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The L- to H-Mode Transition - an Experimental Viewpoint

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The nature of the L- to H-mode transition is re-examined on the basis of the more recent experimental data, especially that obtained from Ohmically-heated plasmas where the transition is generally more gradual. This raises the question whether the transition is better explained as a gradual change in the characteristics of the turbulence at the plasma edge rather than by a sudden bifurcation in the transport process.

I. Introduction

The H-mode of confinement was discovered about 15 years ago by the ASDEX team[1] in an axisymmetric divertor configuration with a double null in the poloidal field and with additional heating by neutral beam injection. The H- or high confinement mode manifests itself by the development of a region just inside the poloidal field separatrix where the transport coefficients are reduced by up to an order of magnitude compared with the L- or low confinement mode, resulting in a pedestal in the plasma pressure and an improvement in global confinement of typically a factor of two. The thickness of this so-called *transport barrier* is about equal to the ion poloidal gyroradius or the width of an ion banana orbit.

The H-mode has since been reproduced in a wide range of different devices with or without divertors and additional heating. The confinement improvement can extend into the plasma core and the improvement in global confinement can reach factors of more than three or four; a clear advantage for achieving thermonuclear ignition in magnetically confined plasma. An understanding of, and an ability to control the transition from L- to H-mode would therefore be of prime importance for the next generation of tokamaks.

II. Control parameters

Since the H-mode is a phenomenon which primarily affects the plasma edge, it is expected that conditions in the plasma edge will play the dominant role in its development. However, in spite of various attempts to determine the controlling parameters, these have not been firmly identified. The collisionality and/or temperature in the edge have been suspected as possible candidates but their role has not been unambiguously confirmed.

Experimentally, the occurrence of the H-mode is promoted by low recycling of neutralised plasma and impurities from the surrounding vacuum vessel walls, by the proximity of a poloidal field separatrix to the last closed magnetic surface, by a low value of the magnetic field and by a high power input. Indeed, plasma heating in addition to Ohmic heating by the plasma current was initially thought to be necessary, and many experimental studies were done to establish the required additional power as a function of other variables. In the early experiments on the power threshold, it was usual for operational reasons to apply powers much in excess of the Ohmic value suddenly. This produced a corresponding rapid increase in the power flux through the plasma edge after a delay corresponding to the energy confinement time and often resulted in a more or less sudden transition to H-mode. Moreover, it was found that the power required to sustain the plasma in H-mode could be reduced substantially below that required to produce it; ie there was hysteresis.

These observations led to the idea that the L- to H-mode transition was due to a bifurcation in the plasma transport at the edge; it could either be high (L-mode) or low (H-mode) but could not take intermediate values. A large amount of the theoretical work which has been done on the H- mode in recent years has been directed towards finding a physical explanation for the supposed bifurcation of the transport[2].

Here, the experimental evidence for a bifurcation will be re-examined in the light of more recent experimental data particularly that from Ohmically heated plasmas, where the transition can be much more gradual[3,4].

III. Hysteresis and bifurcation

In discussing the interpretation of the observed hysteresis in the L- to H-mode transition, it is important to distinguish between the plasma parameters which directly control the transition and those which are employed experimentally to induce it, such as the heating power. The latter only control the edge parameters indirectly and with some time delay. It would indeed be surprising if there was no difference in the power required to produce a transition and that required to sustain it, since the improvement in the energy confinement time will naturally lead to a change in plasma parameters following H-mode onset if the heating power is held constant. Thus the observation of hysteresis in the externally applied power required for L-to H and H- to L-mode transitions is no proof that there is hysteresis in the direct control parameters, whatever they may be.

True hysteresis in the direct control parameters should manifest itself as a sudden transition from L- to H-mode when the external parameters are varied slowly on the time scale required for equilibrium to be attained, so that, in the absence of a bifurcation in the transport processes, a change in the external parameters would produce a reversible change in the plasma.

These conditions are most nearly approached in H-modes induced by Ohmic heating alone. The transition is generally produced by a slow increase in the plasma density, since, for constant plasma current, the Ohmic heating is not under the experimenter's control. What is then observed is a slow transition with a gradual increase in global confinement which is reversible if the controlling parameter, in this case the density, is returned to its initial value. The turbulence in the plasma edge, which is found to be the major cause of particle and energy losses, does not decrease smoothly during this process but becomes more or less intermittent, occuring in bursts lasting for about 0.1ms whose amplitude increases but whose frequency of occurrence decreases as the transition proceeds[3,4]. These bursts are called *type* 111 *ELMs* (edge localised modes) or sometimes *transition ELMs,* since they are invariably found to be present during the kind of slow L- to H-mode transitions described above. Finally, the bursting stops, resulting in a so- called *ELM-free H-mode* in which the confinement reaches its maximum value and the transport barrier is fully established.

Before leaving this section, it is worth noting that recent studies searching for hysteresis in L- to H and H- to L-mode transitions, mainly in Ohmically heated plasmas and those in which the power input is carefully controlled, have found no hysteresis in parameters such as mean plasma density[5], plasma beta (at the ELMy to ELM-free transition)[6,7] or in the electron temperature just inside the separatrix[8]. Such as it is, therefore, the experimental evidence does not support the bifurcation hypothesis.

IV. Edge turbulence characteristics

A further difficulty for the bifurcation hypothesis is to explain the presence of type III ELMs. It is clear that, just before the ELMs disappear, their frequency is such that H-mode characteristics can be almost fully established between the ELM bursts. Since the plasma is then supposed to be in a more stable state, the burst of instability represented by the ELM requires explanation. It does not generally come out naturally from the theory though some attempts have been made in this direction[2].

An alternative explanation is that the L- to H transition occurs simply as the result of a change in the character of the turbulence according to the following sequence of events. In a typical L-mode, the turbulence level is approximately constant and at a high level. There is indeed some evidence that this simple picture is not correct, even in L-mode and that the turbulence has an intermittent character characterised by 'events' which are responsible for most of the transport[9]. As the control parameter is varied and the H-mode is approached, the turbulence resolves into ELMs and then follows the pattern described in the last section.

This description has the merit of including the ELMs as an intrinsic part of the transition process. However, it suggests that this process will not be understood fully until an explanation is found for the turbulence itself, both in L-mode and H-mode. Previous theoretical work in this area[10,11] has some of the characteristics required but has not so far combined the dynamics of L- to H-mode transitions with that of the turbulence, as manifested by the transition ELMs. These models result in a relatively small number of ordinary non-linear differential equations to be integrated simultaneously which display a range of behaviour similar to that observed experimentally. Indeed, it is not difficult to construct equations with the required characteristcs. A completely artificial example in which a single control parameter is varied to simulate the slow transition observed in Ohmically heated plasmas, as described above, is shown in Fig. 1.

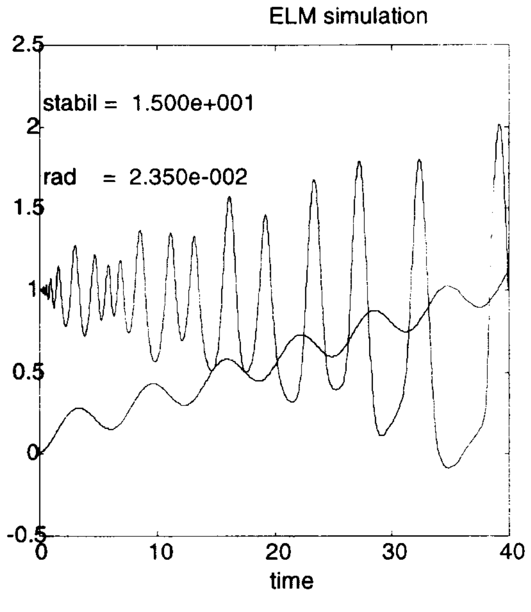

Figure 1. Simulation of transition ELMs using an artificial system of two first order ordinary DEs with a time dependent control parameter, shown as the wavy line.

It can be noted that complex structures, also exhibiting intermittency, are observed in the turbulent boundary layers of ordinary fluids too, and that the mathematical procedures for dealing with such cases are quite well developed[12].

V. Conclusions

The experimental data on slow L- to H-mode transitions provide no firm evidence for a bifurcation in the transport processes at the plasma boundary or for hysteresis in L to H compared with H to L transitions when referred to internal plasma parameters as opposed to external control parameters such as heating power. The main characteristic of such transitions is a reversible change in the edge turbulence, which becomes progressively more intermittent as the H-mode is approached (transition or type III ELMs). Models of the process need to explain this behaviour rather than focus on the sudden transitions which sometimes occur when the plasma parameters are rapidly changed by a step change in additional heating.

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