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1. Introduction

The theory of turbulence decorrelation by E×B velocity shear is the leading candidate to explain the changes in turbulence and transport that are seen at the plasma edge at the L to H transition. Based on this, a key question is: What are the conditions or control parameters needed to begin the formation of the E_r shear layer and thus trigger the L to H transition? On the DIII–D tokamak, we are attacking this question both through direct tests of the various theories and by trying to gain insight into the fundamental physics by investigating the control parameters which have a major effect on the power threshold. In this paper we describe results of studies on oscillating discharges where the plasma transitions continuously between L and H states. By following the dynamics of the plasma state through the forward and back transitions, we can represent the evolution of various control parameter candidates as a trajectory in various parametric spaces [1]. The shape of these control curves can illustrate the specific nonlinearities governing the L–H transition problem, and under the proper conditions may be interpreted in the context of various phase-transition based models [2–4]. In particular, the hysteresis exhibited in the various curves may help to clarify causality (what are the critical parameters) and may serve as tests of the models, given sufficient experimental accuracy. At present we are looking at T_e, E_r and ballooning/dia-magnetic parameters as possible control parameter candidates.

2. Hysteresis as a unifying concept

Numerous experimental observations and theoretical models suggest that hysteresis is a property of the H–mode. Comparisons of L–H and H–L transitions in the DIII–D tokamak are being examined for signs of hysteresis with the goal of determining the relationship between the physics controlling the forward and back transitions. On a global level, substantial hysteresis is found in the loss power, defined as $P_{loss} = P_{oh} + P_{aux} – P_{rad(core)} – dW/dt$ [1]. For a wide variety of experimental conditions, the power flow through the separatrix at the back transition P_{HL} is typically 50% or less of that required to produce the forward transition P_{LH}. Furthermore, while P_{LH} increases linearly with B_T, P_{HL} shows little or no scaling with B_T, indicating that the degree of power hysteresis increases with B_T. Similarly, the P_{LH} approximately doubles when B_T is reversed whereas P_{HL} is unaffected by the field reversal. This result implies large power hysteresis in reversed B_T discharges, with P_{LH} being a factor of 4–5 larger than P_{HL}. In contrast, studies of local edge parameters have generally shown that the most successful predictor found for the H–mode state is the edge electron temperature T_e (possibly a proxy for the much less frequently measured T_i) or a temperature gradient. The L–H transition occurs when T_e achieves a critical value and the H–L transition occurs when T_e falls to near its value at the forward transition [1]. Furthermore, as B_T is increased, the values of T_e observed at the forward and back transitions also increase; nevertheless, the near equality of T_e at the forward and back transition is maintained. The observation of power hysteresis at the global level and lack of hysteresis of T_e at the local level appear to be contradictory. However, this contradiction may result from the fact that it is difficult to maintain all parameters identical at the forward and back transitions. Indeed, as transport, collisionality, beta, electric field, etc all evolve self-consistently during a “steady-state” H–mode it is difficult to clarify the role of various parameters in the transition itself. Listed below in Table 1 is a short list of parameters which show (do not show) hysteresis between the forward and back transitions.

Table 1

Parameters exhibiting hysteresis (L-H /H-L)	no hysteresis
density	electron (ion) temperature(?)
loss power	temperature gradient(?)
pressure gradient	electric field(?)
neutral mean free path, collisionality	

One experimental simplification is to study marginal/threshold states, where the plasma is switching back and forth (mode jumping) between states rapidly enough to minimize the evolution of the various parameters. Figure 1 shows such an oscillating state for DIII–D discharge 93545 (LSN, n_e= 3–6$\times10^{13}$ cm^{-3}, I_p=1.37 MA, B_T = 2.1 T with the direction of the ∇B drift towards the X–point). The discharge displays substantial hysteresis in the loss power when the back transitions occur, due to the increasing P_{rad} and dW/dt corrections to the loss power. This situation may be thought of as an extension of the limit cycle concept used previously for dithering H–mode studies [5], although the cycle timescales are substantially different. Oscillation hysteresis [6] will naturally occur in such a system and the form the hysteresis takes is a consequence of the specific differential equations underlying the dynamics. Figure 2 shows a plot of edge temperature versus density for the first few L–H–L cycles. The timescales are such that the plasma systematically exits H–mode at a higher temperature than it enters. The implication is that T_e cannot be the sole control parameter and that T_e at forward and reverse transitions are not always the same.

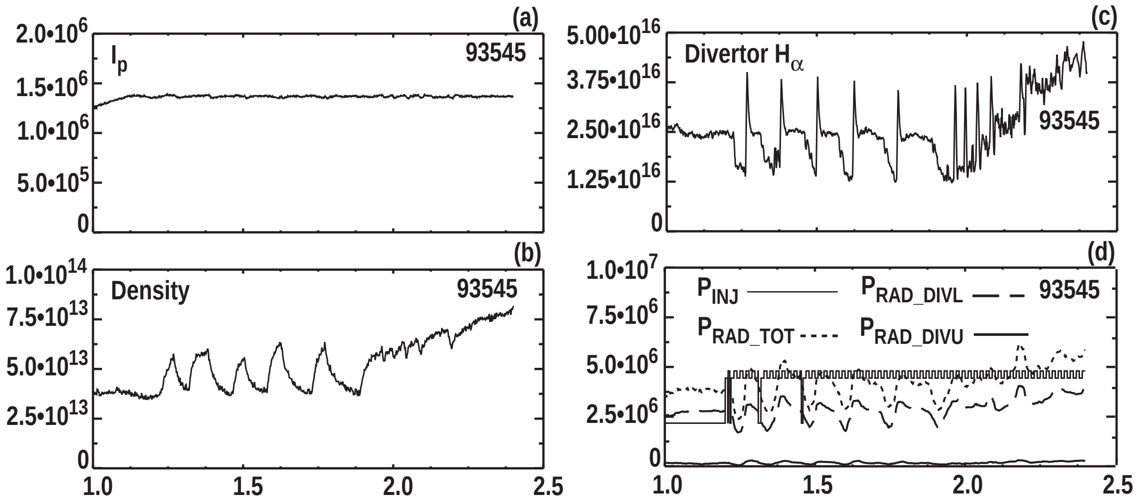

Fig. 1. Plasma parameters for oscillating discharge 93545.

3. Test parameters

Recent 3-D simulations of the Braginskii equations in toroidal geometry [7] have identified two parameters which may play a key role in the edge dynamics: the MHD ballooning stability parameter $\alpha_{MHD} = -q^2R(d\beta/dr)$ and an ion diamagnetic parameter $\alpha_{DI} = v_{DI}(t_0/L_0)$. Where v_0 equals the ion diamagnetic velocity, L_0 is a transverse scale length and t_0 is an ideal ballooning timescale. Although the model does not yet include trapped particles or X–point geometry, it is able to reproduce qualitative features of the edge physics including the L–H transition and density limity. Evaluating these parameters for the DIII–D edge conditions on discharge 93545, at the forward transition α_{MHD} increases while α_{DI} initially decreases, then increases. At the back transition α_{MHD} decreases rapidly. There is an obvious chirality to the shot evolution in (α_{DI}, α_{MHD}) phase space,with the trajectory describing clockwise helices (Fig. 3). While the experimental values of the parameters are comparable to those expected from the model, the evolution of the L–H transition (no particular increase in α_{MHD} prior to the transition and a relatively low α_{DI} at the transition) is inconsistent with the model predictions (higher α_{MHD} and a threshold α_{DI}).

Based on our present theories of the L–H transition, a natural control parameter candidate is the radial electric field. Using CER charge exchange recombination spectroscopy we are able to measure the separate terms of the radial force balance equation needed to deduce the radial electric field in the edge region:

$$E_r = \frac{1}{n_i z_i e}\nabla P_i - v_{\theta i}B_\phi + v_{\phi i}B_\theta \qquad (1)$$

Figure 4 shows the time evolution of the various terms for the first few cycles of the oscillating discharge, calculated for a position which is roughly a cm or so inside of the last closed flux surface. The total field begins to decrease at or near the L–H transition, becoming negative in H–mode. It then begins to increase and becomes positive prior to the back transition, behavior consistent with a control parameter. We also show the calculated E_r gradient in the same region (Fig. 5). Because of the limited time resolution available, the amount of hysteresis (if any) in E_r or its gradient remains unclear at the present time. Further work is needed in this area.

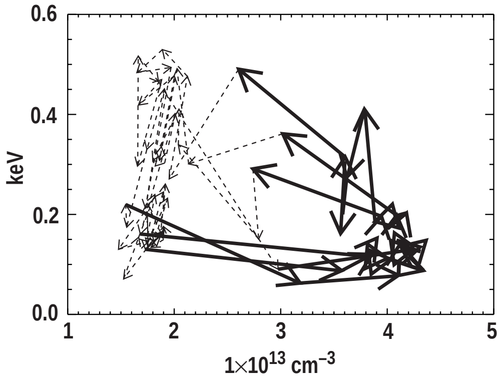

Fig. 2. Parametric plot of edge temperature versus edge density for shot 93545. Time trajectory is indicated by arrow direction. The phase of the shot is indicated by arrow thickness (L–Mode = thin, H–mode=thick).

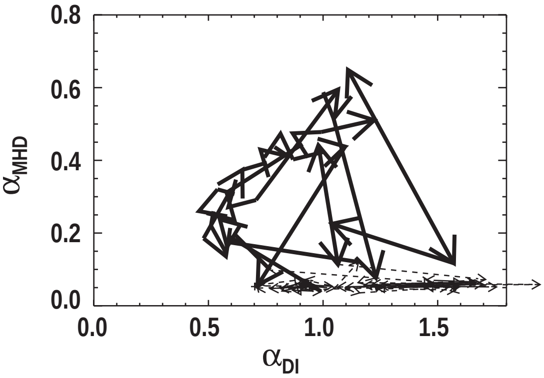

Fig. 3. Parametric plot of α_{MHD} versus α_{DI} for the first few cycles of shot 93545. Time trajectory is indicated by arrow direction. Parameters were evaluated just inside last closed flux surface. Phase is indicated by arrow thickness (L–mode = thin, H–mode = thick).

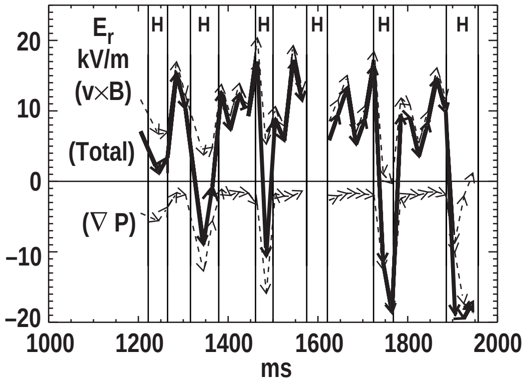

Fig. 4. Evolution of radial electric field terms for shot 93545 during oscillating phase, calculated from CER measurements inside last closed flux surface.

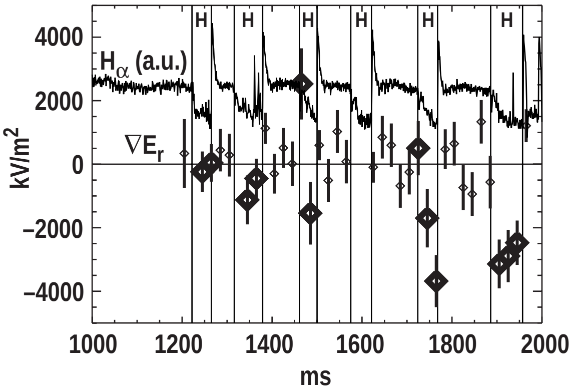

Fig. 5. Evolution of gradient in radial electric field for shot 93545. Also shown is the time trace for the divertor H_α.

4. Conclusions

Hysteresis in various parameters during L–H and H–L transitions is a natural consequence of nonlinearities in the various parametric representations. From this point of view, we have examined several parameters (T_e, E_r, α_{MHD}, α_{DI}) and find that each have features making them solid candidates for control parameters, although the simple picture of a critical temperature is less clear when looked at in a dynamic fashion. The data from oscillation discharges on DIII–D indicates T_e cannot be the single control parameter. In the same view, these studies can provide valuable feedback to model development such as discussed in [7] and serve as fairly stringent constraints to theory. The application of time dependent techniques to tokamak data is presently limited by the discrete sampling rates of the various diagnostics, and would benefit from higher time response. To further understand the nonlinearities, it is intriguing to ask whether the forbidden regions of the phase orbits can be accessed experimentally. One possible technique involves beginning with a marginally stable state and providing progressively stronger perturbations (for example, stronger and stronger ECH heating pulses in the edge) in an attempt to drive the state transiently unstable [8] and study the bifurcation dynamics more closely. Further studies are planned to examine other local parameters which are predicted by various theories to control the transition.

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