variation of κ in JFT-2M. The observed H-mode confinement times have a flat maximum for $\kappa \sim 1.3$ with the improvement in H- compared to L-mode confinement more or less vanishing for $\kappa \geq 1.5$ and, more importantly, also for near-circular plasma cross-sections ($\kappa \simeq 1.0$). This latter observation will be discussed in the next section.

The general experimental finding that τ_E is proportional to I_p (for both L- and H-regimes) allows collation of the H-mode confinement times obtained in the different machines in a normalised plot of τ_E/I_p versus P as shown in Fig. 14. The longer normalised confinement times of JET as compared

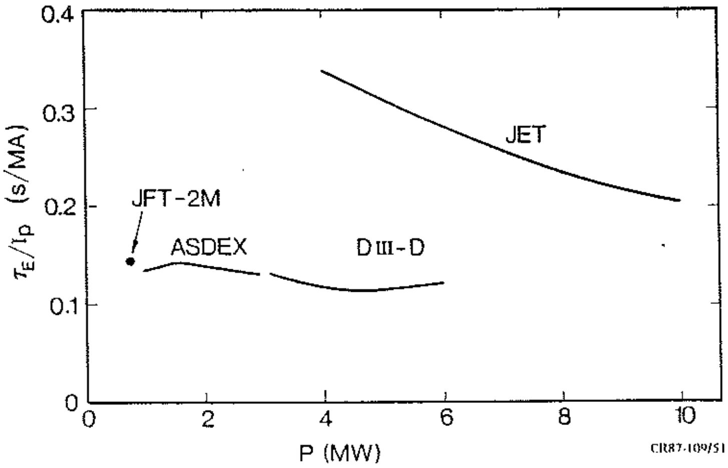

Fig. 14. The dependence of the global energy confinement time (normalised to plasma current) on the total input power for discharges in ASDEX, JFT-2M, DIII-D and JET.

to those observed in the other H-mode experiments, may be due partly to the injection of deuterium rather than hydrogen beams (this mass effect could account for a factor of $\sqrt{2}$ at most since the target plasma is deuterium in all cases). However, there is probably a hidden size scaling, the major radius of JET (R = 3.0m) being roughly twice that of the other machines (R ~ 1.65m for ASDEX/DIII-D and ~ 1.3 for JFT-2M).

With regard to the obvious difference in power dependence between JET and ASDEX/DIII-D, it should be noted that in the latter experiments H-mode discharges close to the power threshold are characterised by high frequency ELMs. These reduce considerably the confinement time and might possibly obscure an underlying improvement at low power.

Obviously more work is needed to clarify the scaling of H-mode energy confinement times with heating power and to establish the dependency on plasma dimensions (beyond that already contained in the I_p-scaling). Until then, present experimental results can be described reasonably well either by a power-independent scaling (which could be the high power limit of an offset linear scaling)

$$\tau_E\ (s) = 0.1 \cdot \sqrt{A_b A_p} \cdot I_p\ (MA) \tag{1}$$

or by a power dependence as developed by Goldston for the L-mode but with a factor of two improved confinement times

$$\tau_E = 2 \times \tau_E^G. \tag{2}$$

If it is possible to upgrade JET for 6MA X-point discharges, energy confinement times of between 0.6s (equation (2) with P = 40MW) and 1.4s (equation (1)) are predicted, the latter value being probably somewhat too optimistic. Even for the rather conservative value of τ_E = 0.6s, however, it should be possible to achieve a thermal Q close to 1 and a total Q of ≥ 1.5 /33,34/.

TENTATIVE THEORETICAL IDEAS RELATING TO THE H-MODE

Any theoretical idea or model that attempts to describe the physics underlying the H-mode has to provide an explanation for:

- the bifurcation nature of the H-transition with an instantaneous change from low T_e, low ∇T_e to high T_e, high ∇T_e at the plasma edge;
- the decisive role of the edge electron temperature (power threshold);
- the pedestals in n_e and T_e-profiles associated with the formation of a transport barrier at the plasma edge;
- and the recent observation of H-modes in a limiter configuration in JFT-2M.

In the following, some tentative theoretical models that have been proposed so far for explaining the H-mode, are discussed. Work in this area has only just started and is by no means complete.

Modified Ballooning Mode Stability

As pointed out by Bishop /35,36,37/, close to a magnetic separatrix the ideal MHD ballooning stability properties of a plasma are strongly modified. Whenever the local current density - or equivalently the local temperature - exceeds some critical value the first and second region of ballooning stability coalesce and the plasma is then stable to all values of the pressure gradient. In this model for an L-mode plasma the edge pressure gradient lies in the first stable region, at or below the marginally stable value, while for an H-mode plasma the edge pressure gradient near the separatrix lies in the second stable region (no longer determined by ballooning mode transport) and the rest of the profile is again in the first stable region. This model leads automatically to a minimum threshold power to achieve the H-mode, being the power needed to place the edge gradient just above the second stability boundary, and to bifurcated temperature profiles as observed at the H-transition.

Predicted H-mode edge temperatures are in good agreement with the pedestal temperatures measured on ASDEX, PDX, JFT-2M and JET. The predicted temperature gradients corresponding to the first and second stable region are about a factor of two larger than the edge pressure gradients measured for L- and H-mode plasmas on ASDEX /25/ (in the case of PDX /2/, predictions are in good agreement with the observed steep H-mode gradients but are about a factor of 5 higher than the measured L-mode profiles). It is necessary to make more precise theoretical estimates based on more exact equilibria before the role of ballooning modes can be fully determined. This applies in particular to a comparison with the limiter H-mode results in elongated and near-circular plasmas. Only exact calculations of the local shear at the plasma boundary of these configurations can show whether ballooning mode stability theory would predict an H-transition, in general, and the observed dependence of energy confinement time on elongation (see Fig. 13), in particular. Of course, it might even be necessary to call on resistive ballooning modes to explain the L-mode, sensing high shear only at high T_e with transition to an ideal ballooning second stability region in the H-mode.

Self-Consistent Stochasticity

An alternative mechanism for limiting the transverse heat flux at the plasma edge could be provided by the critical temperature gradient model for confinement as proposed by Rebut /38,39/. Such a model of self-consistent stochasticity will certainly lead to a pedestal in the edge temperature and may even yield a bifurcation when plasma ion effects are incorporated.

SUMMARY AND OPEN QUESTIONS

Achievements

Since the discovery of the H-mode on ASDEX about 5 years ago this high-confinement regime has now been obtained on a variety of tokamaks. The requirements placed on the magnetic configuration have gradually become less stringent as H-modes have been obtained not only in the original closed divertor geometry but also in open divertor and limiter geometries. There may, however, be a compromise on the quality of the H-mode: while H-mode confinement times in ASDEX, DIII-D and JET are 2 to 3 times above Goldston L-mode scaling, H-mode confinement times in near-circular JFT-2M limiter discharges are not much better than L-mode values although there are still clear signs of an H-transition.

H-mode discharges have also been obtained over a wide range of plasma parameters, with various heating methods and scenarios. H-mode requirements place no practical restrictions on the parameter space normally available for tokamak operation.

Open Questions and Problems

Most unsatisfactory on the physics side is the poor understanding of the physical processes underlying confinement, in general, and H-mode confinement, in particular. Common features between H-mode and other regimes of improved particle or - to a lesser extent - energy confinement, such as the Z (impurity) - and P (pellet) - modes or detached plasmas, are only just emerging. One of these features is the important role of the plasma edge for defining the global particle and energy confinement properties of the plasma. It will be challenging to find experimental conditions under which good energy confinement can be combined with sufficiently degraded particle confinement to prevent accumulation of impurities and, in particular, of helium ash.

To utilise fully the superior confinement properties of the H-mode, there are a number of problems that have to be solved. From the practical, operational point of view it is necessary to excercise control of the plasma density and impurities by provoking and tailoring the occurrence of ELMs and sawteeth. With respect to heating H-mode plasmas, the technical and physical problems of coupling ICRH power to these plasmas have to be overcome. From the physics point of view the scaling of confinement time with power has to be established for high heating powers and close to the β-limit. Causes for any degradation have to be investigated. In addition, the size-scaling of H-mode confinement times will hopefully be determined in the near future now that H-modes have been achieved and are being studied on the larger tokamak experiments.

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