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CONFINEMENT PHYSICS OF H-MODE DISCHARGES IN DIII-D

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ABSTRACT

Our data indicate that the L-mode to H-mode transition in the DIII-D tokamak is associated with the sudden reduction in anomalous, fluctuation-connected transport across the outer midplane of the plasma. In addition to the reduction in edge density and magnetic fluctuations observed at the transition, the edge radial electric field becomes more negative after the transition. We have determined the scaling of the H-mode power threshold with various plasma parameters; the roughly linear increase with plasma density and toroidal field are particularly significant. Control of the ELM frequency and duration by adjusting neutral beam input power has allowed us to produce H-mode plasmas with constant impurity levels and durations up to 5 s. Energy confinement time in Ohmic H-mode plasmas and in deuterium H-mode plasmas with deuterium beam injection can exceed saturated Ohmic confinement times by at least a factor of two. Energy confinement times above 0.3 s have been achieved in these beam-heated plasmas with plasma currents in the range of 2.0 to 2.5 MA. Local transport studies have shown that electron and ion thermal diffusivities and angular momentum diffusivity are comparable in magnitude and all decrease with increasing plasma current.

KEYWORDS

H-mode; confinement; DIII-D; Tokamak; Fusion

INTRODUCTION

Understanding and improving energy confinement remains a major goal of tokamak research. The H-mode of confinement, first observed on ASDEX (Wagner et al., 1982), is one of the most robust

and reactor-compatible of the improved confinement regimes that have been obtained in tokamaks over the last several years since it offers the potential for an improved confinement regime that can persist for long periods of time without the need for extreme wall pumping. Since the initial observation of the H-mode on DIII-D (Luxon *et al.*, 1986), H-mode studies have been a major part of our experimental program. H-mode investigations have been carried out in limiter and single- and double-null divertor discharges with Ohmic heating, electron cyclotron heating (ECH), and neutral beam heating (NBI) over a range of parameters: toroidal field $0.7 \leq B_T$ (T) ≤ 2.1 , plasma current $0.2 \leq I_p$ (MA) ≤ 2.5 , vertical elongation $1.4 \leq \kappa \leq 2.4$, line averaged density $0.1 \leq \bar{n}_e$ (10^{20} m^{-3}) ≤ 1.4 , total plasma energy $W_T \leq 1.4$ MJ, volume averaged toroidal $\beta_T \leq 8$ %, neutral beam injection power $P_B \leq 12$ MW and ECH power ≤ 1.2 MW. Most of our work has concentrated on studies in divertor discharges, with the primary emphasis on the single-null configuration; H-mode has also been observed in elongated plasmas limited on the graphite centerpost of the vacuum vessel.

In order to gain the knowledge needed to apply the H-mode in the reactor regime, we have been studying the physics of the L to H transition, investigating the physics of the edge localized modes (ELMs), and working on the global and local confinement behavior of H-mode plasmas.

At the transition between L- and H-mode, the edge density and magnetic fluctuations decrease as does the heat flux asymmetry between the inner and outer divertor hit spots. This indicates to us that the transition is associated with the reduction in anomalous, fluctuation-driven transport across the outer midplane of the plasma. In addition to the changes in fluctuations, spectroscopic observations of edge poloidal and toroidal rotation have allowed us to infer that the radial electric field just inside the separatrix is negative in the L-mode and becomes more negative at the transition. Furthermore, we have determined the scaling of the H-mode power threshold with various plasma parameters; the roughly linear increase of the threshold with line-averaged density and toroidal field are particularly noteworthy. Finally, we have critically compared published theories of the L to H transition with our data and find need for improvement in those theories.

Investigations of the physics of ELMs over the past two years have allowed us to devise means of controlling the ELMs and utilizing ELMs to produce H-mode plasmas with durations up to 5 sec and with constant or decreasing impurity levels. This work provides evidence that H-mode plasmas can be utilized for long burns in a fusion reactor. As part of this work, we have developed evidence that after the onset of an ELM the plasma transiently returns to L-mode.

Partial installation of neutron shielding has allowed us to begin systematic studies of energy confinement in deuterium plasmas with deuterium neutral beam injection. Energy confinement time in these plasmas increases linearly with plasma current but shows a clear decrease with increasing neutral beam power. At plasma currents between 2.0 and 2.5 MA, we have found that energy confinement time in H-mode can exceed the saturated Ohmic confinement time by more than a factor of two. Confinement times above 0.3 s have been obtained. This observation, coupled with our previous observation of confinement improvement in H-mode with Ohmic heating alone (Osborne *et al.*, 1988; Burrell *et al.*, 1988), demonstrates that saturated Ohmic confinement time does not represent a limit even in discharges with broad, flat density profiles.

Energy confinement does not increase indefinitely with plasma current. At current levels where the safety factor at the 95% flux surface q_{95} is approximately 3, the confinement improvement with current ceases. At q_{95} values below this, energy confinement time depends approximately linearly on B_T at constant q_{95} .

Local energy and angular momentum transport studies have shown that the electron and ion thermal diffusivities and the angular momentum diffusivity are comparable and that they all decrease as I_p is increased. The comparable magnitude of the diffusivities and the similar dependence as current is increased impose significant constraints on theories of plasma transport.

In addition to studying the H-mode, we have used the improved H-mode confinement as a tool in our high β_T program. We have obtained β_T as high as 8 % in $\kappa = 2$ double-null divertor discharges with deuterium NBI.

PHYSICS OF THE L TO H TRANSITION

Transition Phenomena

The initially reported signatures of the H-mode (Wagner et al., 1982) were a sudden reduction in the H_α emission all around the plasma and an equally sudden increase in the plasma energy and particle confinement times. In addition to observing these signatures (Burrell et al., 1987), we have also observed a clear decrease in the edge magnetic and density fluctuations at the L to H transition and a decrease in the heat flux asymmetry at the inner and outer divertor hit spots.

As is illustrated in Fig. 1, at the L to H transition, the magnetic fluctuations in the 10 to 30 kHz range decrease abruptly. This change in the frequency spectrum is seen most clearly on the magnetic probes located where the inner and outer separatrix field lines intersect the wall of the vacuum vessel, possibly due to line-tying effects (Ohyabu et al., 1988). It is also seen on magnetic probes located on the centerpost of the vacuum vessel near the vessel midplane. By looking at the signal on magnetic probe sets at various toroidal locations, we have determined that these fluctuations have toroidal mode number $n = 1$. When L to H transitions occur in plasmas limited on the centerpost, this change in fluctuation spectra can be seen on most of the magnetic probes on the centerpost. These measurements allow an approximate determination of the poloidal mode number as $m \geq 6$ in these limiter H-modes.

Density fluctuations in the 0–200 kHz range have been measured at the outside midplane of the plasma using a microwave reflectometer with multiple, fixed frequency channels (Lehecka et al., 1989). The fluctuations decrease at the L to H transitions on the 3 channels which measure densities that span from just inside to just outside the separatrix. The lower frequency channel, which measures \bar{n}_e well outside the separatrix, does not show this behavior. The highest frequency channel, which measures \bar{n}_e further inside the separatrix than any other, shows this reduction in fluctuations sporadically, depending on discharge conditions (Lehecka et al., 1989).

The time dependence of various edge parameters during the L to H transition indicates that the transition is connected with a reduction in the anomalous heat transport across the outer midplane of the plasma. The density fluctuations at the outside midplane and the magnetic fluctuations decrease at the time of the earliest H_α drop. Changes in the magnetic fluctuations detected at various points around the plasma are coincident within measurement uncertainties. However, the H_α signals at the outer divertor hit spot decrease about 0.5 ms before the H_α signal from the inner divertor (Burrell et al., 1988). This time delay in the H_α signals is part of the evidence supporting the idea that the transition starts at the outside midplane.

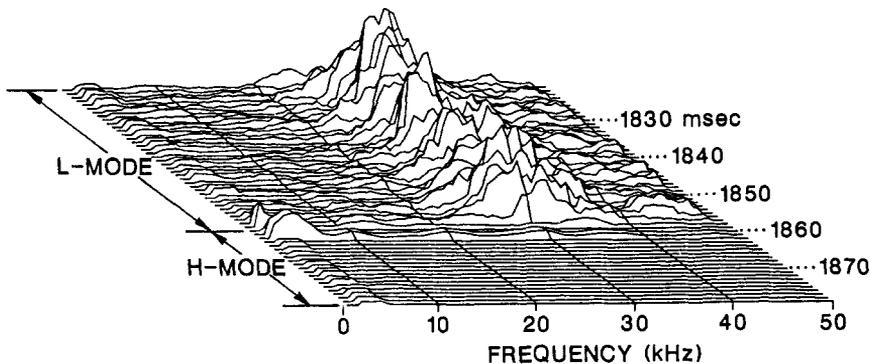


Fig. 1. Plot of auto power spectrum of magnetic fluctuations at various times in a divertor discharge. Note decrease of fluctuations in the 10–30 kHz range at the L to H transition. The signal shown here comes from a magnetic probe under the divertor tiles near the point where the outer separatrix intersects the tiles. The 3 db point of the frequency response of these probes is 50 kHz.

The change in the asymmetry of the heat flow to the inner and outer divertor hit spots at the L to H transition is more evidence for that idea. As is shown in Fig. 2, significantly more power flows to the outer divertor hit spot than to the inner during the L phase of the discharge. This asymmetry is reduced by more than a factor of two after the transition to the H-mode. The observed asymmetry during L-mode is much larger than can be explained due to toroidal effects and suggests that there is an extra, anomalous heat flow across the outside midplane region of the plasma (Hinton and Staebler, 1988a).

The heat flux asymmetry is evidence for an anomalous transport in the bad curvature region at the outer midplane, associated with density and magnetic fluctuations, which is reduced when the fluctuations are stabilized at the H-mode transition. The location in the bad curvature region suggests the stabilization of ballooning modes by entry into the second stable region at the L to H transition (Bishop, 1986). However, comparison of measured edge pressure gradients with the high n , ideal ballooning mode limits (Gohil *et al.*, 1988; Lao *et al.*, 1989) demonstrates that the pressure gradients are at least an order of magnitude below the first stable regime boundary at the L to H transition. Accordingly, stabilization of ideal ballooning modes cannot account for the L to H transition.

In addition to changes in the edge fluctuations and heat flux asymmetry at the L to H transition, we have also seen changes in the edge poloidal and toroidal rotation which indicate that the edge radial electric field becomes more negative at the transition (Groebner *et al.*, 1989). (A negative field points towards the center of the plasma and would tend to confine ions.) The radial electric field can be determined from the lowest order force balance equation for a single ion species, $E_r = (Z_I e n_I)^{-1} dp_I/dr - (\vec{v} \times \vec{B})_r$. Here, Z_I is the charge of the ion, n_I is the ion density and p_I is the ion pressure. At present, we only have information on the $-(\vec{v} \times \vec{B})_r$ term; however, since the pressure gradient term is negative, a negative contribution from the $-(\vec{v} \times \vec{B})_r$ term is sufficient to establish that E_r is negative. As shown in Fig. 3, this contribution to E_r is negative prior to the L to H transition and becomes rapidly more negative at the transition. Estimates of the pressure gradient term indicate that its contribution to E_r is comparable or smaller in magnitude to the contribution of the $-(\vec{v} \times \vec{B})_r$ term. The data shown in Fig. 3 are for neutral beam heated discharges; however, a poloidal rotation also develops at the L to H transition in Ohmic H-mode and ECH H-mode discharges, indicating that the electric field change is fundamental to the H-mode and not a beam-specific effect. At present, the time resolution of our rotation speed measurements is insufficient to determine whether the change in the electric field takes place early enough to be a cause of the L to H transition or whether it is produced by the changes in the profiles that occur at the L to H transition.

We have checked the consistency of our poloidal rotation measurements with the lowest order force balance equation by investigating the poloidal rotation in plasmas with both signs of B_T and with divertor X-points at both the top and bottom of the vacuum vessel. In all cases, the contribution from the observed poloidal rotation gave an inward contribution to the radial electric field. In other words, the poloidal rotation changes sign when the toroidal field changes sign, but the poloidal rotation is in the same direction for an X-point on the top and the bottom of the vacuum vessel.

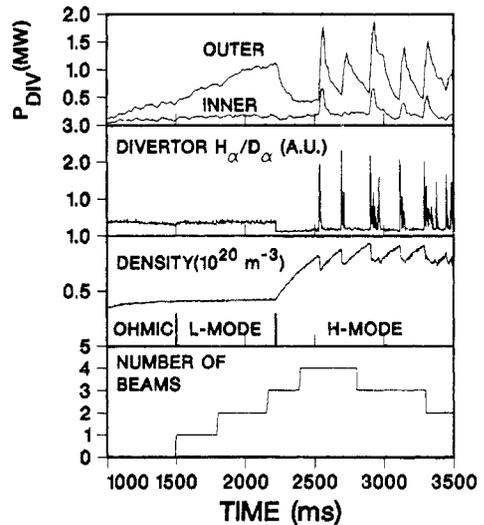


Fig. 2. Variation of the heat flow to the inner and outer divertor hit spots as a function of time in a divertor discharge. This measurement is based on infra-red thermography. Notice the increase in the heat flow to the outer divertor hit spot during the L phase of the discharge. The heat flow to the outer hit spot returns approximately to the Ohmic level after the transition to the H-mode. The time variation of the the inferred heat flow between the L and H phases is limited by the choice of a 50 ms integration time for the detection system for this shot.

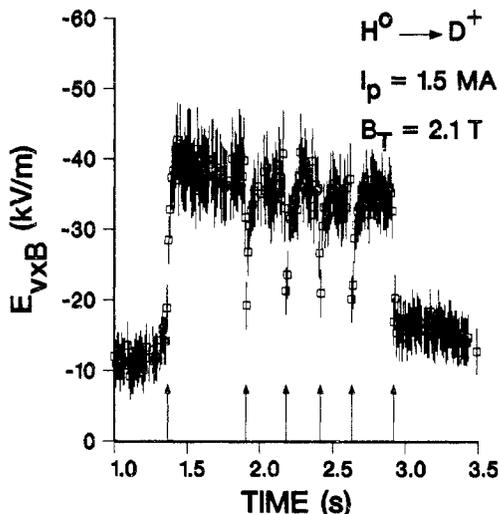


Fig. 3. Contribution to the edge radial electric field from plasma rotation as a function of time across the L to H transition. The first arrow on the X-axis indicates the time of the L to H transition. The next four arrows show when ELMs occur. The final arrow indicates the H to L transition. Notice that the electric field returns almost to its L-mode value during an ELM event. Time resolution of the spectroscopic system is 10 ms for these data.

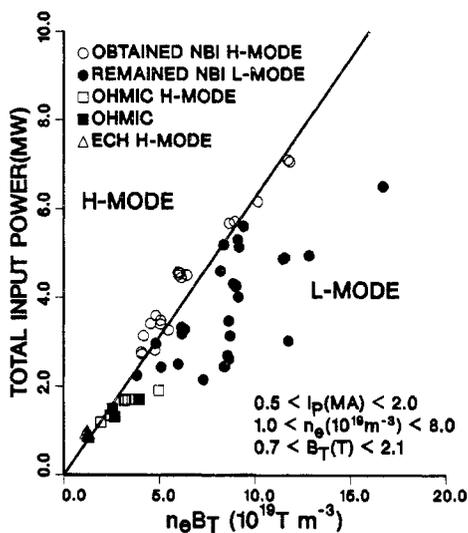


Fig. 4. Dependence of the H-mode power threshold on the product of line-averaged \bar{n}_e and B_T for discharges heated with NBI, ECH or Ohmic heating only. Except where otherwise indicated, the data are for plasmas with NBI. The NBI cases are for hydrogen beam injection into deuterium plasmas. The solid line dividing H-mode and L-mode regions is based on NBI data only.

H-Mode Threshold Dependence on Plasma Parameters

The initial observations of the H-mode in AS-DEX (Wagner et al., 1982) established that there are certain thresholds in \bar{n}_e and P_B that must be crossed to establish the H-mode. Early observations on DIII-D (Burrell et al., 1987) demonstrated that at $B_T = 2.1$ T and $I_p = 1.0$ MA, we must have a total input power (Ohmic plus NBI) $P_T > 3$ MW and $\bar{n}_e > 2 \times 10^{19} \text{ m}^{-3}$ to obtain the H-mode in deuterium plasmas with hydrogen beam injection and with the ion ∇B drift towards the X-point. We have subsequently established that the threshold power P_{th} depends on \bar{n}_e , B_T , heating method, plasma ion species, direction of the ion ∇B drift, direction of NBI relative to I_p , distance between the divertor X-point and the floor of the vessel and distance between the separatrix flux surface and the graphite centerpost of the vacuum vessel. We have seen no dependence of P_{th} on I_p , in contrast to the results from JFT-2M (Suzuki et al., 1987).

As is discussed in detail in the conference (Carlstrom et al., 1989), P_{th} depends approximately linearly on \bar{n}_e and B_T . In the experiment used to produce this scaling data, the lower density limit for the H-mode could not be observed owing to the onset of locked MHD modes, which seriously degrade confinement; these modes were not present at the lower current used in the initial experiments (Burrell et al., 1987).

Utilizing the linear dependence of P_{th} on \bar{n}_e and B_T allows us to make a comparison of P_{th} for various types of plasma heating. As shown in Fig. 4, both ECH and Ohmic heating are slightly more efficient than NBI at producing the H-mode. The lowest threshold seen to date is $P_{th} = 0.8$ MW for ECH in a deuterium plasma at $I_p = 0.5$ MA, $B_T = 1.1$ T and $\bar{n}_e = 1 \times 10^{19} \text{ m}^{-3}$ (Lohr et al., 1987). Achieving H-mode with Ohmic heating alone requires high currents (≥ 1.2 MA) at low toroidal field (≤ 1.1 T) and moderate $\bar{n}_e = 4 \times 10^{19} \text{ m}^{-3}$ to obtain sufficient Ohmic power to cross the threshold.

Since the H-mode can be created using a variety of heating methods, we can definitely conclude that the physics of the H-mode transition is independent of heating method. Accordingly, models of the L to H transition need not consider the specifics of the heating method.

Deuterium plasmas have the lowest P_{th} of any studied to date. In contrast to $P_{th} = 2$ MW at 2.1 T and $\bar{n}_e = 3 \times 10^{19} \text{ m}^{-3}$, P_{th} is about 5 MW in a hydrogen plasma with hydrogen NBI or in a helium plasma with hydrogen, deuterium or helium NBI. P_{th} increases by a factor of about

2.2 when the direction of the ion ∇B drift is changed by reversing the direction of B_T . P_{th} for double-null divertors is intermediate between that for single-null divertors with ion ∇B drift towards the X-point and those with ion ∇B drift away from the X-point. In addition, changing from co-NBI to counter-NBI lowers P_{th} by about 20% (Schissel *et al.*, 1988b). Since a negative change in the edge electric fields seems to be associated with the L to H transition (Groebner *et al.*, 1989), this lowering of the power threshold with counter-NBI may be associated with the negative electric field produced by neutral-beam-induced toroidal rotation counter to the plasma current. Furthermore, reducing the distance between the divertor X-point and the floor of the vacuum vessel from 25 cm to 3 cm lowers P_{th} by almost a factor of two (Carlstrom *et al.*, 1989). Finally, limiting the plasma on the graphite centerpost of the vacuum vessel raises P_{th} . When the separatrix flux surface is 4 cm behind the limiter, P_{th} is a factor of two higher than in a divertor discharge with a 4 cm gap between the limiter and the separatrix. In spite of the higher power threshold, elongated limiter H-mode plasmas can have confinement times as good as those in divertor H-mode.

There has been considerable speculation in the community that the edge T_e , or something related to it, is the critical parameter for the H-mode transition (Wagner *et al.*, 1984; Keilhacker *et al.*, 1986; Hoshino *et al.*, 1987; Keilhacker *et al.*, 1987). As is shown in Fig. 5, we observe that the ratio of T_e/B_T must reach a critical value before H-mode is obtained (Carlstrom *et al.*, 1989).

If edge T_e is a critical parameter, then we can understand the linear scaling of P_{th} with n_e . Since energy confinement time is basically independent of n_e , increasing the density causes T_e to drop, thus requiring more power to reach the threshold. If one could work in an Alcator-like regime, where confinement improves linearly with density, then P_{th} would be independent of n_e .

ELM CONTROL AND LONG-DURATION H-MODE

The confinement improvement in the H-mode is due to the creation of a transport barrier just inside the separatrix flux surface (Wagner *et al.*, 1984). Periodically, this barrier is breached by the ELMs, which transiently allow a burst of particles and energy to flow into the divertor. Up to 20% of the energy and particles in the plasma can be lost during an ELM. Although this loss can affect energy confinement, having a controlled level of ELM activity actually allows control of impurities. By properly tailoring the ELM activity, we have produced basically steady-state H-mode plasmas which have lasted for up to 5 s (Mahdavi *et al.*, 1989). Impurity content, radiated power and energy confinement are all constant throughout these long-duration H-mode plasmas. Achievement of such steady-state plasmas demonstrates that H-mode can be used for long burns in reactor plasmas.

Over the last year and a half, we have developed a model of ELM behavior which allows us a reasonable level of control over the ELMs. This model is based on two main points. First, we have demonstrated that the ELM onset occurs when the edge pressure gradient reaches the first regime, ideal ballooning mode stability limit (Gohil *et al.*, 1988; Stambaugh *et al.*, 1988; Burrell *et al.*, 1988; Lao *et al.*, 1989). Second, once the ELM has started, there is considerable evidence that the plasma behaves as though it has returned to L-mode. This suggests the hypothesis that the ELM event is terminated by the L to H transition. A corollary to this is the idea that the ELM duration should depend on the same parameters that we have found to be important in our L to H transition studies. For example, plasmas where the power flowing through the plasma

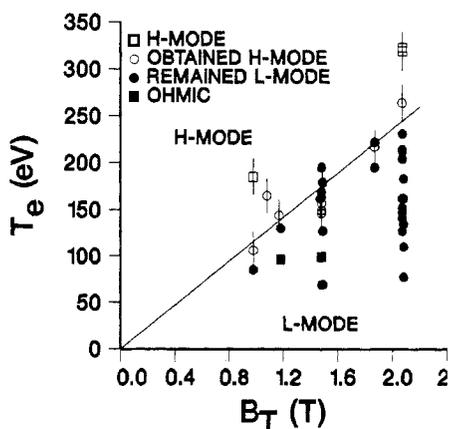


Fig. 5. Variation of T_e at $r/a = 0.97$ with B_T for Ohmic and NBI L-mode and H-mode plasmas. T_e is determined from Thomson scattering. NBI cases are for hydrogen beam injection into deuterium plasmas.

edge is well above the H-mode power threshold should have short ELM durations. Where we have been able to check this hypothesis, ELM duration agrees with this idea.

H-mode plasmas which are completely ELM free have such a good particle confinement time that impurities accumulate in the plasma, leading ultimately to levels of radiated power from inside the plasma that quench the H-mode. However, as has been previously discussed (Brooks et al., 1988; Content et al., 1988), possibly due to the flat electron density profiles in H-mode, the impurity density profiles are also broad and an ELM event can expel significant numbers of impurities. We have found empirically that we can adjust the duration of the ELM event to maintain constant impurity levels while losing only 10% to 20% in energy confinement.

The idea that the ELM is a transient return to L-mode is consistent with a number of observations. The magnetic fluctuations have basically the same frequency spectrum in L-mode and during an ELM. The density fluctuations are also very similar in L-mode and during an ELM (Burrell et al., 1988; Lehecka et al., 1989). In addition, the edge poloidal and toroidal rotation returns to almost the L-mode value during an ELM (Groebner et al., 1989) and, as is shown in Fig. 3, the rotation contribution to the edge electric field returns to nearly the L-mode level. Furthermore, from the time delay in the H_α signals at various points around the plasma and from the time delay in the heat pulses to the inner and outer divertor hit spots (Hill et al., 1988), the ELM event happens at the outside midplane of the plasma. Finally, the H_α level rises and both energy and particle confinement degrade during an ELM.

We have observed that ELM frequency increases and ELM duration gets shorter as the power input to the plasma increases. This is illustrated in Fig. 6. The decrease in duration is consistent with our model that the ELM is terminated by an L to H transition, since this transition happens more rapidly as the input power increases. In addition, since the ELM is triggered when the edge pressure gradient reaches the ballooning limit, the plasma should approach that limit more rapidly as the power is increased.

As is illustrated in Fig. 7, by applying enough power to the plasma, we are able to produce fairly rapid ELMs with a short enough duration that their effect on energy and particle confinement is relatively minor. However, their duration is sufficiently long that the impurities are controlled and a near steady-state condition can be reached. As is shown by the visible Bremsstrahlung and the spectroscopic signals, both the carbon and nickel impurity levels are constant. $Z_{\text{eff}}(\rho)$ is between 2.0 and 2.5 and the radial profile is basically flat. However, as shown in Fig. 8, when the input power is too low, the duration of an individual ELM is much longer and the effect on the energy and particle confinement is much larger. In addition, in this low power case, the ELMs are sufficiently infrequent that the impurities build up and, ultimately, quench the H-mode. Accordingly, ELM control is quite important for obtaining steady-state H-mode conditions.

COMPARISON WITH THEORIES OF L TO H TRANSITION

There are a number of theories of the H-mode in the published literature. We have considered these in the light of the H-mode data that we and other groups have assembled (Keilhacker, 1987). We have collected a series of observations that we feel any complete theory of the H-mode must explain. First, the L to H transition is a rapid event, usually taking a few milliseconds at most. This is in contrast to the

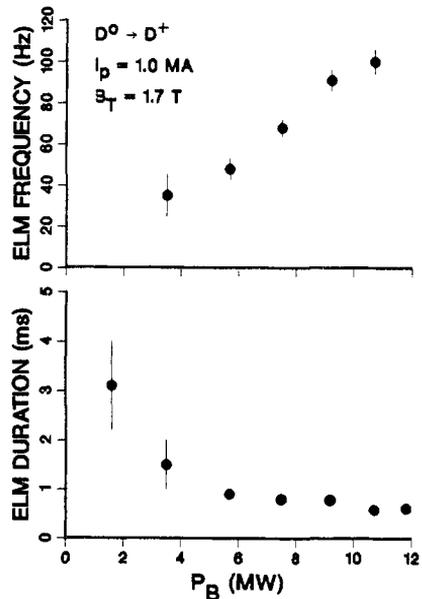


Fig. 6. ELM frequency and ELM duration as a function of neutral beam input power for otherwise constant conditions, $B_T = 2.1 \text{ T}$ and $I_p = 1.0 \text{ MA}$. These single null divertor shots have deuterium beam injection into deuterium plasmas.

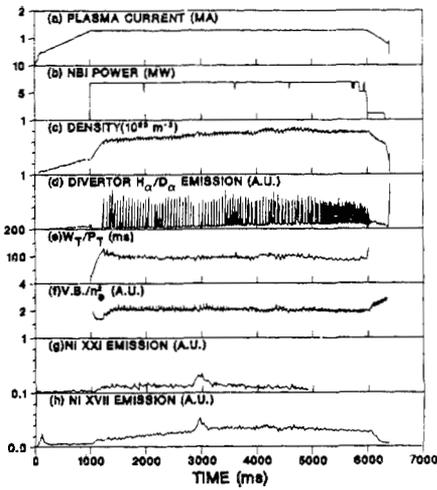


Fig. 7. Time histories of \bar{n}_e parameters for quasi steady-state H-mode: (a) I_p , (b) NBI input power, (c) line-averaged electron density, (d) H_α/D_α radiation from the divertor, (e) energy confinement time, (f) visible Bremsstrahlung signal divided by \bar{n}_e^2 , (g) Ni XXI line emission (near plasma center), (h) Ni XVII line emission (near plasma edge). The small peak in the middle of the spectroscopic traces is due to a small bit of copper entering the plasma. NBI used in this case consisted of one ion source running in deuterium and three running in hydrogen.

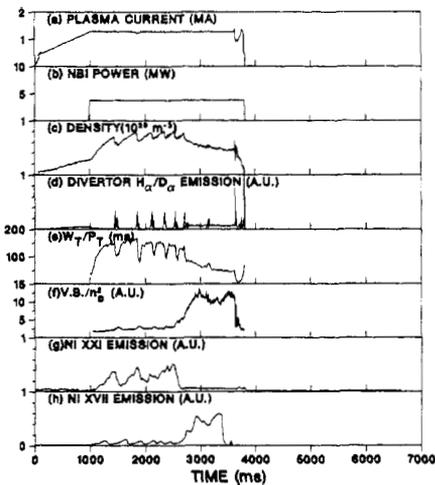


Fig. 8. Time histories as in Fig. 7 but for a plasma with lower NBI input power. Note factor of 10 increase in Ni XVII and factor 7 increase in visible Bremsstrahlung relative to that in Fig. 7.

ASDEX improved Ohmic confinement and counter-injection cases (Söldner *et al.*, 1988; Gehre *et al.*, 1988; Fussmann *et al.*, 1988); this rapidity suggests a need for a theory capable of bifurcation. Second, the transition has a threshold that involves the edge temperature or some quantity related to it (*e.g.* ∇T). A complete theory must specify what this quantity is. Third, a transport barrier forms just inside the separatrix at the transition and the edge gradients of density and temperature become quite steep; edge heat and particle flux are reduced and, simultaneously, edge magnetic and density fluctuations decrease. The edge electric field becomes more negative at the transition. A complete theory must account for these changes. Fourth, the transition occurs first at the outer midplane of the plasma and the asymmetry of the heat flux to the divertor is reduced; this implies anomalous transport through the outer midplane of the plasma decreases. A complete theory should explain this behavior. Fifth, H-mode can be obtained with a variety of heating methods; accordingly, models of the L to H transition should be independent of heating method. Finally, H-mode transitions are possible in plasmas limited on the centerpost; the presence of an X-point inside the vacuum vessel is not necessary for the L to H transition to occur. However, limiter H-modes with appreciable vertical κ (>1.4) have significantly better energy confinement than circular cross section limiter H-mode discharges (Senogoku *et al.*, 1987; Matsumoto *et al.*, 1987).

The earliest theory of the H-mode was the thermal barrier theory of Ohkawa *et al.* (1983). The theory involves creation of a thermal barrier for electron heat flow along the open field lines in the scrape off layer just outside the separatrix in a divertor plasma. The theory was devised when some experimental observations seemed to show that the steep edge gradients in density and temperature in the H-mode occurred on the open field lines. Observations on DIII-D and, earlier, on ASDEX (Wagner *et al.*, 1984) indicate that the steep edge gradients exist inside the separatrix. In addition, in limiter H-mode plasmas in DIII-D, the steep gradient region occurs inside the limiter defined flux surface. The presence of a transport barrier just inside the plasma edge is also indicated by the simultaneous increase in the density and temperature inside the plasma edge and the decrease in the density and temperature on the open field lines (Wagner *et al.*, 1984; Allen *et al.*, 1988). Since the theory of Ohkawa *et al.* does not consider the physics on the closed field lines inside the plasma edge, it is inapplicable to the region where the main confinement improvement occurs.

Hinton (1985), Tang and Hinton (1987), and Hinton and Staebler (1988a, 1988b) have considered how known, calculable neoclassical effects would modify the edge physics of the H-mode. Although this theory in its most recent form does not try to propose an H-mode threshold condition, it can explain the experimentally observed factor of two increase in the H-mode power threshold when the ion ∇B drift is changed from toward the divertor X-point to away from the X-point. An earlier version of this theory (Hinton, 1985) speculated that the H-mode threshold would occur when the edge ion collisionality parameter ν_{i*} dropped below unity. This speculation agreed with observations on ASDEX (Wagner et al., 1985); however, measurements in the edge of DIII-D show that ν_{i*} is in the range of 2–5 even after the transition to the H-mode. The success of this theory in explaining the ∇B drift effect indicates that, even when we identify the anomalous transport mechanism that is stabilized at the L to H transition, one will still have to include neoclassical effects in order to produce a complete theory.

Saito et al. (1985) have postulated that the L to H transition is caused by a bifurcation caused by the physics of the plasma in the divertor itself. The equations that describe the plasma flow along the open field lines in the scrape-off layer have a character that admits two seemingly stable solutions, called the high and low recycling solutions. The high recycling solution has electron temperatures near the divertor plate around 10 eV and densities around 10^{20} m^{-3} while the low recycling solution has divertor plate temperatures of several hundred eV and densities around 10^{18} m^{-3} . The low recycling case is identified with the L-mode while the high recycling case is identified with the H-mode. Unfortunately, the low recycling case, with its extremely low density, has never been observed in a tokamak; most divertor measurements, even in the L-mode, yield temperatures and densities more like those predicted by the high recycling solution. In addition, the divertor density in DIII-D L-modes is usually higher than in the H-mode. Accordingly, the data do not agree with this theory. An additional problem with theories based on the physics of the divertor is that they cannot explain the edge transport barrier inside the separatrix.

Hahn and Diamond (1987) have suggested that the increased pressure gradient in the edge of the H-mode plasma might suppress either the ideal ballooning and/or the resistive ballooning mode at the plasma edge by increasing the diamagnetic drift speed, thus altering the edge transport. The stabilization of ideal ballooning modes echoes the previous suggestion of Bishop (1986). As we have mentioned in the last section, the edge plasma in DIII-D is well below the ideal ballooning limit at the L to H transition (Gohil et al., 1988), so there is no unstable ideal ballooning mode present prior to the L to H transition. If one considers the resistive ballooning mode, one can obtain an expression for the electron thermal diffusivity by combining the expression for the electron thermal diffusivity caused by resistive ballooning modes (Carreras et al., 1983) with the correction caused by a diamagnetic drift frequency large compared with the resistive ballooning mode growth rate (Diamond et al., 1985). This produces an expression that scales like

$$\chi_e \propto \frac{n^{5/2}}{T^{1/2}} \left(\frac{\nabla n}{n} \right) \left(\frac{\nabla p}{T \nabla n} \right)^{3/2}. \quad (1)$$

As the plasma in DIII-D goes from L-mode to H-mode, edge density rises proportionally more than edge temperature and the edge density and temperature gradients steepen. Accordingly, each ratio in this expression gets larger, predicting an electron thermal diffusivity that would be larger in H-mode than in L-mode. Accordingly, the proposed diamagnetic stabilization of resistive ballooning modes cannot account for the reduced edge transport in the H-mode. An additional problem with this theory is the continuous dependence of the transport rates on the plasma parameters. Such continuous dependences make it difficult to obtain the bifurcation needed to explain the rapid L to H transition.

Work by Ohya et al. (1987) has considered the possibility that stabilization of microtearing modes at the plasma edge might be the cause of the L to H transition. This is based on theoretical work by Gladd et al. (1980) concerning the stability of high m tearing modes. Gladd et al. (1980) have shown that, under certain conditions, the microtearing modes can be stabilized if the electron temperature gradient at the edge of the plasma is sufficiently large. This effect is attractive for a theory of the L to H transition, since experimental evidence points to edge T_e or ∇T_e as a key factor in the L to H transition. Ohya et al. have stated the stability criterion as $\nu_{ei} < \eta_e \omega_{e*}$, where ν_{ei} is the electron-ion Coulomb collision frequency, ω_{e*} is the electron diamagnetic drift frequency and η_e is the ratio of the logarithmic derivatives of electron temperature and density

(exact definitions can be found in Gladd *et al.*, 1980). This can be restated as $T_e^{3/2} \nabla T_e > C n_e B_T / m$, where C is a constant and m is the poloidal mode number. Since $T_e^{3/2} \nabla T_e$ should increase with power, this stability criterion is reminiscent of the experimental result that the H-mode power threshold increases linearly with \bar{n}_e and with B_T . However, as is shown in Fig. 9, plotting $T_e^{3/2} \nabla T_e$ versus $n_e B_T$ does not seem to lead to a natural division of the H-mode and L-mode points, although the points for shots that went into H-mode do cluster at one edge of the parameter space covered. This lack of a clear separation indicates that this parameterization may not be the proper stability criterion. The stability criterion for the microtearing mode is actually sufficiently complex that the relation given by Ohyabu *et al.* is a considerable oversimplification. Although the n_e and B_T dependence are suggestive of the experimental results, considerable work needs to be done to compare the actual stability criterion to the experimental results. In addition, since these modes turn on gradually after the stability boundary is crossed, it is not clear whether this theory can produce the bifurcation needed to explain the L-H transition.

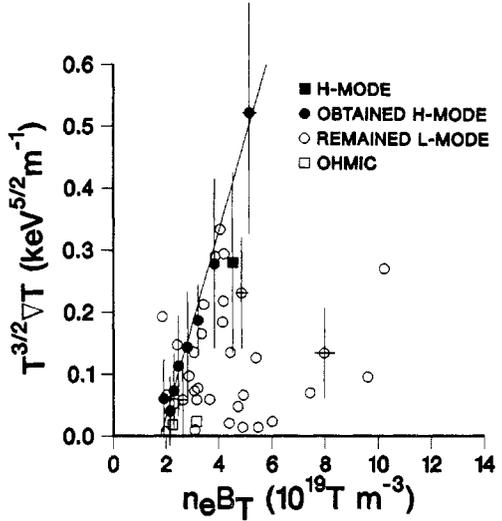


Fig. 9. Plot of the edge values of $T_e^{3/2} \nabla T_e$, determined from Thomson scattering, versus the product of the line averaged \bar{n}_e and B_T for the H-mode and L-mode phases of a series of shots. Those points labeled "Obtained H-mode" were taken in the L phase just prior to transition. The solid line is drawn through the "Obtained H-mode" points. All data are for hydrogen beam injection into a deuterium plasma.

Two theories of L-H transition involve the effects of radial electric field at the edge of the plasma. In the first (Itoh and Itoh, 1988a,b; Itoh *et al.*, 1988), the authors consider the effect of the electric field on loss of trapped ions at the plasma edge and couple this with a model of anomalous electron loss at the edge which is also electric field dependent. The structure of the theory contains a clear bifurcation. The theory predicts, however, that the edge electric field should become more positive at the L-H transition. As we have shown in Fig. 3, experimental observations across the L-H transition show that the electric field becomes more negative. The second theory (Shaing *et al.*, 1988a,b) is based on a generalization of neoclassical transport in a plasma containing a background of fluctuations. This theory produces a negative change in the electric field at the L-H transition, in accord with experimental observations. However, the transition criterion in the published work is $\nu_{i*} = 1$. As was mentioned previously, the edge ion collisionality in DIII-D is above unity even in the H-mode. Accordingly, revision of the stability criterion is needed and is in progress (Shaing, 1989).

Rebut *et al.* (1988) have based an edge bifurcation theory on the transport equations for the plasma edge. The basis of this bifurcation is the nonlinear relationship between the total heat flow across the plasma edge and the heat flow in the electron channel. From the equations given in the paper, one can derive an equation involving the edge electron and ion temperatures,

$$\frac{T_i}{T_e} = \frac{q}{\bar{Q}_e^{3/2} + q}$$

Here, \bar{Q}_e is the normalized heat flow in the electron channel and $q = \chi_e / \chi_i$ is the ratio of the electron and ion thermal diffusivities. It is easy to show that the theory allows a bifurcation only when $q < 1/24$; this means that the ratio of the edge temperatures must satisfy $T_i / T_e < 1/5$. However, the measured edge electron and ion temperatures during H-mode in DIII-D show that edge T_i is comparable to or greater than edge T_e . Accordingly, the temperature ratio demanded by the bifurcation condition in this theory is not seen in the experiments.

After considering all these theories, it is clear that none meet all the criteria that a theory of the H-mode needs to meet. Each one appears have part of what is needed but the complete theory remains elusive.

GLOBAL CONFINEMENT STUDIES

Energy Confinement in Deuterium Plasmas with Deuterium NBI

Partial completion of the neutron shielding on DIII-D has allowed us to begin systematic experiments with deuterium beam injection into deuterium plasmas. In order to minimize accumulated neutron production, we have made single parameter scans of the variation of energy confinement with total input power ($P_B \leq 12$ MW) at moderate current ($I_p = 1$ MA) and with current ($I_p \leq 2.5$ MA) at moderate input power ($P_B \leq 5.5$ MW). This work was done in H-mode in single-null divertor plasmas. The present power scan results should be superior to previous single parameter power scans which were done with hydrogen injection into deuterium plasmas. These suffered from potential systematic errors caused by changes in plasma isotopic composition with increasing beam power.

Even at the 1 MA level used for the data in Fig. 10, there is a clear increase in the energy confinement time τ_E when the plasma goes from Ohmic to low power H-mode. In addition, these results are better than our best previous results from deuterium plasmas with low hydrogen fractions (Burrell et al., 1987; Schissel et al., 1988a). These new results also show a stronger decrease of τ_E with input power than our previous results (Burrell et al., 1987). In spite of the degradation, the τ_E values are about 3 times the Kaye-Goldston value (Kaye and Goldston, 1985) at high power. A fit to the data using a functional form of P_T^{-a} gives a value of $a = 0.37$. This is somewhat smaller than the Kaye-Goldston exponent of $a = 0.58$. Fitting the data in Fig. 10 with an offset linear model gives an incremental confinement time of about 95 ms. Since the global confinement time observed at the highest power is about 110 ms, only a minor decrease in τ_E with power above the 12 MW level is to be expected.

Variation of energy confinement time with plasma current is shown in Fig. 11. The slope of the deuterium beam data gives $\tau_E/I_p = 120$ ms/MA. These data also show a significant improvement over the previously reported 85 ms/MA (Schissel et al., 1988a) obtained in a deuterium plasma with hydrogen injection. As was seen previously, from the 1.0 to the 2.0 MA levels, τ_E increases approximately linearly with plasma current. There is some sign of saturation in confinement above the 2.0 MA level. This may be the onset of the confinement saturation at low q discussed in the next section, or it may simply be due to lack of optimization at these new current levels.

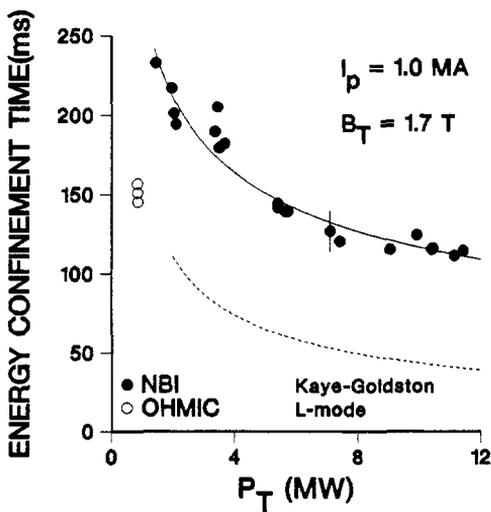


Fig. 10. Global energy confinement time as a function of total input power for deuterium H-mode plasmas with deuterium beam injection. The line fit through the data has a power dependence of $P_T^{-0.37}$. Also shown on the graph is the Kaye-Goldston L-mode scaling curve.

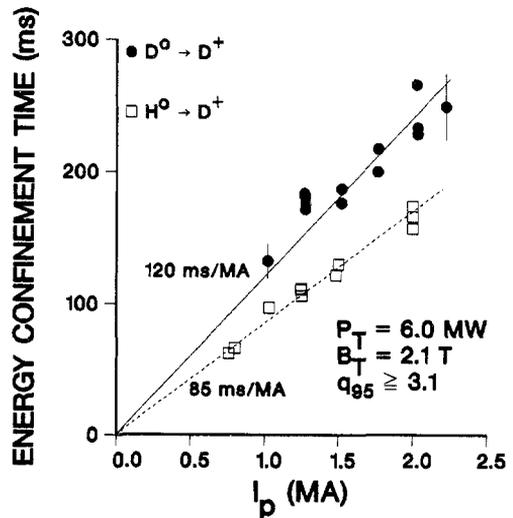


Fig. 11. Energy confinement time versus plasma current for discharges with deuterium beam injection or hydrogen beam injection into single-null divertor H-mode plasmas.

Based on our previous observations of confinement in Ohmic H-mode (Osborne, 1988) and at high current in H-mode plasmas with hydrogen NBI (Burrell *et al.*, 1988), we had concluded that it was possible for the energy confinement time in discharges with broad, flat density profiles to exceed the saturated Ohmic value. Our deuterium beam work has allowed us to extend our parameter range and make this conclusion even stronger. As is shown in Fig. 12, in deuterium H-mode plasmas with deuterium beam injection, the τ_E of 340 ms at low input power is at least twice the saturated Ohmic τ_E of 150 ms in similar discharges. Previous work has shown that the saturated Ohmic confinement time can be exceeded in discharges with peaked density profiles (Greenwald *et al.*, 1984; Söldner *et al.*, 1988). Our present results show conclusively that saturated Ohmic confinement does not represent a maximum confinement time even for discharges with broad profiles.

Energy Confinement at Low q

As the plasma current is increased in H-mode discharges, we find that a point is reached where the linear increase of τ_E with current ceases. As the toroidal field increases, the current at which saturation occurs increases linearly with the toroidal field. For discharge shapes that we usually run, this saturation occurs when the safety factor at the 95% flux surface q_{95} reaches 3. After this point, τ_E is basically independent of plasma current, as is shown in Fig. 13, and, as is shown in Fig. 14, τ_E in this low q regime depends linearly on toroidal field at constant q .

By varying the plasma elongation from 1.7 to 2.05 in an H-mode divertor discharge, we have varied q_{95} by about 30%. As is shown in Fig. 13(b), we find that the confinement saturation occurs at the same current and at a higher q_{95} value in the more elongated plasma. Accordingly,

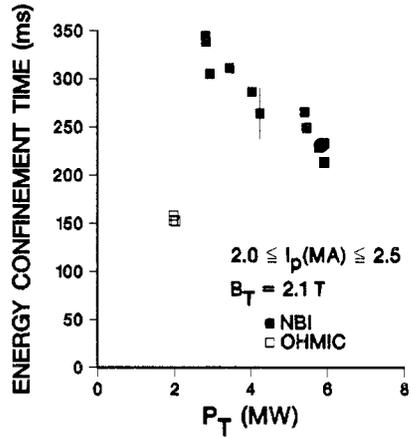


Fig. 12. Energy confinement time in deuterium plasma vs. total input power for Ohmic discharges and H-mode discharges with deuterium beam injection for I_p at or above 2.20 MA. Notice the doubling of energy confinement time when the plasma goes from Ohmic to beam-heated H-mode. Some of the decrease of confinement in H-mode with increasing input power may be related to increasing impurity levels in the plasma.

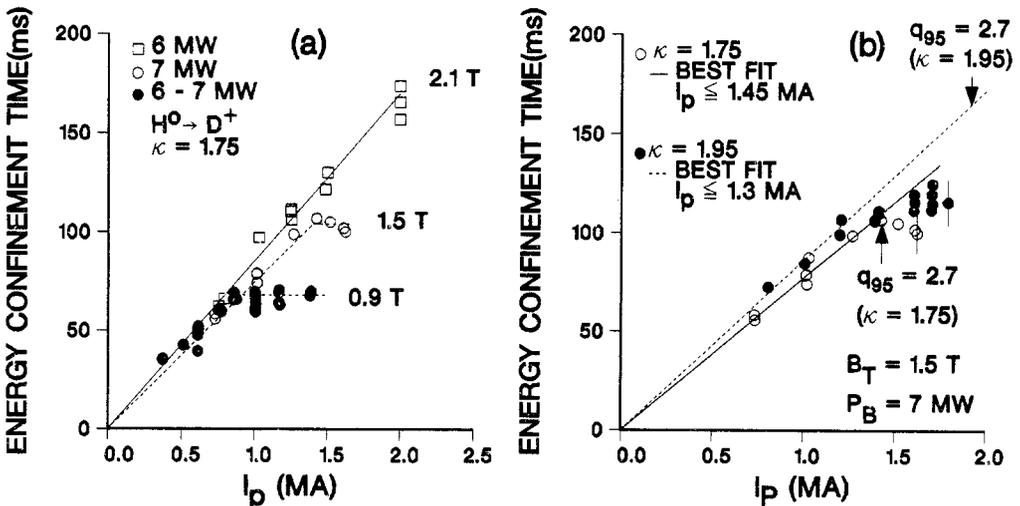


Fig. 13. Energy confinement time vs. I_p for H-mode discharges with hydrogen neutral beam injection; (a) as B_T increases, the I_p at which confinement time becomes independent of I_p increases. At 2.1 T, this point is beyond 2.0 MA. (b) Confinement saturation occurs at the same I_p but different q_{95} when plasma elongation is changed.

we conclude that $q_{95} = 3$ is not the proper criterion for confinement saturation with current, but that some other quantity involving I_p/B_T must be the correct one.

We have looked into and rejected a number of possible explanations for this loss of current scaling. First, this saturation is not caused by reaching the β_T limit, since the saturation can occur at β_T values only 50% to 60% of the observed β_T limit (Strait et al., 1988). Second, even though the saturated Ohmic confinement time scales linearly with B_T (Shimomura et al., 1987), this saturation with increasing current is not due to reaching the saturated Ohmic value. As was discussed in the last section, saturated Ohmic confinement does not represent a limit to confinement in DIII-D. In addition, the value of τ_E in the saturated region does depend on input power, contrary to what one would expect if a maximum τ_E were imposed by Ohmic confinement. Third, although at low B_T there appears to be a coupling of the ELMs and the sawtooth oscillation which could degrade confinement (Stambaugh et al., 1988; Schissel et al., 1988a), this effect is absent at higher fields and currents where the ELMs are more stable and the interval between the ELMs is longer.

We are left with two possible explanations for the confinement saturation with increasing current which we are actively investigating. The saturation could be due to sawtooth activity by itself. A problem with this model is that the sawtooth mixing radius correlates well with q_{95} when the plasma shape is changed, thus making it hard to understand why the saturation occurs at different values of q_{95} when the shape is changed. The other possibility requires looking at current scaling in a different way. Instead of thinking of the linear increase with current as normal and the saturation as a defect, one could consider a model in which the saturated region is the one showing the optimum confinement. The linear region would be a degradation that occurred when the current was too small. One possible mechanism that we are considering for this is the effect of systematic variations of temperature profiles on the ion temperature gradient driven modes (Biglari et al., 1989) Since the ion temperature profile should be systematically broader at higher current, the gradients which drive the instability could be reduced, perhaps finally leading to a state at high current where the modes have turned off.

LOCAL CONFINEMENT BEHAVIOR

In addition to investigating global energy confinement as a function of plasma current, we have also studied local ion and electron thermal transport and global and local angular momentum transport (St. John et al., 1989) as a function of current in H-mode plasmas.

Local transport is inferred by steady-state transport analysis with the ONETWO transport code (Pfeiffer et al., 1985) using electron density and temperature profiles measured by a 28 point Thomson scattering system, ion temperature profiles measured by a 16 point charge exchange recombination spectroscopy system, angular rotation speed profiles from the 8 tangentially viewing chords of the charge exchange recombination spectroscopy system, Z_{eff} profiles from a 16 chord visible bremsstrahlung measurement and radiated power profiles from a 21 channel bolometer system. Additional density profile information, including the normalization of the Thomson density data, was provided by a 4 chord CO_2 interferometer system. All these experiments were done with hydrogen NBI into a deuterium plasma.

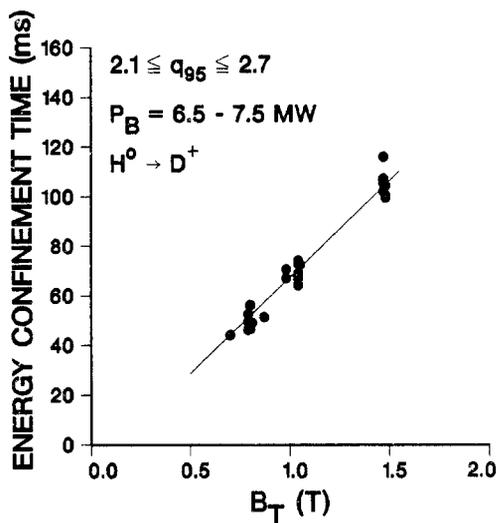


Fig. 14. Energy confinement time versus toroidal field for low q discharges in the regime where energy confinement time is independent of current. All discharges were run at a neutral beam input powers between 6.5 and 7.5 MW. Energy confinement increases linearly with toroidal field.

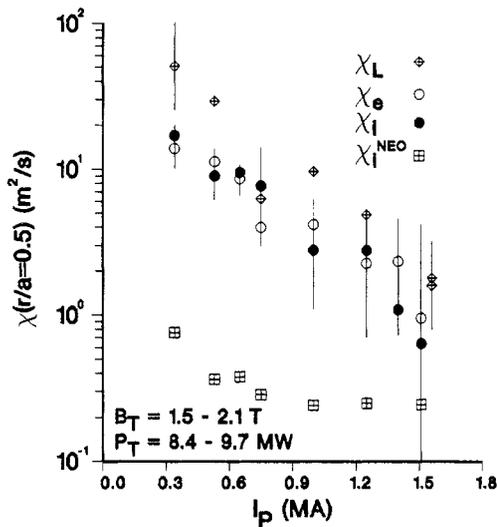


Fig. 15. Plot of inferred electron and ion thermal diffusivities and angular momentum diffusivity at the half-radius as a function of plasma current. Also shown is the neo-classical prediction for ion thermal diffusivity for the same discharges. All of these cases are for hydrogen beams injected into deuterium plasmas. Plasma current and toroidal field were such that all shots are in the regime where global confinement depends linearly on plasma current.

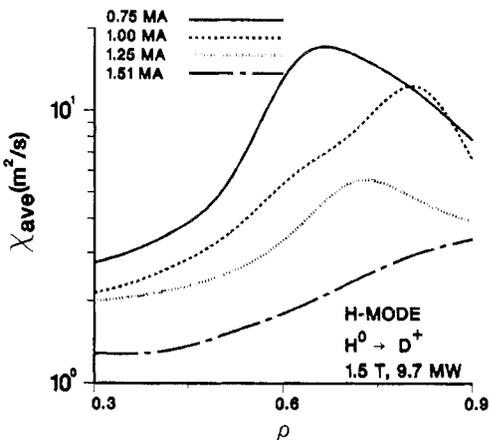


Fig. 16. Average of the electron and ion thermal diffusivity plotted as a function of the normalized minor radius coordinate for H-mode discharges with different plasma currents. Thermal diffusivity decreases everywhere as the I_p increases. Plasma current and B_T were such that all shots are in the regime where global confinement depends linearly on plasma current.

In the central two-thirds of the H-mode discharges, the overwhelmingly dominant energy loss process is electron and ion thermal conduction. We find that the local thermal transport decreases in both the electron and ion channels as the current increases. This is shown in Fig. 15. In addition, even at the highest currents, the inferred ion thermal diffusivity is still about a factor of three above the neoclassical prediction. In the H-mode, there is a linear relationship between the plasma current and the plasma density. Accordingly, at low plasma densities, the electron-ion energy exchange is relatively weak, and the thermal transport in the electron and ion channels can be readily separated. As current and density increase, the electron-ion coupling becomes stronger, leading to greater error bars on the individual thermal diffusivities. However, in spite of the larger error bars, the decrease in the thermal diffusivities is sufficiently rapid that we can still conclude that the diffusivities decrease as the current increases.

Because of the large error bars on the individual thermal diffusivities at high density, we have also considered the variation of the average thermal diffusivity as a function of current. As is shown in Fig. 16, the average diffusivity decreases everywhere in the confinement zone as the current increases.

The correlation of density and current in the H-mode makes it difficult to unambiguously distinguish a density dependence of confinement from a current dependence. We have some data (Burrell *et al.*, 1987) which indicates that the global confinement in H-mode is independent of density. However, a clearer determination of the density dependence of the confinement remains to be done when we have better tools for controlling density.

The angular momentum confinement also improves with increasing current in the H-mode plasmas (St. John *et al.*, 1989). The global angular momentum confinement time increases with the current and, as is shown in Fig. 15, the local momentum diffusivity decreases as the current increases. Owing probably to the high densities in H-mode, the toroidal rotation speeds observed to date are small enough that viscous heating is a small contribution to the power input to the ions. In

addition, the rotation speeds are small enough that no modifications are needed in the standard fast ion slowing down models, which assume negligible bulk plasma motion.

In the cases where we can separate the electron and ion channels, we find that the electron and ion thermal diffusivities are comparable. In addition, as is shown in Fig. 15, the angular momentum diffusivity is usually within a factor of two of the others, although it is systematically somewhat higher than either. This near equality of the transport coefficients and their simultaneous decrease with increasing current should provide significant constraints on theories of transport in tokamaks.

ACKNOWLEDGEMENT

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