Real Time Control of EC Heating & Current Drive Systems on TCV

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Abstract. The ability to control, in real time, the electron cyclotron heating & current drive systems for the control of MHD instabilities is particularly important for large tokamaks operating at high performance. Several algorithms have been developed and tested on TCV to explore possible control techniques, first in simple experiments to control the plasma current and elongation and subsequently in experiments to control the sawtooth instability and profile parameters. A summary of these experiments are presented in this paper together with the application of the break-in-slope technique as a possible real time calculation of the location of EC deposition.

1. Introduction

TCV uses a multi megawatt electron cyclotron system for plasma heating, generating current and control of instabilities. It has been developed to allow the EC launcher injection angles and injected powers to be actuated in real time and experiments have been carried out demonstrating the use of these actuators to control the plasma shape, profiles and plasma current as well as the sawtooth instability. The ability to use real time EC launchers to control MHD instabilities such as neoclassical tearing modes and sawteeth is particularly important as they will be used for MHD control in ITER. A controller was developed for TCV to tailor the sawtooth period to a pre-determined, time-dependent value, relying on real time detection of the sawtooth crash in soft X-ray signals and adjusting the EC launcher angle to tailor the current profile in the vicinity of the q=1 surface. Experiments were carried out which demonstrated the success of this controller to obtain and maintain sawteeth at the requested period. Techniques for profile control were also investigated, including real time acquisition and spline fitting of soft X-ray channels to generate profile parameters and feedback control of the magnitude of the peak in the profile was demonstrated by adjusting the EC launcher angle. In addition methods of determining the deposition location of the EC beam in the plasma are being investigated, which do not rely upon CPU intensive ray tracing calculations.

1.1. The TCV EC systems

TCV (major radius = 0.88 m, max toroidal field = 1.5 T, max current = 1 MA) has a flexible EC heating and current drive system, providing up to 4.5MW of injected power [1]. The second (X2 – 3MW at 82.6GHz) and third harmonic (X3 – 1.5MW at 118GHz) subsystems both allow real time control of the injection angles and powers. The X2 subsystem consists of 6 x 0.5 MW gyrotrons with independent waveguides and launcher assemblies, providing real time control of the 6 injection angles as well as the injected power of each cluster of 3 gyrotrons (which have common power supplies).

2. Real time control applications and algorithms

2.1. Real time plasma current and elongation control using EC actuators

Following previous experiments to maximise the X3 absorption in the plasma [2], X2 EC power and launcher actuators were used in experiments to control the plasma current and elongation in real time [3]. In fully non-inductive plasmas with the plasma current driven entirely by ECCD and the Ohmic coil set to zero volts, a proportional-integral feedback controller was implemented, generating an error signal from the plasma current measurement and actuating the gyrotron cathode voltage to change the injected EC current and therefore control the plasma current. This controller was able to actuate up to 30kA out of a total of 160kA of plasma current and was able to track step changes in the target plasma current reference signal.

A simple elongation controller was also implemented which used a linear combination of the poloidal flux on a fixed, pre-determined boundary at the nominal plasma edge to calculate the elongation in real time. Off-axis heating with the EC system leads to a change in the overall plasma current profile and in a constant (quadrapole) shaping field this leads to a change in the plasma elongation. The real time elongation measurement was compared to a reference signal to generate the error and an analogue PI controller used to actuate the EC power, thereby controlling the elongation. Constant and step target reference elongations were tested successfully.

Further details on these experiments can be found in reference [3].

2.2. Real time feedback control of the sawtooth instability

The sawtooth instability occurs in the plasma core when the plasma current is large enough for a *q*=1 surface to exist within the plasma. Large, long period sawteeth, can induce secondary instability, known as a neoclassical tearing modes (NTM) which degrade the plasma confinement and may also cause a disruption – a rapid termination of the plasma discharge [4,5]. Sawteeth are also known to remove impurities from the plasma core, which is important for burning plasmas as a build-up of the helium ash may occur in the core, reducing the core reaction rate. For these reasons, it may be necessary to have some control over the sawtooth instability.

By driving current in the region of the *q*=1 surface, sawteeth may be destabilised/stabilised as necessary [6]. ECRH is a highly localised heating system that can modify the local resistivity and thus the local current profile. ECCD can also be used to directly inject local current. An actuator to modify the sawtooth period [7] is therefore available.

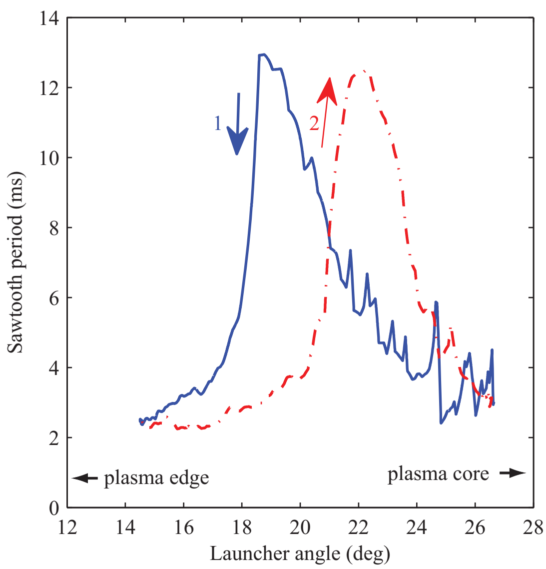

Figure 1. Sweeping EC deposition across the q=1 surface, from the plasma core to the edge (1) and then returning to the core (2). The peak in the sawtooth period shifts to larger angle on the return sweep, due to the redistribution of plasma current as the EC beam heats off-axis which shrinks the q=1 surface.

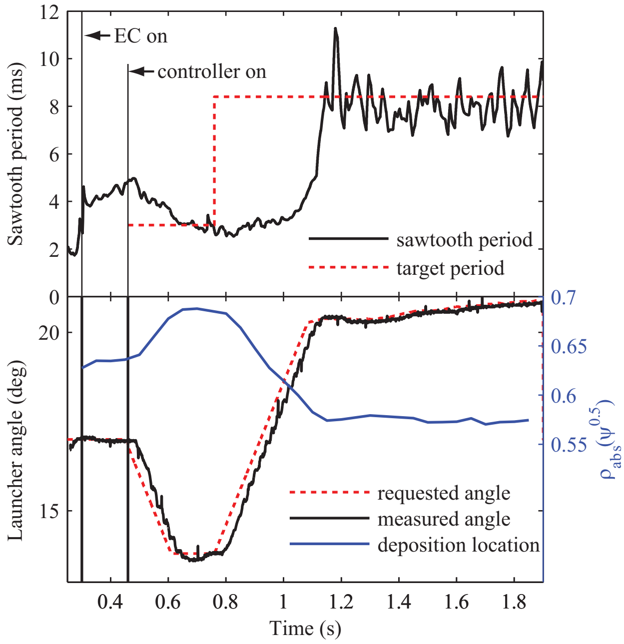

Figure 2. Real time, closed loop control of the sawtooth period for shot 35833. The controller moves the launcher to successfully obtain and track the target.

By sweeping the ECCD deposition across the *q*=1 surface in feedforward sweeps of the launcher, plots of the launcher angle versus sawtooth period were obtained (Figure 1). These experiments showed the sawtooth period varies rapidly with launcher angle only in a very localised region, consistent with being near the *q*=1 surface [8]. Away from this region, there is very little change in the sawtooth period. The direction of the EC beam sweep was found to change the position of the peak in the sawtooth period. This is due to the change in the global plasma current profile and therefore movement of the *q*=1 surface [9]. For example, sustained off-axis EC deposition broadens the temperature profile, shrinking the *q*=1 surface within a global current redistribution time.

The control aim is to generate sawteeth of a pre-determined period (with the accessible range given by Figure 1). In order to ensure the controller is stable both when large and small sawteeth are requested, a gain-scheduling controller was designed which moves the launcher at an either fast or slow speed. A proportional-integral controller was also tested, but was found to require careful selection of the controller gains for each target sawtooth period requested due to the non-linearity of the plasma response.

The gain scheduling controller was successfully able to track a range of target sawtooth periods, including step references as shown in Figure 2. Work is now underway to develop more advanced control algorithms using multiple diagnostics and multiple launchers. A method of maximising the sawtooth period will also be investigated.

2.3. Real time profile control

Using the high resolution 64 channel soft X-ray diagnostic (DMPX [10] – see Figure 4a), an algorithm was developed to generate a spline fit of the X-ray emission profile in real time. The signals are calibrated and fitted with a cubic spline (in total a matrix multiplication on a pre-defined grid). From the fit, several parameters of the profile may be calculated, such as the maximum, width, gradients etc. In these experiments, the maximum in the profile was calculated and used to build a peak-in-

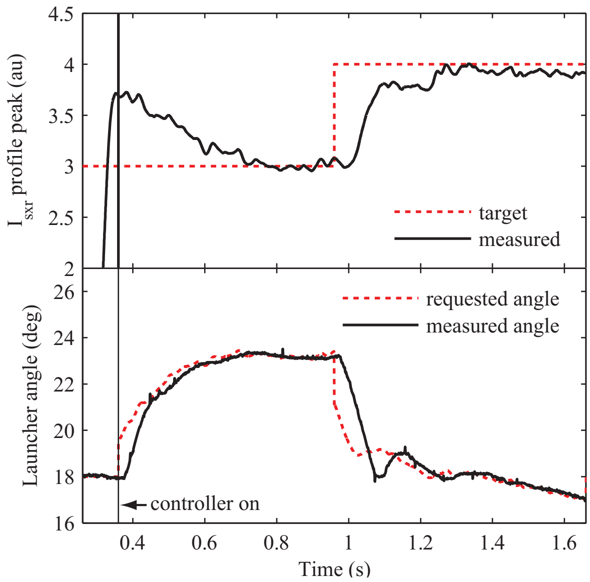

Figure 3. Real time peak-in-profile control for shot 35857. The controller is successfully able to track the target signal by actuating the EC launcher angles to provide central or off-axis heating.

profile controller (ie controlling the maxima in the profile) by controlling the EC launcher injection angle. The controller was successful at tracking a step reference with only small steady-state error (Figure 3). In a separate experiment, a disturbance was artificially introduced by reducing the gyrotron power. The controller successfully compensated for the decrease in X-ray profile peak by moving the launcher towards the centre. Future experiments will demonstrate control of both the profile peak and shape, using not only the ECRH launcher angles but also the ECRH power.

2.4. Determining the location of the EC wave deposition

A significant problem in the use of feedback with EC systems is the ability to determine the location of the EC absorption in the plasma in real time. Typically this is done using offline ray tracing codes which do not yet have the capability to run with sufficient accuracy in real time. Alternatives include inducing a modulation in the EC beam power and observing the plasma response using Fourier transform or singular value decomposition methods. In addition, a break-in-slope [11,12] method has recently been explored and applied to TCV. In this method, a square modulation is induced in the gyrotron power and the response is observed across each channel of a multi-chord soft X-ray diagnostic. At each time the EC beam powers-up or powers-down, a linear fit of the line integrated X-ray intensity is performed (as shown for 3 channels in Figure 4b). The difference in the gradient of the fitted lines (ie the second derivative) produces the break-in-slope parameter. The maxima in this parameter across all of the soft X-ray lines of sight provides the line of sight closest to the deposition region.

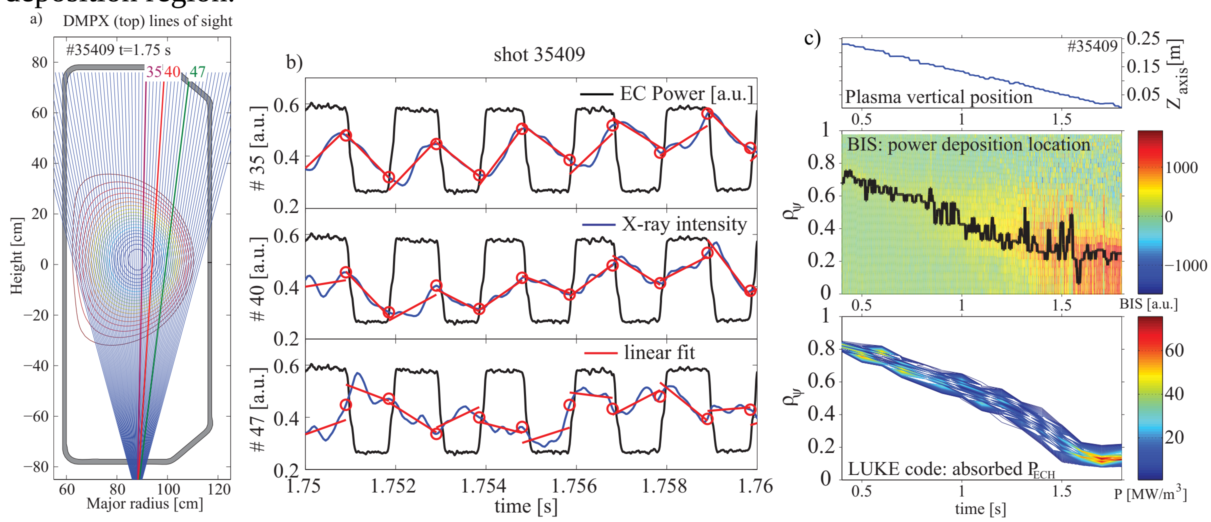

Figure 4: a) Lines of sight of the TCV soft X-ray diagnostic (DMPX). b) An example of the break-in-slope method applied to 3 (filtered & normalised) soft X-ray channels. The break-in-slope is calculated as the difference in the gradient of the linear fits (in this case at each EC beam power step-up.) The soft X-ray channel giving the largest break-in-slope is closest to the EC deposition. c) The break-in-slope was calculated for a plasma vertical position sweep experiment with the EC launcher held at fixed position. The EC deposition became more centralised (moved to lower ρ) and compared well with LUKE calculations of the EC deposition.

Figure 4c shows a plasma vertical position sweep with the EC launcher held at fixed position. The break-in-slope was calculated across all the channels and plotted against normalised radius (note: the ρ is taken as the flux surface that is tangential to the soft X-ray channel line of sight.) As expected the EC deposition moved from off-axis to become more centralised and is in good agreement with the deposition as calculated using the ray tracing – Fokker-Plank solver LUKE [13]. The break-in-slope procedure is now being optimised and developed to run in real time control algorithms.

3. Summary

EC is a powerful tool for real time control of instabilities. Recent experiments on TCV have provided several demonstrations of real time control of the plasma current, shape, sawtooth instability and profile using the EC power and launcher actuators. Controlling the sawtooth instability in particular has demonstrated some of the control techniques involving mechanical launcher systems that will be required for ITER and beyond.

Techniques and algorithms are now being developed for the control of neoclassical tearing modes, shape, internal transport barriers and others.

4. Acknowledgements

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5. References

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