COMPARISON OF L–H TRANSITION MEASUREMENTS WITH PHYSICS MODELS*

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Abstract

Sawteeth and neutrals are found to have a significant influence on the H–mode power threshold scaling. The ion ∇B drift direction has only a small effect on the edge plasma conditions measured near the plasma midplane but a large effect on the divertor plasma. Since the power threshold changes dramatically with the direction of the ion ∇B drift, this implies that phenomena in the divertor region are critical for the L-H transition. Local conditions at the plasma edge are consistent with several theories of the L-H transition that use edge gradients in their formulation of a critical threshold parameter. However, scatter in the database is too large to distinguish between conditions that lead to an L-H transition and those that remain in L–mode.

1. INTRODUCTION

Global scaling of the H–mode power threshold (P_{TH}) and local conditions at the edge of the plasma just before an L-H transition have been studied in the DIII–D tokamak. Besides the usual dependence on density and toroidal field, at least three other effects have been found to have a significant influence on P_{TH}. These include: the effect of a sawtooth crash, which can trigger an L-H transition; the direction and magnitude of the ion ∇B drift relative to the X–point location, which can change P_{TH} by factors of 2 to 3; and the effect of neutrals, which may have more subtle and counter-intuitive effects on P_{TH}. In our analysis, P_{TH} is defined as the power flowing across the separatrix, P_{SEP}. Each of these effects has been studied experimentally and compared with physics models or numerical calculations. In addition, parameters measured at the plasma edge just before an L-H transition have been analyzed and compared to theories of the L-H transition. Operational space of L– and H–mode is given in terms of dimensionless edge parameters. It is found that the edge pressure gradient may be more important than the magnitude of the edge temperature.

2. SAWTEETH EFFECTS

Over half of the L-H transitions in the DIII–D transition database are triggered by sawteeth. The sawtooth crash provides an additional transient power flow to the edge of the plasma where the L-H transition takes place. This power flow depends on the inversion radius of the sawtooth, the stored energy, and the dissipation of the power as it flows to the plasma edge. In an experiment in which the sawteeth were suppressed by neutral beam heating during the early current ramp phase of the discharge, P_{TH} increased from 3 MW in the sawtooth triggered case to 5 MW when the sawteeth were suppressed, (reverse B case in Fig. 1). Including the additional power flow to the plasma edge due to sawteeth [1] in the calculation of the power flowing across the separatrix, P_{SEP}, we find the toroidal

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field dependence of P_{TH} is weakened. Thus edge power flow due to sawteeth may significantly influence the observed P_{TH} scaling.

3. ∇B DRIFT EFFECTS

The direction of the ion ∇B drift relative to the X–point location has a dramatic influence on the magnitude of P_{TH}. Hinton [2] and later Hinton and Staebler [3] have attributed this effect to neoclassical cross-field fluxes of both heat and particles driven by poloidal temperature gradients on the open field lines in the scrape-off-layer (SOL). The magnitude of these fluxes scale like $\sim(n/r)(T/B)(\partial T/\partial \vartheta)$, where r is the minor radius, T the temperature, and ϑ the poloidal angle. The flux surface average of these cross-field fluxes is zero unless asymmetries such as the gradient of B and/or the poloidal temperature gradient lead to a net flux. In its simplest form, these fluxes influence P_{TH} by either adding to or subtracting from the power flow to the edge of the plasma. A 1D analysis of heat conduction in the SOL suggests that these cross-field fluxes can be a significant fraction of the input power [4]. It was proposed that some of the observed scaling of P_{TH} is due to the variation of the magnitude of these fluxes and may not be intrinsic to the scaling of the physics of the L–H transition itself. For instance, the increase of P_{TH} at low density may be due to the reduction of the ∇B effect as the sheath limit for parallel heat conduction is reached and the poloidal temperature gradient is reduced. Many qualitative features of this model are in agreement with observations of P_{TH} scaling, such as the existence of a density threshold, the importance of the X–point position, and the increase of P_{TH} in double-null configurations.

In order to further test these ideas, a series of experiments was carried out in which plasmas with identical operational parameters except for the direction of the toroidal field were compared. In these discharges, the neutral beam power was modulated at a low level (12.5%, 0.3 MW) in order to keep the plasma in L–mode in the forward B case (∇B drift toward the X–point). This resulted in power levels far below P_{TH} in the reverse B case where P_{TH} ~5 MW. Motivated by the idea that edge parameters control the L-H transition, we compare the edge n_e, T_e, T_i, and ∇P_e profiles evaluated at the pedestal of the density profile determined by a hyperbolic tangent fit [5] in Fig. 2. There is almost no difference in the value of these parameters between the two directions of the toroidal field, even though one discharge is very near the L-H transition and the other is very far away in terms of power. Also shown in Fig. 2, are the edge parameters for the reverse B case, when the power level is just below the threshold, (5 MW). Although the edge density remains the same, (the line average density was held constant), the edge temperatures and pressure gradients are much greater than the forward B case.

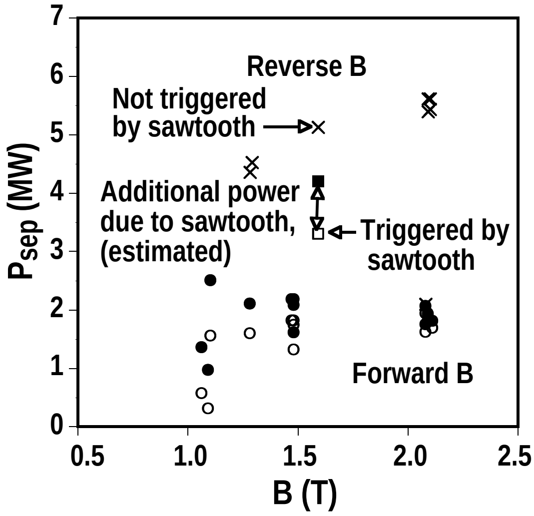

FIG. 1. Toroidal field scaling of the H–mode power threshold when accounting for sawteeth power. Open symbols indicate L–H transitions triggered by a sawtooth crash, closed symbols indicate threshold power when additional sawteeth power is taken into account, crosses indicate transitions not triggered by sawteeth. Forward B data < 3 MW, reverse B data > 3 MW.

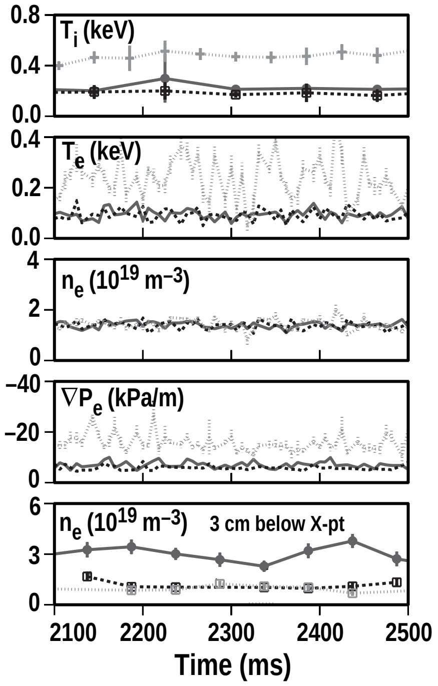

FIG. 2. Edge and divertor parameters for forward (solid) and reverse B (dashed) at 1 MW and reverse B at 5 MW (light dashed).

Preliminary analysis of the divertor conditions show that significant differences between these discharges appear near the X–point region. The electron density just below the X–point measured by Thomson scattering in the forward B case is 4-5 times greater than the reverse B case, as shown in Fig. 2. The cause of this high-density region and its influence on the L-H transition is under investigation. It may be evidence of the ion ∇B drift carrying heat and particles across the X–point into the private flux region, or it may be the result of $E \times B$ flows in the divertor. If neutral penetration into the core plasma raises P_{TH} as discussed in the next section, then this high-density region may reduce P_{TH} in the forward B case by preventing neutrals from reaching the X–point region of the core plasma.

Several theories of the L-H transition consider the edge pressure gradient as a key parameter for the transition (Section 5). As shown in Fig. 2, the forward B edge electron pressure gradient is slightly higher than the reverse B case at 1 MW. This may be evidence for cross-field fluxes in the SOL playing a role in determining the edge pressure gradient. However, calculations of the cross-field fluxes described above, based on measured SOL and divertor temperatures and densities, result in powers of only a few tens of kilowatts. These fluxes are considered to be too small to contribute significantly to the overall power balance. However, it is still possible that these fluxes affect the edge plasma, especially near the X–point, and influence the L-H transition threshold.

4. NEUTRALS

The effect of neutrals on the L-H transition has been studied in a series of experiments where a heavy gas puff was used to ramp up the density and a divertor cryopump was used to ramp down the density during an L-H transition. Extensive transport and neutral modeling of the plasma edge region using B2.5 and DEGAS indicates that during heavy gas puffing, the SOL density increases and shields the region just inside the separatrix from neutrals [6]. This reduces the neutrals in this region and lowers P_{TH}. When the cryopump is used, the neutral penetration is greater and P_{TH} increases. There is a good correlation between $P_{SEP}/\overline{n}$ and the ratio of the maximum charge exchange damping rate $(\nu_{cx})_M$ to the neoclassical damping rate (μ_{neo}) of the poloidal flow when evaluated for average radii in the range $0.9 < r/a < 0.95$ as shown in Fig. 3 [6]. Good correlation is also found with the poloidally averaged neutral decay length. Further experiments and inter-machine comparisons are needed to identify the proper dimensionless parameter for the effect of neutrals on the power threshold.

5. LOCAL EDGE PARAMETERS

A technique of fitting a hyperbolic tangent to the edge profiles themselves has eliminated the scatter caused by the flux surface reconstruction [7] and has improved the localization of the plasma edge [5]. With this technique, we have determined that the position of the maximum edge density gradient remains relatively constant across the L-H transition, and is therefore, a good location to evaluate the local edge conditions relevant to the formation of the edge transport barrier in H–mode. However, in order to facilitate comparisons with other devices, we have evaluated edge parameters 2 cm inside the separatrix. We find this location roughly corresponds to the edge density pedestal determined from the hyperbolic tangent fit. An operational space diagram of T_e and n_e evaluated 2 cm inside the separatrix is shown in Fig. 4. Although there is a trend for pre-transition data (LH) to be at higher temperatures, these data are not well separated from the normal L–mode data. Therefore, these parameters do not clearly resolve the L–H transition operating space. For comparison, a fit to the L-H data on ASDEX-Upgrade is also shown. The DIII–D data generally fall a factor of 2 below the ASDEX-Upgrade data, indicating that the edge temperature alone is not a critical parameter for the L-H transition. Collisionality of the edge plasma varies in the range of 5–50, and often increases slightly after the L-H transition as the edge density rises. Collisionality alone is therefore, not likely to be a key parameter.

The improved localization of the edge parameters now permits more detailed comparisons with L-H transition theories. In a model based on 3D simulations of edge turbulence by Rogers and Drake [8], the threshold condition is parameterized in terms of α_{MHD} and α_{DIAM}, both of which contain edge gradients. Figure 5 shows that α_{MHD} may provide a better separation of the L–mode and pre-transition data than edge n_e and T_e in Fig. 4, indicating it may be important for the L-H transition. Due to the lack of separation of the data with α_{DIAM}, the importance of this parameter is not clear. Quantitative comparisons will require improvements in the model to include realistic geometry.

In another model of the L-H transition based on the stabilization of Alfvén drift waves by O. Pogutse *et al.* [9], the threshold condition is parameterized by a normalized beta and collision frequency such that $\beta_n > \beta_{crit} = 1 + \nu_n^{2/3}$. Figure 6 shows data evaluated at the maximum edge density

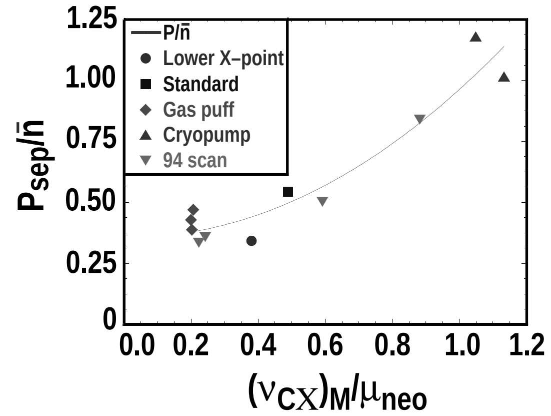

FIG. 3. The dependence of $P_{SEP}/\bar{n}$ versus $(\nu_{cx})m/\mu_{neo}$ for the r/a =0.95 surface (taken from Fig. 18, Ref. [6]).

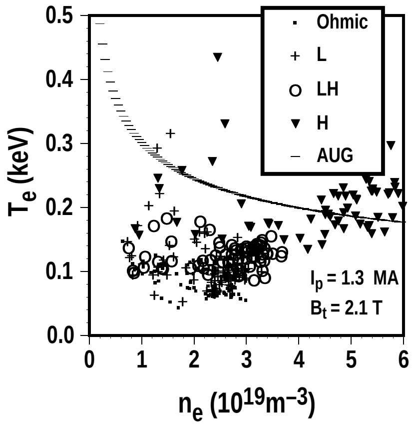

FIG. 4. Operational space diagram evaluated 2 cm inside the separatrix. A fit to LH data from ASDEX-Upgrade is shown for comparison.

gradient on the $\beta_n - \nu_n$ plane. The value of β_n has about the right magnitude but no clear distinction exists between points just before the L-H transition and points that remain L–mode or Ohmic. H–mode points, taken just after the L-H transition, are well above the threshold condition in both these models. Therefore, comparison of the edge gradients between L– and H–mode is not particularly useful in distinguishing among these models.

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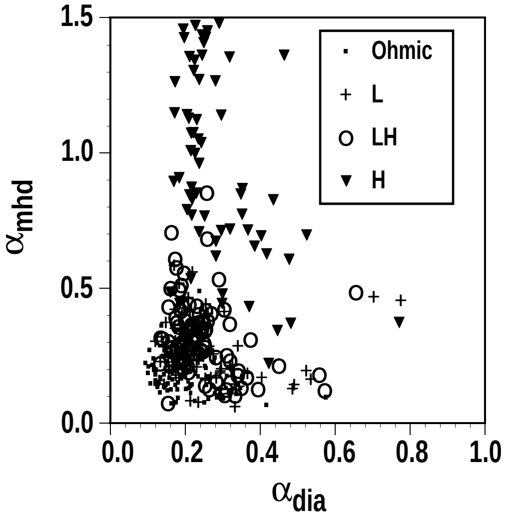

FIG. 5. Operational space diagram for critical parameters of Ref. 8.

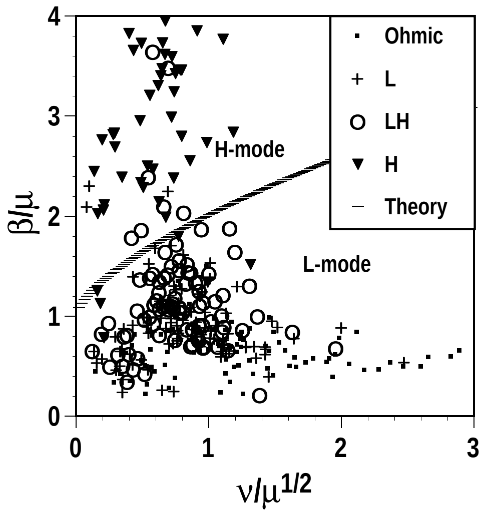

FIG. 6. Operational space diagram for critical parameters of Ref. 9.