THE EVOLUTION OF FEEDBACK CONTROL IN TOKAMAKS

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Abstract

We briefly introduce the tokamak to identify the parameters which are or will be under feedback control. A short historical overview of tokamak equilibrium control is presented to illustrate the various evolutionary stages of feedback control. During the last few years, the flexibility of plasma heating systems has led to an improved ability to modify plasma profiles with significant impact on the plasma performance of tokamaks and an example is presented. Features of feedback control for the proposed ITER tokamak which are not yet on a sure footing are mentioned.

INTRODUCTION TO THE TOKAMAK

A tokamak consists of a circular (toroidal) magnetic field typically 1-6 Tesla with a major radius 0.6-3 metres. An electric field induced parallel to this field breaks down low pressure gas, like any gas discharge, and the magnetic field guides an electric current in the ionised gas, parallel to the field. The sum of the toroidal field and the self-generated (poloidal) field creates a helical set of field lines which form nested surfaces. The plasma current tries to expand due to the magnetic energy and the plasma pressure but a vertical magnetic field can be used to create a force balance, or equilibrium. The plasma current is maintained by transformer action for 0.1 to 100's of seconds.

The plasma current heats the plasma electrically, due to the plasma resistivity. The latter decreases with increasing temperature, unlike a solid, and the temperature increases to a stationary value. To obtain still higher temperatures, additional power must be added.

The plasma parameters vary according to their depth in the plasma, being hotter and denser in the core of the tokamak discharge. The resulting spatial distribution, or profile, is determined by the natural heat conduction properties of the plasma, together with the spatial distribution of the source power, according to simple diffusion or transport equations. Particles obey similar transport equations.

This paper discussed the evolution of our ability to control the plasma we obtain experimentally. In the space allotted it cannot claim to be a review.

EQUILIBRIUM CONTROL IN 1970'S

The first tokamaks operating on the principles described were controlled by guessing the required equilibrium fields and pre-programming their evolution using sequential discharging of capacitor banks. This was adequate for generating impressive scientific results which led to an explosion of the number of such devices operating over the world.

However, it was difficult to obtain a well-positioned plasma when the plasma parameters were different from those expected, and the plasma tended to hit the walls of the surrounding vacuum vessel. The vertical equilibrium field was therefore put under feedback control deriving the position from magnetic sensors which estimated the centre of the plasma current.

As tokamaks became larger and the pulses lengthened, the variation of the plasma current became a nuisance and was also put under feedback control. Pulse lengths increased to many 10's of milliseconds, allowing experiments to change the plasma density during the pulse, opening the door to new scientific results. Measuring the density with an interferometer allowed it to be brought under feedback control as well.

During this period, the problems were electro-technical and the modelling of the tokamak was primitive, but sufficient to generate working feedback loops.

SHAPE CONTROL IN 1980'S

It was realised from an improved understanding of tokamak performance that the plasma current should be increased as much as possible. One method of increasing the current-carrying capacity of a tokamak is to break away from the circular cross section. The other method is to increase the size of the device or increase the toroidal magnetic field.

Shaping the tokamak plasma brought two new challenges. Firstly, there was no longer a relatively direct effect of each actuator – the feedback variables became coupled – and a better model and better control logic were needed. Secondly, it was necessary to develop estimates of the plasma shape to provide a target for the feedback loops. These problems were addressed on several tokamaks and adequate solutions were obtained to advance the scientific research.

VERTICAL CONTROL IN 1980'S

When the plasma is not only shaped but also elongated (taller than wider), then new physics appears. Elongating a plasma can be considered as two coil currents pulling at a circular plasma, from above and below, like a pair of magnets with a ball between them. This view of the force balance shows that the plasma is likely to fly off vertically one way or the other if it leaves an exact equilibrium position – the plasma has become positionally unstable.

Unstable systems cannot be pre-programmed and positional feedback is necessary for closed loop stability, not just for precision. There are now limits on power supply bandwidth and measurement bandwidth. Simple

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models were developed to gain insight into this problem and to demonstrate a solution – which worked well.

As the elongation is increased further, a simple proportional gain feedback no longer provides a stable closed loop and derivative feedback is required. Simple modelling of vertical position control explained this and allowed the range of stabilised plasmas to be extended.

Figures 1 and 2 illustrate plasma shape control.

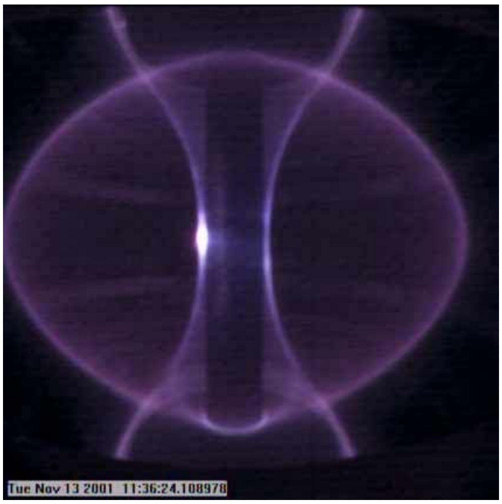

Figure 1: MAST spherical tokamak, showing the outside of the plasma and the magnetic configuration.

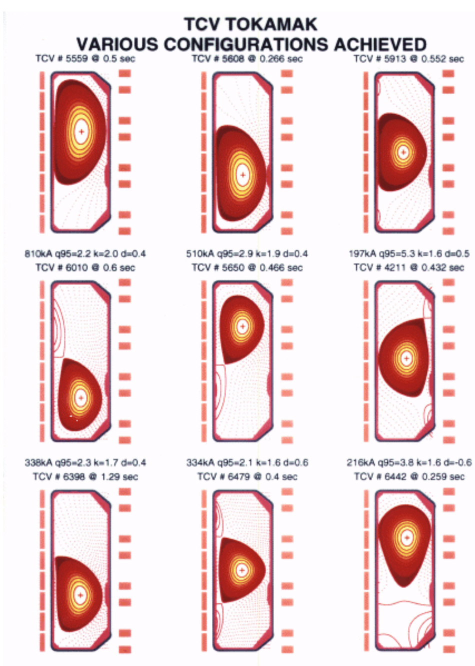

Figure 2: TCV tokamak, showing the tremendous range of achieved magnetic configurations.

EQUILIBRIUM CONTROL

As experiments became more precise, the demands on plasma control increased. In addition, new challenges to be posed by the ITER project were on the horizon.

In the 1990's effort was dedicated to improving the modelling of plasma current, shape and position control, since it was realised that we could no longer manually tune an increasing number of control knobs. Models used for designing ITER feedback control loops were improved and validated against operating experiments. These models explicitly defined the coupling between the different control inputs and consequently solved their decoupling.

Given an adequate numerical model of the tokamak, controllers can be designed using advanced algebraic methods, such as the $H\infty$ approach. This was demonstrated on TCV, but has not yet delivered the improvements to justify the complexity of its implementation.

Methods of refining the feedback control to respect other criteria, minimising total power excursions or minimising heating of the superconducting coils, were developed.

During this period more attention was given to reconstructing the plasma shape in real-time, requiring faster processing, but using existing algorithms. Alternative methods of approximate mapping using neural networks or function parameterisation were also investigated. The emphasis was on precision.

EQUILIBRIUM CONTROL ISSUES

The major outstanding challenges in equilibrium control are linked to nonlinear phenomena, dominated by actuator saturation and the evolution of the plasma during a pulse, rather than any nonlinear behaviour of the tokamak itself.

Saturation of the coil currents leads to a loss of control of the shape. However, the integrating nature of the tokamak, converting actuator volts into magnetic flux, means that current saturation takes time, can be foreseen and therefore avoided. It becomes a problem of changing the control goals during the pulse. Saturation of the coil voltages occurs instantaneously, reacting to a large-scale disturbance for example, and is discussed in detail in a companion paper.

Changing the control targets during a pulse has only become realistic since tokamak control was implemented in digital processors. Several methods of embedding knowledge into such an adaptive approach are being tested, and results are extremely encouraging. This will certainly be an area of intensive research in the near future.

PROFILE CONTROL

In early tokamak experiments, additional heating power was provided by injecting a maximum amount of power using several different methods, using particles or RF waves. The methods were not very precise but the major results were a global increase of the plasma temperature.

More recently, methods have been developed which allow a high power density to be accurately located in the plasma, typified by the multi-beam ECH launching system in TCV, Fig. 3.

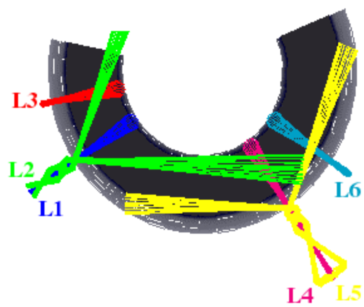

Figure 3: Top view of the TCV electron cyclotron wave launching structure, illustrating the degree of flexibility

The result of this new precision is that instead of leaving the plasma to solve the diffusion equations to establish the radial profile of the plasma current, we can now impose it. Over the last few years, different experiments have demonstrated that by imposing a non-natural profile of the plasma current, the transport of energy within the plasma can be drastically reduced, to the extent of referring to this as an "Internal Transport Barrier". Figure 4 illustrates the change between natural and modified current profiles.

This enhancement to the plasma performance has a cost, since the additional power is expensive. Time will tell whether the tokamak reactor is optimised using this degree of tailoring.

CONTROLLING OR MODIFYING?

In spite of the impressive achievements, the current profile is not yet under full feedback control. Two difficulties dominate this challenge. Firstly, there is the difficulty of measuring the current profile itself, which requires diagnostic information which is readily available. Secondly, the actuators are not as flexible enough for closed loop control. For these two reasons, most work today is performed with careful model-based pre-programming.

On the other hand, if we ignore controlling the current profile itself, but simply want to control the position of an observed transport barrier, then things are more positive. The information on the transport barrier is directly available from existing standard diagnostics and controlling this in real-time is already the subject of experiments on the JET tokamak.

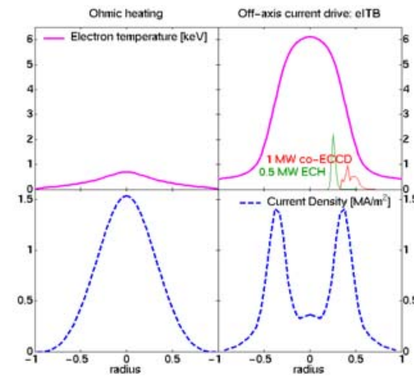

Figure 4: Left – a normal profile of temperature and plasma current. Right – a modified profile, showing the change in the current profile and the presence of an Internal Transport Barrier in the temperature profile.

BURN CONTROL

The aim of the future ITER tokamak is to reach a burning plasma and control it for 100's of seconds. This will introduce new physics since the heating power is no longer determined by the experimentalist, but is generated by the alpha-particles born in the fusion reactions. Controlling the burn, to provide a constant power output, requires controlling the plasma density, or fuel mix, or the temperature, or the losses. The plasma density evolves more slowly than the temperature, making such control sluggish with a characteristic timescale of 10's of seconds. The same is the case for the fuel mix. Increasing the radiation losses by injecting heavy impurities is the method of abnormally terminating a discharge, but is not a control method. Changing the heating power is only a feedback method if there is still power required, but is the ideal case. The difficulty of burn control will depend sensitively on the physics of burning plasmas, one of the goals of the ITER project.

OUTLOOK

Our experience with feedback control of tokamaks is still increasing, giving us confidence that all the ITER control challenges can be met. Issues which have been modelled, but not yet demonstrated experimentally are:

- Handling voltage saturation
- Minimising the total power demand
- Minimising the self-heating of the superconducting magnets.