

# INVESTIGATION OF PLASMA LOSS DYNAMICS DURING TRANSITION FROM L-MODE TO H-MODE IN OHMICALLY HEATED TOKAMAK PLASMAS

J. Hugill, D.S. Broomhead and M. Barratt

*UMIST, PO Box88, Manchester, M60 1QD, UK*

## Abstract

In ohmically heated plasmas in COMPASS-D and other tokamaks, the L- to H-mode transition occurs gradually as the plasma density is increased, accompanied by the appearance of type III or transition ELMs, manifested by spikes on the Balmer-alpha line radiation of neutral hydrogen lasting typically a few 100  $\mu\text{s}$ , due to outflow of ionised material from the confinement zone. The size and spacing of the ELMs increase with density until finally an 'ELM-free' H-mode is obtained. Various theoretical models have been developed to explain the L- to H-mode transition, invoking the stabilisation of the turbulence responsible for particle and energy transport across the edge of the confinement zone. In their simplest form, such models can be represented by a set of nonlinear first-order differential equations for the time variation of global parameters such as velocity shear, turbulence levels and particle transport. Here we attempt to derive the dynamics of the process from the time behaviour of one of the parameters: the Balmer-alpha signal. Several recent papers have indicated this method can be successful, where the structure of the underlying process is not too complicated. The method is illustrated by application to the COMPASS-D data.

## 1. Introduction

Since its discovery by the ASDEX group in 1982 [1], the H- or high confinement mode of tokamak operation has received much attention and, although not without problems, is favoured for the next generation of tokamak devices such as ITER. Indeed, in separatrix-bounded plasmas with strong additional heating, it is not clear that it can be avoided.

In early experiments, where additional heating much in excess of the Ohmic dissipation was applied suddenly, the H-mode manifested itself by an equally sudden change in confinement accompanied by the formation of a 'pedestal' in the plasma pressure profile at the edge of the confinement zone. It appeared that the confinement exhibited bifurcation into two distinct modes: the L-mode, with a high level of broadband turbulence in the edge region and correspondingly high coefficients of heat and particle transport, and the H-mode, in which the turbulence level and transport were reduced by an order of magnitude within a few cm of the edge. Detailed measurements of the turbulence showed that it was suppressed in a very short time scale; of order 100  $\mu\text{s}$  [2]. Several theoretical models focussed on trying to explain the bifurcation by linking transport models with a mechanism for suppression of the turbulence by shear in the  $E \times B$  drift velocity [3-5].

Later work showed that the H-mode could also be produced by Ohmic heating, typically by increasing the electron density in low field, high current, separatrix-bounded plasmas [6].

In this case the transition from L- to H-mode is gradual and is accompanied by intermittent bursts of turbulence and plasma loss lasting for a few 100  $\mu\text{s}$  called type III or ‘transition’ ELMs, whose amplitude and spacing increases with density (similar to the response with increasing power in the case of additionally heated plasmas.) Ohmically heated plasmas have the advantage that the parameters of the discharge can be changed on a time scale long compared with the particle and energy confinement times, so that the plasma remains in a quasi-steady-state. In this case no bifurcation or hysteresis is observed and the process appears to be reversible, at least until the ELM-free H-mode is achieved and density control is lost [7]. These experiments indicate that the transition ELMs are a fundamental part of the transition process and that no theoretical model is complete unless it can explain them. At an empirical level, the ELMs can be regarded as due to intermittent turbulence localised in the boundary layer which show some similarities with boundary layer processes in ordinary fluids [8].

Theoretical models of the transition based on the bifurcation hypothesis can sometimes be represented by a set of first order, nonlinear differential equations for the time variation of parameters such as velocity shear, turbulence levels and particle transport. These may have a similar structure to the predator-prey models used to study animal populations and can give rise to oscillatory and intermittent behaviour similar to that observed experimentally. However, there has been no systematic attempt to model the ELMs as part of an overall model of the L- to H-mode transition. Here we adopt an alternative approach: to uncover information on the underlying dynamics by an analysis of the experimental data, as represented by a time series of measurements of one experimental parameter. Previous studies of this kind have shown that this method can be fruitful when the structure of the controlling equations is not too complicated, i.e. the dimensionality is not too high [9-12].

## 2. Methodology

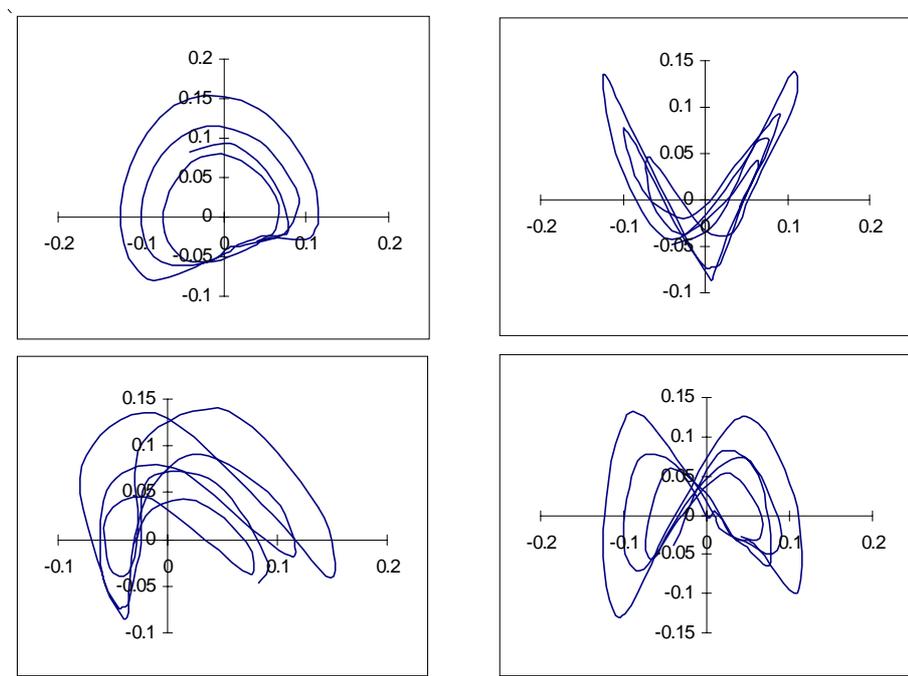
Since the objective of the analysis is to find the simplest set of equations which will describe the experimental observations, we look first at measurements which describe the global behaviour of the tokamak boundary, rather than measurements of local parameters. Among the available measurements, that of the Balmer-alpha radiation from neutral hydrogen seems quite appropriate. It represents the rate of reionisation of neutral particles which have escaped as ions and recycled from the walls of the vacuum vessel or from the region of intersection of the separatrix magnetic surface with the target, in case of tokamaks with a divertor. As such it closely follows the ion loss rate from the confinement zone (hence also the level of turbulence in the boundary) albeit with a time delay corresponding to the transit time of ions in the scrape-off-layer and the reionisation time of the recycling neutrals. In the results to be analysed this should amount to no more than about 0.1ms, comparable with the duration of an ELM. This means that there will be some smoothing of the underlying dynamics but this should not be too serious when the spacing of the ELMs is much larger than the smoothing time, i.e. when the ELMs are sufficiently well developed to be distinguishable in the Balmer-alpha signal.

The first stage of the analysis is to form a ‘trajectory matrix’,  $X$  from the time series, in which each row of  $X$  consists of a ‘window’ of a small number,  $n$  of consecutive data points,

typically covering a time period of the same order as that of significant fluctuations in the signal; in this case the ELM period. For example, in a time series of 400 data points separated by  $100 \mu\text{s}$ , we have taken  $n = 7$ , forming a  $393 \times 7$  matrix. The row vectors can be considered as points in an  $n$ -dimensional phase space with an arbitrary basis. Singular value decomposition of  $X$ , s.t.  $X = S \Sigma C^T$  (where  $\Sigma$  is an  $n \times n$  diagonal matrix of singular values) provides an orthonormal basis for the phase space (the columns of  $C$ ) and a new trajectory matrix,  $S$  with orthogonal columns. Taking the first  $m$  columns of  $S$  to represent the first order dynamics for some  $m < n$ , we can now plot the trajectory as a sequence of points (rows of the truncated trajectory matrix) in  $m$ -dimensional space. Projections of such trajectories are shown in figure 1. Their form gives a first indication of the underlying dynamics and suggests ways of proceeding further [11,12].

### 3. Results

We have examined data from Ohmically heated plasmas in the COMPASS-D tokamak [6] in which the L- to H-mode transition took place over a time of typically 60-100 ms compared with an energy confinement time of less than 15 ms. Time series analysis has focussed initially on periods where the turbulence appeared to be in a quasi-stationary state, as for example between 130-170 ms in shot 9532. Figure 1 shows various projections of the trajectory for a window of 7 data points giving singular values of 0.44 0.38 0.24 0.23 0.18 0.15 0.13.



**Fig. 1.** Projections of the normalised trajectory in 7-D phase space for H-alpha data from COMPASS-D, shot 9532,  $t = 130 - 134$  ms during L- to H-mode transition: top left,  $S(1) \text{ v } S(2)$ ; top right,  $S(1) \text{ v } S(3)$ ; bottom left,  $S(2) \text{ v } S(3)$ ; bottom right,  $S(1) \text{ v } S(4)$ .

At this simple level, the analysis shows that the trajectory has a quite complicated harmonic structure - it is not confined to a linear subspace - but it is quite coherent, showing

evidence of recurrence within the state space. There is a section of the trajectory corresponding to low H-alpha emission where the system evolves rather slowly. It seems that, here, it is passing close to a fixed point corresponding to the ELM-free H-mode. The observed dynamics can then be interpreted as repeated returns to the neighbourhood of an unstable fixed point, suggesting the existence of a homoclinic orbit.

There is a large literature dealing with the dynamical consequences of homoclinic orbits. It is known, for example, that their presence can indicate chaotic attractors and the existence of extremely complex patterns of bifurcations in nearby parameter space. We speculate that this type of orbit is involved in the change of stability at the L- to H-mode transition; a speculation encouraged by evidence for similar behaviour in the boundary layer of ordinary, flowing fluids [8].

#### 4. Conclusions

Initial analysis of the data from slow L- to H-mode transitions in Ohmically heated plasmas in COMPASS-D suggests that the dynamics is better represented by a homoclinic orbit, with the ELM-free H-mode representing an unstable fixed point, rather than a transition between two separate states. In this model the transition (type III) ELMs are naturally represented by orbits around the fixed point in phase space. The time resolution and accuracy of the H-alpha data used for the present study is not good enough to study the details of the dynamics near the fixed point [12]. Future work will make use of spatially averaged data from Mirnov coils with much better time resolution to address this issue. Such data will also have the benefit of representing the underlying turbulence more closely.

#### Acknowledgements

We gratefully acknowledge the assistance of Steve Fielding at UKAEA Fusion in making available data from the COMPASS -D experiment. One of us (MB) is supported by a studentship on EPSRC research grant GR/L48706.

#### References

- [1] The ASDEX team: Nucl. Fus. **29**, 1959 (1989)
- [2] H. Matsumoto, K.H. Burrell, T.N. Carlstrom et al.: Pl. Phys. Control. Fus. **34**, 615 (1992)
- [3] S-I. Itoh, K Itoh and A Fukuyama: Nucl. Fus. **33**, 1445 (1993)
- [4] P.H. Diamond, Y-M. Liang, B.A. Carreras and P.W. Terry: Phys. Rev. Lett. **72**, 2565 (1994)
- [5] H. Sugama and W. Horton: Plasma Phys. Control. Fus. **37**, 345 (1995)
- [6] P.G. Carolan, S.J. Fielding, S. Gerasimov et al.: Pl. Phys. Control. Fus. **36**, A111 (1994)
- [7] J. Hugill: Brazilian Journ. of Phys. **27**, 407 (1997)
- [8] N. Aubry, P. Holmes, J.L. Lumley and E. Stone: J. Fluid Mech. **192**, 115 (1988)
- [9] J.D. Farmer and J.J. Sidorowich: Phys. Rev. Lett. **59**, 845 (1987)
- [10] J.J. Healey, D.S. Broomhead, K.A. Cliffe et al.: Physica D **48**, 322 (1991)
- [11] G. Rowlands and J.C. Sprott: Physica D **58**, 251 (1992)
- [12] D.S. Broomhead and R. Jones: Proc. R. Soc. Lond. A **423**, 103 (1989)