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ABSTRACT

The "back" transition from H-mode to L-mode has been studied on DIII-D as a part of our investigation of the L-H transition power threshold scaling. Based on a density-dependent scaling for the H-mode power threshold, ITER will require substantial hysteresis in this parameter to remain in H-mode as n_e rises. Defining the hysteresis in terms of the ratio of sustaining to threshold power, P_{HL}/P_{LH} may need to be as small as 50% for ITER. Operation of DIII-D at injection powers slightly above the H-mode threshold results in an oscillatory behavior with multiple forward-backward transitions in the course of a discharge. These discharges represent a unique system for studying various control parameters that may influence the $H \leftrightarrow L$ state transition. Careful analysis of the power flow through the edge gives values for the sustaining power which are well below the corresponding threshold powers ($P_{HL}/P_{LH} = 35\% - 70\%$), indicating substantial hysteresis can be achieved in this parameter. Studies of other control parameter candidates such as edge temperature during the back transitions are less clear: the amount of hysteresis seen in these parameters, if any, is primarily dependent on the nature (ELMing, ELM-free) of the parent H-state.

1. INTRODUCTION

The achievement of an enhanced confinement regime for ITER seems to be necessary in order to obtain the desired fusion power levels of ~1.5 GW with feasible auxiliary heating levels. The preferred candidate — ELMing H-mode — represents a favorable compromise of energy and particle confinement, wall loading, and quasi-steady state operation [1]. The identification of the threshold power (P_{LH}) scaling for the L–H-mode transition has therefore been the object of considerable research, and various parametric scaling laws are more or less successful in predicting the threshold behavior on existing experiments [2–4]. The relevant power is the edge power flow, defined generally as

$$P_{SEP} = P_{AUX} + P_{OH} - P_{CORE} - d(W_P)/dt \quad , \quad (1)$$

where the power terms on the right hand side are due to auxiliary heating, ohmic heating, radiation from inside the separatrix, and changes in the plasma-stored energy, respectively.

A feature common to most of these scaling laws is a near linear density scaling; the implication for ITER is that H-mode access will occur at low densities, with a reliance on an observed power hysteresis [5] to sustain the H-mode as the density is raised. Scenarios for H-mode access and exit which rely on a factor of two hysteresis and are compatible with ITER requirements have been identified [6]. Hence, complementary scaling studies of the H–L or “back” transition are required to identify the sustaining power (P_{HL}) required to stay in H-mode for various machine parameters. Given the parametric behavior of P_{HL} and P_{LH} , the scaling behavior of the power hysteresis, here defined as

$$\eta = P_{HL}/P_{LH} \quad , \quad (2)$$

can in turn be predicted.

Back transition studies can also shed light on the basic physics of the H-mode. A key concept for understanding the plasma state transitions is that of a control parameter. Formally, a control parameter is one that determines the dynamical evolution of the state. In the case of the H-mode, one can characterize the evolution of the state transitions (H→L→H) in terms of various control parameters that may or may not exhibit hysteresis themselves. Heuristically, we hope to identify experimental parameters, such as the edge power flow or edge temperature, that exhibit analogous control over the state of the actual plasma. A useful representation of this concept is a control curve, a simple example of which is shown in Fig. 1.

Fig. 1. A plot of power versus edge pressure gradient for the forward and back transitions demonstrating power hysteresis. The illustration shows mode hopping and critical points typical of a first order phase transition. Note the existence of hysteresis results in regions that the plasma would pass through quickly as it jumps from one mode to the other.

As elegantly illustrated by Toda [7], complex phase behavior (multiple type ELMs, dithering, etc.,) can be described by a single control curve (flux versus gradient). We are using this sort of representation to assess control parameter candidates on the DIII-D tokamak. In particular, we have started with the loss power P_{SEP} and edge parameters, which are measured with good spatial and temporal precision on DIII-D.

2. EXPERIMENTAL METHOD

The shots analyzed include a series of threshold experiments on DIII-D where the injected power is increased and decreased in a stepwise fashion in order to create the forward and back transitions. The loss power terms are separately calculated from EFIT equilibrium reconstructions, beam injection power, and inversion of the bolometry data to identify the core radiation term. The edge profile data obtained from Thomson scattering and CER is processed using a hyperbolic tangent fitting procedure (TANHFIT) [8] which yields parameters such as pedestal width, height, and symmetry point for the ion and electron density, temperature, and pressure profiles. This type of edge parameterization avoids errors associated with magnetic reconstruction of the separatrix location, and allows us to compare edge behavior in a convenient, systematic way for a wide range of plasma discharges and conditions.

3. POWER HYSTERESIS

As an example we show control curve plots for DIII-D shot 92091, one of a series of lower single-null (LSN) discharges where the direction of the toroidal field was reversed in order to investigate grad-B drift effects on the power threshold [9]. For these shots we have found a substantial power hysteresis, with the required sustaining power being only 15%–20% of the threshold power. These shots may be contrasted with LSN shots having the grad-B drift towards the X-point, where the threshold power is lower, the sustaining power is about the same, and we obtain about a factor of two in the power hysteresis as opposed to a factor of five or six. In Fig. 2, we plot the value of the electron pressure gradient as a function of P_{SEP} for the time period (500,4100) ms for this shot. The plot represents the evolution of the shot through L, ELMing H, ELM-free H, and L phases as a trajectory in this parameter space. Despite the complexity of these curves, some similarities with Fig. 1 are evident, including the power hysteresis and minimal amount of time the plasma spends at intermediate values of the pressure gradient (25–50 kPa/m). A histogram (Fig. 3) of the data shows a clear bimodal distribution in the pressure gradient, consistent with the structure of the model control curve.

Fig. 2. Control diagram of edge electron pressure gradient versus P_{SEP} as defined in Eq. (1) for shot 92091. Arrows show the evolution of the shot as it transitions through L, ELMing-H, and ELM-free H phases. The two boxes mark the L-H and H-L transition times as determined from the divertor D_α signals. The large power hysteresis is indicated by the disparity in the P_{SEP} values for the initial L and ELM-free H-states. This shot has plasma current 1.0 MA, toroidal field 2.1 T, vertical elongation 1.8, line-averaged density of $2.35 \times 10^{19} \text{ m}^{-3}$ at the forward transition and $4.48 \times 10^{19} \text{ m}^{-3}$ at the back transition.

Fig. 3. Histogram of ∇P values from Fig. 2, showing bimodal distribution.

Figure 4 shows the pressure gradient versus electron temperature at the knee of the pedestal for the shot 92091. (The knee is defined as the point of maximum curvature in the hyperbolic tangent fit to the edge density profile.) In this case, the knee temperature shows little hysteresis, with the plasma entering and exiting H-mode at about the same value. This near constancy of the electron temperature at the forward and reverse transitions has been noted previously [10,11] as has the near constancy of the ion temperature at the forward transition during power scan where the input power changed by a factor of eight [12]. These measurements suggest that the edge temperature may be a key control parameter; however, further investigations show that the edge temperature value at the transitions varies with other plasma conditions, such as the direction of the ion ∇B drift [11].

Fig. 4. Control diagram of edge electron pressure gradient versus the value of the electron temperature at the knee of the hyperbolic tangent fitted T_e profile for the shot of Figs. 2 and 3. Again, the arrows indicate the time evolution of the shot through the different phases. The two boxes mark the forward and back transition times as before. $T_e(L-H) \sim T_e(H-L) \sim 375$ eV.

As a final example, in Fig. 5 we show plasma behavior for a sawtoothing discharge where the power was very near threshold, resulting in multiple transitions between L- and ELM-free H-mode. Figure 6 shows the corresponding ∇P - P_{SEP} diagram for this oscillating state. In this example, the various power terms and their timescales are so closely coupled that, although again substantial (factor of two) hysteresis is seen in the calculated P_{SEP} , the evolution proceeds in a direction opposite to the case shown in Fig. 2. The sawtooth heat pulses are a key portion of the plasma behavior in this case. Unfortunately, we do not have a way of including their effect in P_{SEP} at present. The power hysteresis would be even larger than the quoted factor two with the sawtooth power included.

Fig. 5. Plasma parameters for a shot near the forward transition power threshold, where the plasma undergoes periodic transitions triggered by sawtooth heat pulses. The plasma then back transitions as the density rises. Shown are plasma current and density, injected power (in kW), calculated loss power (W), photodiode signal, and central and edge SXR signals.

Fig. 6. Control diagram of edge electron pressure gradient versus P_{SEP} for multiple state transitions on shot 90139. Arrows show the evolution of the shot as it oscillates between L and ELM-free H phases. Although good power hysteresis is seen, the calculated P_{SEP} increases rapidly at the back transition, counter to our standard picture.

Analysis of other shots does not always reveal power hysteresis; in particular for our low density, low-power threshold studies we have found very little difference in the calculated values for P_{SEP} . This may be due to poor resolution of the specific terms or omission of terms (such as sawtooth heat pulses) that are known to affect the transition power but are poorly characterized. Conversely, there may be no power hysteresis for certain plasma conditions.

4. CONCLUSIONS

The observed power hysteresis is as large as required by ITER in the higher density regime on DIII-D. The parametric evolution of a wide variety of discharges and confinement phases can be represented in a basic way using control diagrams; these can in turn be used for tests of critical parameters and may offer insight to further hidden variables, and the underlying nonlinearities that lead to such novel behavior. We plan to improve our estimates of the various P_{SEP} terms in the future, as well as including analogous ion parameters as control parameters, in a further effort to characterize the forward and backward state transitions on DIII-D.

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