STUDY OF H–MODE THRESHOLD CONDITIONS IN DIII–D*

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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 achieve these goals. Studies have been done of the dependence of the H–mode power threshold P_{th} on global parameters to provide urgent information needed for the design of ITER, which must operate in the H–mode regime to be successful. Studies have been initiated to determine the local edge conditions which are required for transition to the H–mode to occur. This latter work is required to provide a needed database for the development of quantitative predictive models of the transition.

The present scaling relationship for P_{th} ($P_{th} \propto \bar{n}_e$ BS, where $\bar{n}_e$ is the line-averaged density, B is the toroidal magnetic field and S is the surface area of the plasma) leads to predictions for high values of P_{th} in ITER. Thus, for economic and physics reasons, the design of ITER needs improved empirical data regarding this scaling. Work has been done in DIII–D to study the issues related to the dependence of P_{th} on $\bar{n}_e$ and S .

Density scans in DIII–D show that the radiated power P_{rad} systematically rises as $\bar{n}_e$ is raised. Under the assumption that it is the power flux through the plasma boundary which controls the transition, it is necessary to subtract P_{rad} from the input power to obtain the intrinsic value for P_{th}. When this is done, it is found that P_{th} increases weakly, if at all, with $\bar{n}_e$. The range in $\bar{n}_e$ 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. At low densities, locked modes can inhibit or raise P_{th} for the H–mode; when locked modes are removed with coils to correct error fields, the H–mode is obtained without an increase in P_{th} 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. Thus, for the lowest possible P_{th}, ITER must have clean plasmas and must avoid the locked mode and MARFE boundaries of parameter space.

Discharges in the ITER shape and with similar control parameters have been performed in JET and DIII–D to study the dependence of P_{th} on machine size [1]. These experiments indicate that P_{th} is proportional to $S^{0.5}$. This dependence is more favorable for ITER than the scaling relationship shown above. However, the measured P_{th} in DIII–D was high by normal DIII–D standards and more work is required to determine if this result was affected by systematic effects related to shape or neutral pressure.

The planned operating scenario for an ITER discharge assumes that the discharge can be maintained in H–mode with a loss power of 50% of P_{th}. The ITER design needs empirical

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information from H-L (back) transitions to determine how much hysteresis can be expected. Quantitative studies of the hysteresis in DIII–D are somewhat inhibited because the L-H threshold is low and discharges tend to remain in H–mode even when auxiliary heating is turned off. However, significant hysteresis is observed in DIII–D H–mode discharges, which can be maintained with loss powers of less than or equal to 30–60% of P_{th}. Thus, the ITER design strategy is consistent with empirical evidence in DIII–D but has little margin for error. In addition, P_{rad} must be kept low to maximize the power flux through the plasma boundary.

An improved basic physics understanding of the L-H transition, needed for development of quantitative models for the transition, requires a detailed characterization of the edge conditions which are required for the transition to occur. 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 ms or better, has been 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 search for a critical edge parameter which must be achieved so that the H–mode transition can occur. As shown in Table I, the database contains discharges whose control parameters cover a wide range of the DIII–D operating space. The local edge parameters have been evaluated at $\rho = 0.95$, which typically is about 1 cm inside the last closed flux surface. The most salient feature of these data 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, which is strong evidence that the threshold condition is some function of temperature. The range of T_i values observed at the transition is smaller than the range of T_e values, suggesting that the ions may control the transition. 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 8 in the database.

Theoretical and empirical guidance suggests that gradients of the edge parameters may also be important in controlling the H–mode threshold. As shown in Table I, initial evaluations of 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 ρ_i which in turn is nearly constant at 0.5–0.8 cm. The scatter in the data is too large to assess whether or not the transition could be related to some function of the gradients. Improved methods to evaluate relevant edge gradients are being developed.

TABLE I. Range of machine control parameters and edge parameters in transition database. All edge data are evaluated in L–mode less than 10 ms before transition to H–mode

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

In summary, studies in DIII–D indicate that the dependence of P_{th} on $\bar{n}_e$ is weak when corrections are made for P_{rad} and when constraints to the normal operating space are avoided. Coordinated experiments performed with JET indicate that P_{th} scales as $S^{0.5}$ although further testing of this result is needed. Significant H–mode hysteresis is observed with the loss power required to sustain the H–mode being 30–60% of the power required to produce the transition to H–mode. 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. The primary result to date is that the transition condition appears to much more closely related to temperature than to density.

[1] CARLSTROM, T.N., et al. "JET/DIII–D Size Scaling of the H–Mode Power Threshold," in Proc. of International Atomic Energy Agency Meeting on H–Mode Physics, Princeton, New Jersey, September 18–20, 1995.