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*Massachusetts Institute of Technology, Cambridge, Massachusetts.
†University of California, Los Angeles, California.
‡Oak Ridge Associated Universities, Oak Ridge, Tennessee.
△University of California, San Diego, California.
◊Sandia National Laboratory, Livermore, California.

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ABSTRACT

Studies have been conducted in DIII–D to determine the dependence of the power threshold P_{lh} for the transition to the H–mode regime and the threshold P_{hl} for the transition from H–mode to L–mode as functions of external parameters. There is a value of the line-averaged density n_e at which P_{lh} has a minimum and P_{lh} tends to increase for lower and higher values of n_e. Experiments conducted to separate the effect of the neutral density n_0 from the plasma density n_e give evidence of a strong coupling between n_0 and n_e. The separate effect of neutrals on the transition has not been determined. Coordinated experiments with JET made in the ITER shape show that P_{lh} increases approximately as $S^{0.5}$ where S is the plasma surface area. For these discharges, the power threshold in DIII–D was high by normal standards, thus suggesting that effects other than plasma size may have affected the experiment. Studies of H-L transitions have been initiated and hysteresis of order 40% has been observed. Studies have also been done of the dependence of the L-H transition on local edge parameters. Characterization of the edge within a few ms prior to the transition shows that the range of edge temperatures at which the transition has been observed is more restrictive than the range of densities at which it occurs. These results suggest that some temperature function is important for controlling the transition.

1. INTRODUCTION

The H–mode discharge provides one of the most important regimes of improved confinement in both the present generation of tokamaks and in designs of future machines, particularly ITER. Study of the transition to H–mode (L-H transition) provides a high leverage route to obtain a basic understanding of the physics of the tokamak boundary layer, particular of edge transport, and is needed to provide reliable predictive capability for future machines. A two-part approach has been used in DIII–D to study H–mode transition physics. Primarily in support of the design of ITER, which must operate in the H–mode regime to be successful, studies have been done of the dependence of the H–mode power threshold P_{lh} on global parameters. These parameters include density, neutrals and machine size. In addition, studies have been initiated of the power P_{hl} at which back (H-L) transitions occur. The second part of the approach to H–mode studies involves determining the local edge conditions which are required for transition to the H–mode to occur. This latter work is required in order to obtain a more fundamental understanding which is required for the development of quantitative predictive models for the transition.

2. DEPENDENCE OF TRANSITION ON GLOBAL PARAMETERS

The candidate scaling relationship for P_{lh} in terms of global (or control) parameters proposed for ITER [1] is $P_{lh} \propto n_e B S$, where n_e is the line-averaged electron density, B is the toroidal magnetic field and S is the surface area of the plasma.

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Because this relationship leads to predictions of high values of P_{lh} (~150 MW) in ITER, improved confidence in this scaling is needed. During the last two years, DIII–D has studied the dependence of P_{lh} on n_e and S. One improvement in analysis techniques is that P_{lh} is now based on improved measurements of P_{sep}, the power flowing through the separatrix [2,3]. $P_{sep} = P_\Omega + P_{aux} - dW_p/dt - P_{rad}$ where P_Ω is the ohmic heating power, P_{aux} is the auxiliary heating power, dW_p/dt is the rate of change of the stored energy in the plasma and P_{rad} is the radiated power from inside the last closed flux surface. This approach is consistent with the power flux through the plasma boundary controlling edge parameters which probably control the transition.

The range in n_e over which the H–mode can be obtained in DIII–D is not controlled by fundamental limits to H–mode accessibility but rather by operational constraints [4]. At low densities, locked modes can inhibit or raise P_{lh} for the H–mode; when locked modes are removed with coils to correct error fields, the H–mode is obtained at low n_e. At high densities, achieving the H–mode is limited by MARFE activity associated with high values of neutral pressure due to gas puffing.

Threshold studies performed in DIII–D in 1993 indicated that P_{lh} increased approximately linearly with n_e [5]. New data for the density scaling of the threshold were taken in 1994 and some of these data examined P_{lh} at lower values of n_e than obtained in 1993. The analysis of the 1994 data [Fig. 1(a)] indicates that there is a value of n_e at which P_{lh} tends to increase for higher values of n_e [4], consistent with the 1993 results, and also to increase for lower values of n_e. Thus, over the entire density range, the variation of P_{lh} with n_e is weaker than linear with P_{lh} having a range of factor of two and n_e a range of a factor of four. The actual values of P_{lh} for the 1994 data are somewhat less than for the 1993 data. This change may be due partially to gradual improvements in vessel conditioning. However, part of the change is due to the fact that P_{lh} for the 1994 data was adjusted by P_{rad} whereas earlier data had not been corrected in this way.

It has long been suspected that neutrals play a hidden role in the H–mode transition. In order to examine this issue, an experiment was performed in DIII–D to measure P_{lh} at a fixed value of n_e as the ratio of neutral density n_0 to n_e was changed by ramping the density up with a large gas puff and by ramping the density down with the aid of the DIII–D cryopump. A serious impediment to studies of neutrals is that no direct measurements of the neutral density at the separatrix are readily available. Under the assumption that the neutral pressure and D_α emission are reasonable indicators of n_0, this experiment showed that n_e and n_0 are tightly coupled and that the original goals of the experiment were not achieved. For example, Fig. 1(b) compares the D_α emission from the divertor for the 1994 density scan, in which the time rate of change of the electron density *dn/dt* was 0, and for the neutrals experiment in which *dn/dt* was varied from negative to positive. The D_α signals are more strongly correlated with the value of n_e than with the value of *dn/dt*. Study of neutral pressure provides the same result. However, the power threshold values obtained from this experiment show a different trend than expected from the 1994 n_e scaling data. Figure 1(a) shows that the values of P_{lh} obtained with a negative density ramp (using the cryopump) were about a factor of two higher than observed in the 1994 data, P_{lh} without a ramp was moderately higher than the 1994 data and P_{lh} with a positive density ramp was comparable to the 1994 data. These effects are not yet understood. One possibility is that the correlation between n_0 and n_e was actually broken, particularly with the aid of the cryopump, and that P_{lh} does have a dependence on n_0. Perhaps this result is due to some unknown divertor or scrape-off layer effect. Further analysis and further experiments are required to study this result.

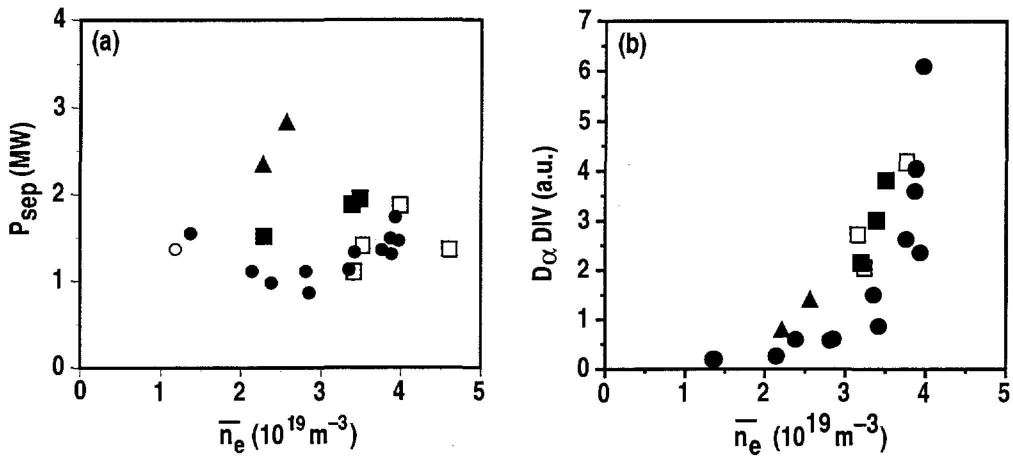

Fig. 1. (a) P_{lh} (P_{sep}) required to produce H–mode vs. line averaged density n_e. (I_p = 1.35 MA, B_T = 2.1 T) Data from 1994 with (open circle) and without (solid circles) error field correction coil show that P_{lh} is minimum for n_e in range of 2–3 × 10^{19} m^{-3} and increases for lower and higher values of n_e. Data from neutrals experiment shown for positive density ramp (open squares), no gas puff (solid squares) and negative density ramp (diamonds). (b) Divertor D_α emission, assumed to be an indicator for neutral density, as a function of n_e. 1994 n_e scan (circles) shows that D_α increases nonlinearly with n_e. D_α values obtained from experiment which attempted to break correlation of neutral density and n_e are comparable to values from 1994 scan, evidence that neutral density is strongly correlated with n_e. Symbols have same meaning as in (a).

The dependence of P_{lh} on surface area has been studied with coordinated discharges in JET and in DIII–D which were performed in the ITER shape and with similar control parameters [6]. These experiments indicate that P_{lh} is proportional to $S^{0.5}$, a dependence which is much more favorable for ITER than the scaling relationship shown above. However, the measured P_{lh} in DIII–D was high by normal DIII–D standards and work is required to determine if this result is due to systematic effects related to shape or neutral pressure. In particular, discharges in DIII–D which have the ITER shape have a large outer gap, and perhaps effects related to neutrals were different than for more conventional discharges with smaller gaps.

It is well known that the H–mode exhibits significant hysteresis; that is, it is possible to sustain a discharge in the H–mode with less heating power than is required to produce the transition to H–mode. This effect is of interest both because of its implications regarding the basics physics of the H–mode and because the design for ITER plans to operate in a regime where the hysteresis will be used to maintain the H–mode. Quantitative studies of the hysteresis in DIII–D have been initiated. Data have been obtained by increasing the heating power in small increments to assess P_{lh} and then decreasing the power in small steps to measure P_{hl}, the power level at which the transition from H– to L–mode occurs. These studies are somewhat inhibited because the L-H threshold is low in DIII–D and discharges tend to remain in H–mode even when auxiliary heating is turned off. As with studies of P_{lh}, it is very important to account for P_{rad} in assessing the net loss power required to sustain the H–mode. Systematic studies of the hysteresis in DIII–D have not yet been completed. However, it is clear that significant hysteresis is observed in DIII–D H–mode discharges, as is illustrated in Fig. 2. In this example, the back transition occurs at a loss power which is about 60% of the loss power required to produce the L-H transition.

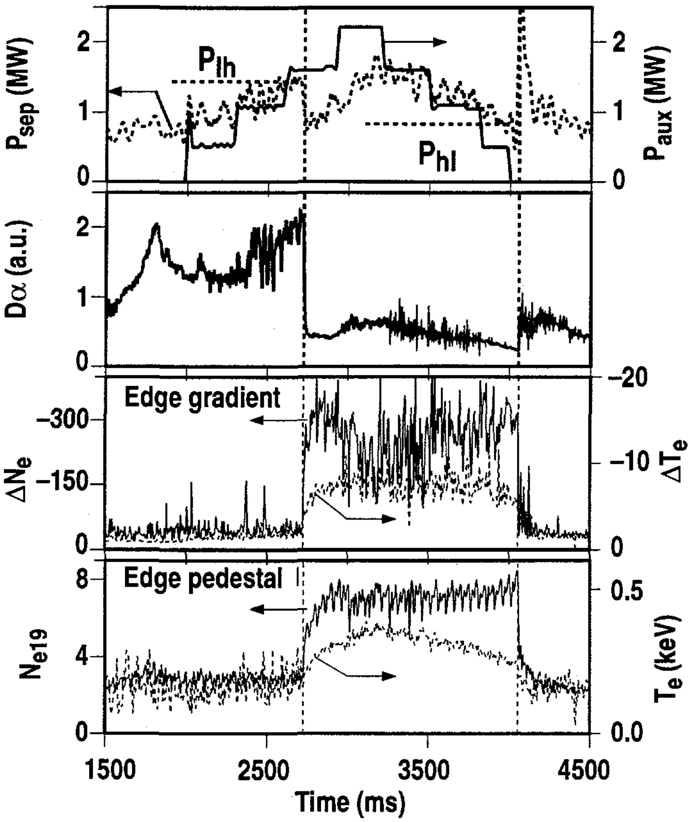

Fig. 2. (a) Solid line shows injected neutral beam power P_{aux} which was ramped up and then ramped down in stairstep fashion. Dashed line shows P_{sep}. H-L transition occurred after beam power was turned off. Nevertheless, H–mode was sustained with P_{sep} of about 60% of P_{lh}. (I_p = 1.35 MA, B_T = 2.1 T) (b) D_α as a function of time. Dashed vertical lines mark time of L-H transition (about 2700 ms) and H-L transition (4100 ms). (c) Gradients of T_e (keV/m) and n_e 10^{19} m^{-4}) in the transport barrier show similar time behavior. They rise rapidly after L-H transition and drop abruptly at H-L transition. (d) Pedestal values of T_e and n_e, determined from hyperbolic tangent fit, show that T_e starts to decrease as P_{sep} is decreased. In contrast, n_e remains unchanged until back transition.

3. DEPENDENCE OF TRANSITION ON LOCAL EDGE PARAMETERS

A major goal of L-H studies is to obtain a fundamental physics understanding which will provide the basis for quantitative predictive models of the transition. For this goal to be obtained, improved knowledge of local edge conditions required for the transition must be obtained. The DIII–D diagnostic set, routinely providing measurements of edge T_e, n_e, and T_i profiles with sub-centimeter spatial resolution and temporal resolution of 6 milliseconds or better can make such measurements and is being used to construct a database of these edge quantities and their gradients just prior to the transition to H–mode. This database is being used to assess the range of edge conditions present at the L-H transition and the ultimate goal is to search for a critical edge parameter which must be achieved so that the H–mode transition can occur.

Local edge parameters are evaluated with the aid of a non-linear least squares algorithm which is used to fit spline functions [7] to the measurements which have been mapped to a magnetic coordinate system. In this paper, the "edge" of the plasma is defined as the center of the region which becomes the transport barrier in H–mode. For the data examined so far, it appears that $\rho = 0.95$ (where ρ is the normalized toroidal flux) is close to being in the center of many H–mode transport barriers, so the L–mode profiles have been evaluated at this ρ value.

The range of edge parameters observed just prior to the transition to the H–mode is summarized in Table I. This table indicates that the database contains discharges whose control parameters cover a wide range of the DIII–D operating space. The most salient feature of the local edge parameters is that the transition occurs for a fairly wide range of density but for a relatively small range of temperature. This result is obtained even though the power threshold varies by more than an order of magnitude, and suggests that the threshold condition is some function of temperature. If the transition is related to the ion collisionality ν_{i*}, it is more complex than the requirement to achieve a fixed value of ν_{i*}, which varies by a factor of eight in the database. The scale lengths for T_e, n_e, and T_i are in the range of one to a few times the ion poloidal gyroradius $\rho_{\theta i}$ which in turn is nearly constant at 0.5–0.8 cm.

A weakness of this approach is that some scatter is introduced into the results because the the chosen ρ value is somewhat arbitrary and probably not correct for all plasma conditions and because there is an uncertainty of about ±0.5 cm in the location of the separatrix obtained from the equilibrium fit. An improved analysis for H–mode transport barriers has been developed which uses a hyperbolic tangent plus a linear term to fit edge profiles as functions of space in physical coordinates. An advantage of this approach is that edge profiles can be conveniently parameterized in terms of a few fit parameters, including the symmetry point of the hyperbolic tangent and a pedestal value, and the evolution of these parameters during a discharge can be readily obtained by fitting a time series of edge profiles. The usefulness of this technique for studying L–mode edge plasmas is under study.

4. SUMMARY AND CONCLUSIONS

In summary, H–mode studies have been conducted in DIII–D to examine the dependence of P_{lh} on external control parameters, to examine the hysteresis of the H–mode and to characterize the local edge parameters at the time of the transition. One improvement in the power threshold studies is that P_{lh} is being defined as P_{sep} where P_{sep} is the power flowing through the plasma boundary and is obtained by adjusting the heating power for radiation and the time rate of change of the plasma

Table I
Range of Machine Control Parameters and Edge Parameters in Transition Database. All Edge Data are Evaluated in L–Mode <10 ms Before Transition to H–Mode

Control parameters	Edge parameters (ρ = 0.95)
$1.3 < B_T < 2.1$ (Tesla)	$0.034 < T_e < 0.13$ keV
$1.0 < I_p < 2.0$ (MA)	$0.11 < T_i < 0.22$ keV
$1.2 < n_e < 4.0 \times 10^{19}$ m^{-3}	$0.5 < n_e < 4.4 \times 10^{19}$ m^{-3}
$1.0 < P_{lh} < 14.0$ (MW)	$2 < \nu_{i*} < 17$ (n_i assumed equal to n_e)
	$0.5 < \rho_{\theta i} < 0.8$ (cm)
	$1 \times \rho_{\theta i} < L_{n_e} < 6 \times \rho_{\theta i}$
	$1 \times \rho_{\theta i} < L_{T_e} < 4 \times \rho_{\theta i}$
	$1 \times \rho_{\theta i} < L_{T_i} < 12 \times \rho_{\theta i}$

stored energy. Although this approach may provide better insights into the true scaling of P_{lh}, extrapolations of such values of P_{lh} to ITER tend to underestimate the actual heating power needed to overcome line radiation and transient effects.

The dependence of P_{lh} on n_e is weak when constraints to the normal operating space are avoided. More precisely, P_{lh} has a minimum for densities in the middle of this operating space and tends to rise for lower or higher values of n_e. Coordinated experiments performed with JET indicate that P_{lh} scales as $S^{0.5}$. This result is favorable for ITER, but further work is required to determine if the large gaps required to produce the ITER-shaped plasmas tend to produce a high power threshold in DIII–D. Both the studies of density and of size scaling here have produced results which are different than those indicated by the ITER scaling relationship [Eq. (1)].

Initial studies of the effects of neutrals on P_{lh} suggest that it is very difficult to decouple neutral density from electron density. These studies are also hampered by lack of direct measurements of the neutral density inside the plasma. Modeling of the neutral density is required to help overcome these problems. Studies of H–mode hysteresis in DIII–D have been initiated. Significant hysteresis has been observed with P_{hl} being of the order of half of P_{lh}. However, significant variation in the amount of hysteresis has been observed and the relation between P_{lh} and P_{hl} in DIII–D remains to be determined.

A systematic study of the local edge conditions required to obtain H–mode has been initiated with the establishment of a database of edge T_e, T_i and n_e observed just prior to the transition. This database shows that the range of edge temperatures observed just prior to the transition is relatively narrow. These observations suggest that the transition condition is some function of temperature, a hypothesis originally suggested by sawtooth-triggered transitions in ASDEX [8] and supported by a significant amount of data from several machines. This idea is also supported by some observations of H-L transitions in DIII–D. For instance, Fig. 2 shows that as the heating power was decreased, the pedestal value of T_e also decreased and the back transition occurred as T_e approached the level it originally had before the L-H transition. However, there are counter-examples which show that the pedestal value of T_e remains high and unchanged until the H-L transition. Such transitions may be triggered by ELMs, but this is not yet known for certain. It can also be argued that the database reflects boundary conditions imposed by the scrape-off layer (SOL) rather than any fundamental H–mode physics. In particular, electron heat conduction along the open field lines in the SOL is very large and ensures that T_e at the last closed flux surface will be low. In turn, the electron-ion equilibration will tend to keep T_i relatively low and possibly in a small range. Thus, it is necessary to develop further experimental tests which will reveal unambiguously whether or not the threshold condition is some function of edge temperature.

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