Real time plasma current and elongation control using ECRH actuators

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Experiments have been carried out on TCV using Electron Cyclotron Resonance Heating (ECRH) actuators to control the plasma current and elongation in real time. In fully non-inductive plasmas, the plasma current may be driven entirely by ECCD on TCV. By replacing the Ohmic coils with the gyrotron power supplies, we were able to control the plasma current in real time.

In tokamak plasmas, the elongation is usually controlled by the quadrupole magnetic field from the poloidal field coils. Applying off-axis ECRH, the current profile is flattened reducing the plasma internal inductance, and at constant quadrupole field, the plasma elongates ($\kappa \sim 2.4$) [1]. This paper reports on experiments to control the plasma elongation using a real time elongation observer and the ECRH power actuator to control the current profile. As the plasma elongates, the ECRH deposition becomes more central. Therefore a deposition tracking control was developed which tracked the ECRH deposition at constant ρ by controlling the ECRH launcher mirror position.

Introduction

ECRH systems are required for heating, current drive and for suppressing MHD activity in tokamaks (eg NTMs and sawteeth). This will require the ability to control the ECRH launcher mirror angles and ECRH power in real time. Therefore experiments have been carried out on TCV with the aim of demonstrating control of ECRH systems.

TCV has a highly flexible ECRH system consisting of 6 X2 gyrotrons providing up to 3MW of power and 3 X3 gyrotrons providing a further 1.5MW. There are 3 independent power supplies, each providing power control of 3 gyrotrons in real time. Each gyrotron is connected to the vacuum vessel by evacuated waveguides and terminated by a launcher system consisting of several mirrors, providing poloidal and toroidal control of the ECRH beam orientation. The poloidal angle may be controlled in real time during a plasma discharge, however the toroidal angle is currently only adjustable inter-shot.

The TCV real time controller (Figure 1) is based upon matrix multiplication of signals. For example, the plasma current control: The A matrix calculates the observer – the plasma
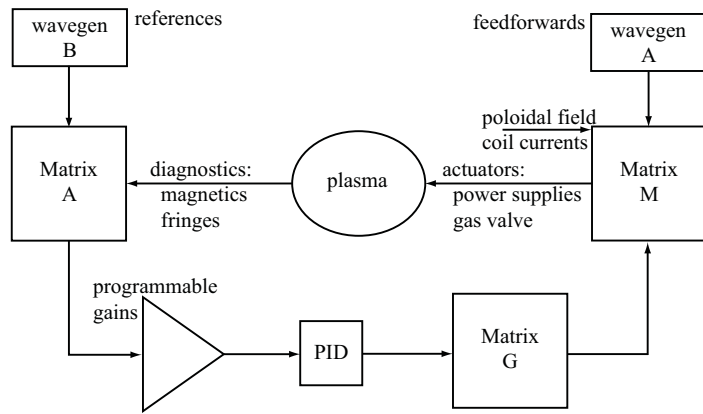
Figure 1. Diagram of the TCV real time controller which is based upon linear matrix operations on signals and a PID controller. Matrix coefficients may be changed at pre-set intervals throughout the shot.

current - by summing signals from magnetic coils surrounding the plasma. This is subtracted from a reference current signal produced by a waveform generator (wavegen B). A PID controller and further G matrix produce the output – in this case the required Ohmic coil voltages. Finally the M matrix corrects the signal for the mutual coupling between coils.

The coils are all supplied by independent power supplies, each with an internal PID controller. In our experiments, we replaced some of the coil control loops in the TCV controller with their internal power supply control and used the freed channels for the ECRH systems.

Plasma current control

Firstly the plasma current was controlled, simply by replacing the output of the plasma current control loop (the Ohmic coil power supply) with the gyrotron power supply and appropriate modification of the matrix elements, gains, references and feedforwards. During the ECRH phase, the Ohmic coil power supply was set to produce constant current (i.e. zero loop voltage) to ensure the plasma current is driven entirely non-inductively. Figure 2 shows the response of the gyrotrons and plasma current to the controller with a step function reference current. At the step-up in the current reference from ~160 to 180kA, the ECRH power increases and the plasma current responds (in time ~0.3s) and the error signal is minimised as expected.

Elongation control

The plasma current profile can be tailored by off-axis ECRH. In a constant quadrupole shaping field, when the current profile is
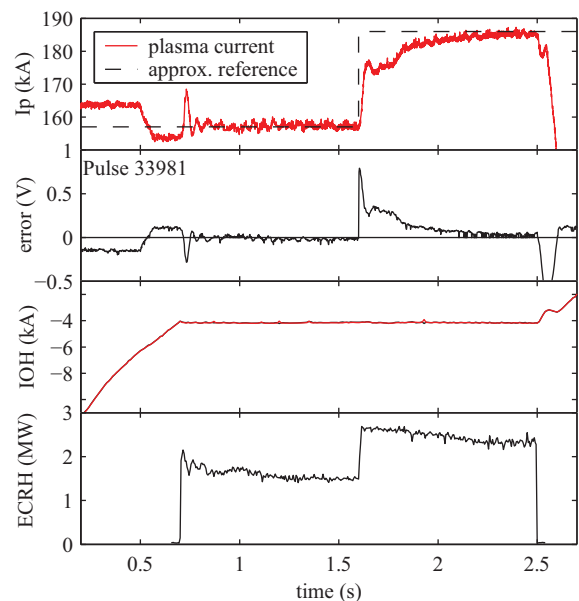

Figure 2. Current control with a step reference. The current in the Ohmic coil is also shown to demonstrate fully non-inductive plasma current.

broadened, the plasma elongates and therefore, by controlling the ECRH power supply, we have an actuator to control the elongation. Figure 3 shows the elongation response to off-axis ECRH. The poloidal field coil currents are also shown in this figure to demonstrate the ECRH is applied in constant quadrupole field.
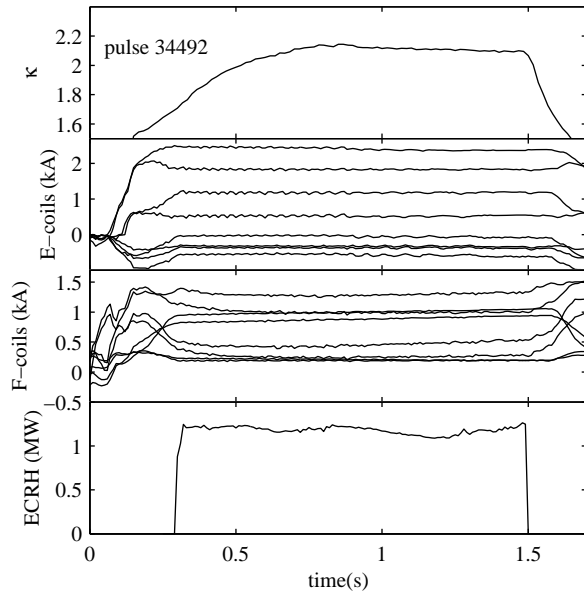

Figure 3. Elongation by off-axis ECRH. At ECRH switch-on, the quadrupole shaping field is held constant and the plasma elongates.

TCV has no real time equilibrium reconstruction and therefore the elongation signal must be calculated using a simplified model, developed for previous elongation control experiments (using magnetic actuators) [2]. This uses a finite element model of the plasma as six current filaments which are used to calculate the flux at the plasma up-down and in-out extremes. The difference in flux at these points is then related to the elongation; this quantity is zero if the plasma boundary lies precisely upon the selected reference points.

Figure 4 shows the results of an elongation control experiment with a step down in the elongation reference at 1.0s. Only proportional control is used in this pulse. The plasma is unfortunately unable to attain the initial high elongation reference, but settles to the step-down reference in ~0.3s. Experiments with step-up references generally showed no further elongation at the step, despite the increase in ECRH power. This is due to poor off-axis absorption; during the ECRH phase, the density drops rapidly, providing insufficient ECRH absorption when the increase in elongation is requested [3].

Deposition tracking

In the elongation control experiments, ECRH is provided by the upper launcher, aimed above the plasma centre. As the plasma elongates, the ECRH deposition becomes more centralised, possibly saturating the elongation effect. To maintain the deposition at constant ρ, real time control of the ECRH launcher mirror angle was developed [4]. This
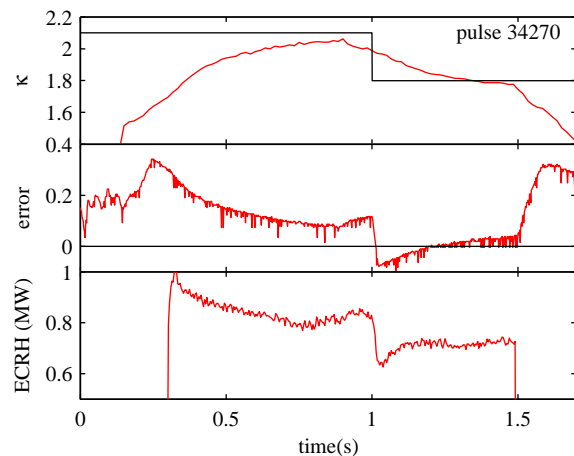

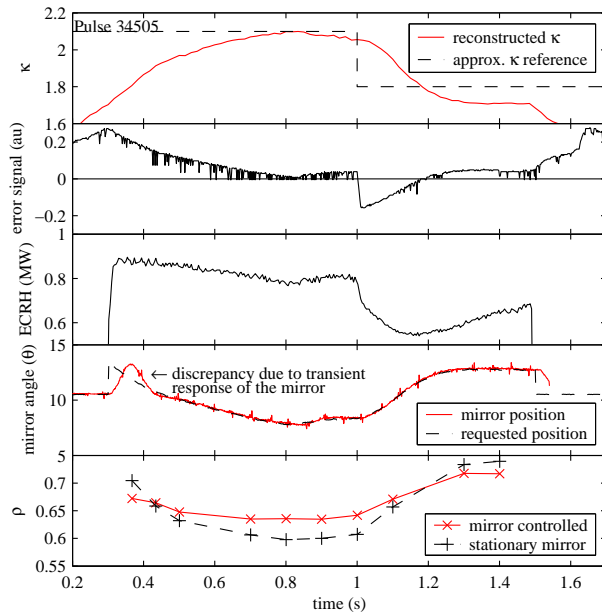Figure 4. A step-down reference is used to control the elongation.

Figure 5. Elongation control and deposition tracking. The absorption ρ (TORAY-GA) is shown for the controlled and stationary mirror cases. The ρ=0.65 surface is successfully tracked, especially in the first part of the pulse.

control uses the real time elongation signal to predict the angle required to maintain the deposition at a constant ρ. As the TCV controller is a simple linear controller, the relation between real time elongation and mirror angle was also assumed to be linear, the offset term provided by the controller feedforward and the proportional term by the matrix coefficients.

Figure 5 shows the results of an experiment to control the elongation and deposition. Proportional and integral control is used for the elongation control loop. As the plasma elongates, the mirror moves from θ = 11 to 7 degrees and the absorption, as calculated by the TORAY-GA ray tracing code [5] successfully remains on the ρ = 0.65 (+/-0.02) surface. Also shown is the position of absorption, assuming the mirror remains at constant position (at the feedforward angle of θ=11.25deg): the absorption moves from ρ = 0.6 to 0.7. During the second phase when the elongation decreases, the absorption moves from ρ = 0.65 to 0.7 despite the control, which may be due to the inherent error in the approximation of the elongation observable, however it remains an improvement over the stationary mirror case.

Conclusions

We have successfully controlled the plasma current and elongation using ECRH actuators. We were also able to track the ECRH absorption by controlling the ECRH mirrors in real time. TCV is currently installing an entirely digital, multi-DSP (Digital Signal Processor) based plasma controller [6]. This will provide a much more flexible environment to develop advanced control algorithms using multiple observables and actuators.

References

[1] A. Pochelon et al., Nuclear Fusion 41 (2001) 1663-1669
[2] F. Hofmann et al., Nucl. Fusion 30 (1990) 2013
[3] Y. Camenen et al., to be published Nuclear Fusion 2007
[4] J.I. Paley et al., submitted to PPCF 2007
[5] K. Matsuda, IEEE Trans. Plasma Sci. 17 (1989) 6
[6] B.P. Duval et al., IEEE Trans. Nucl. Sci. 53 (2006) 2179