Real time control of the sawtooth period using EC launchers

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Abstract. Tokamak plasmas operating at high performance are limited by several MHD instabilities. The sawtooth instability limits the core plasma pressure and can drive the neoclassical tearing mode unstable, but also prevents accumulation of impurities in the core. Electron cyclotron heating and current drive systems can be used to modify the local current profile and therefore tailor the sawtooth period. This paper reports on demonstrations of continuous real time feedback control of the sawtooth period by varying the EC injection angle.

Pacs numbers. 28.52-s, 52.50.Sw, 52.55-s, 52.55.Fa, 52.55.Tn, 52.55.Wq
Submitted to. Plasma physics and controlled fusion

1. Introduction

The sawtooth instability develops in the plasma core when the safety factor (q) on axis is less than 1, ie at high plasma current. In TCV, this is most noticeable on line integrated measurements of the core soft x-ray emission as repeating sequence of increasing intensity, followed by a rapid drop on a much faster timescale (the crash), giving the characteristic sawtooth shape. As well as limiting the core plasma pressure, the sawtooth instability has been shown to trigger neoclassical tearing modes (NTM) [1] and in extreme cases, this may lead to a rapid termination of the plasma discharge in a disruption, dumping the entire energy of the plasma into the tokamak's material structures [2]. They may also couple to edge-localised modes [3]. For these reasons, large sawteeth causing plasma temperature drops of more than 1 keV have been identified as a possible threat to ITER operation [2]. As well as the above detrimental effects on the plasma performance, the sawtooth instability will remove helium ash and impurities from the core of burning plasmas, thereby preventing a degradation of the core temperature. An additional concern for burning plasmas concerns the plasma self-heating. If the sawtooth period is shorter than the timescale for thermal equilibration of the fusion alpha particles, the alphas could be scattered or lost together with the corresponding loss of energy [2]. For these reasons, significant effort has been placed by the community in observing, understanding and controlling the sawtooth instability.

Previous characterisation of the sawteeth in typical TCV plasmas has shown they are generally described by resistive MHD in the Porcelli model [4], with the instability threshold being the threshold against $n = 1$, $m = 1$ magnetic reconnection [5,6]. In the TCV plasmas considered in this paper, the instability threshold is described by a crash triggering condition whereby the shear at the q

= 1 surface has a critical value: $s_1 < s_{1\ crit}$ [6]. Fast particles are not important in the description of TCV sawteeth due to the absence of ion heating. This model can be described as follows: during the sawtooth ramp phase the pressure builds in the plasma core and the plasma current profile becomes peaked, increasing the magnetic shear. The crash occurs when the magnetic shear at the $q = 1$ surface achieves this critical value, at which point the reconnection event triggers rapid loss in core plasma pressure and relaxation in the current profile, and the cycle is restarted.

As well as through control of the overall plasma current profile, the magnetic shear at the $q = 1$ surface may be tailored by a localised injection of current using auxiliary heating and current drive systems. Electron cyclotron (EC) resonance heating (ECRH) and current drive (ECCD) systems provide one of the most flexible options due to the ability to easily and quickly change the EC beam injection angle and therefore the localisation of the beam deposition by adjusting the angle of the launcher mirror. Localised current is injected by EC systems either by reducing the resistivity of the local plasma thorough heating (ECRH) or by direct current drive (ECCD). By placing this current source immediately inside/outside the $q = 1$ surface, the magnetic shear is enhanced/decreased, reducing/increasing the time until the shear limit is achieved and therefore shortening/lengthening the sawtooth period [6].

The central aim in controlling the sawtooth period is to be able to generate sawteeth of a predetermined (or dynamically determined) period. That is, the period could either be set before the plasma shot, or be modified in response to events in the plasma, such as a build-up of helium ash in the core.

The ability to control sawteeth in this manner has been previously characterised in both EC launcher sweeps in TCV [6] and toroidal magnetic field scan experiments in Asdex-Upgrade [7]. The ITER EC launchers have been specified to include the ability to control sawteeth and will most likely require a real time feedback control system to achieve this. Previously at TCV, we have demonstrated control over the plasma current and plasma elongation by controlling the EC injection angle [8]. DIII-D has successfully demonstrated real time control of NTM activity using fixed ECRH mirrors, instead varying the plasma major radius [9]. Tore-Supra has showed the period of fast ion stabilised sawteeth can be switched between short and long, using EC launchers in feedback control of the launcher velocity [10] and in JET, ion cyclotron current drive (ICCD) was used to control the sawtooth period [11]. In this paper we report on experiments to successfully control, in real time, the sawtooth period using EC launcher actuators.

The TCV EC and real time systems will first be described, followed by a short overview of the sawtooth model used to build the controller. The diagnostics and algorithms used to detect and control the sawteeth is also explained. The paper will finish with a discussion of the behaviour of the controller.

2. Experimental setup

2.1. TCV EC and real time systems

The 2nd harmonic X-mode (82.7GHz - X2) EC heating system at TCV (major radius 0.88 m, max toroidal field = 1.5 T, max current = 1 MA) consists of 6 x 0.5MW gyrotrons with individual launchers [12]. The gyrotrons are connected to their respective launchers via a series of evacuated waveguides and matching optics units, which set the desired polarisation. Each launcher is rotated about its longitudinal axis (inter-shot) to change the parallel wave number (ie changing between ECRH and ECCD). The final launcher mirror rotates to control the location of the poloidal deposition, however in general this motion also affects the current drive. It is this final mirror controlling the ‘poloidal’ angle which is controllable in real time. There is a proportional-integral-differential (PID) controller operating on each remotely steered launcher mirror motor, with the analogue angle reference signal for the ‘poloidal’ direction provided either in feedforward by waveform generators or by our control system. One equatorial X2 gyrotron was used in all the experiments described in this paper with the toroidal angle set to generate co-current ECCD/ECRH (20 degrees with respect to perpendicular launch). In TCV one gyrotron is sufficient to significantly modify the sawtooth period [6]. Figure 1 shows the layout of the plasma, $q = 1$ surface, EC injection and deposition for the plasma configuration used throughout these experiments.

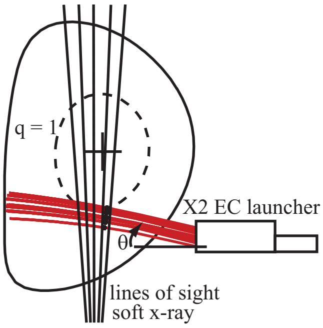

Figure 1. Injection and deposition of EC into the plasma, as calculated by the TORAY-GA [13] ray tracing code. The deposition is in the vicinity of the $q = 1$ surface (shown only approximately in this figure) and is set by the poloidal mirror angle (θ) which is controlled by the d-tAcq real time controller. Also shown are the lines of sight from the DMPX soft x-ray diagnostic which are used to detect the sawtooth crash.

The recent development of a new generation of digital real time control systems [14] for TCV provides a powerful platform for EC control experiments. We used a real time controller based upon the d-tAcq ACQ196 acquisition card [15] together with an analogue output module, connected over the compact-PCI backplane to a C-PCI single board PC. At each acquisition clock (at 10kHz), the acquisition card acquires the signal and passes the data to the PC. The PC executes the real time algorithm, passing the requested angle result back to the DAC on the acquisition card. The algorithms were developed using Simulink® and the Real-Time Workshop Embedded Coder. This provides the ability to quickly generate and modify algorithms, test them against models of the plasma response and generate and compile the real time C code to be executed on the real time PC. Further information on this system may be found in the reference [14].

2.2. Plasma configuration

Similar deuterium plasmas were used throughout the experiments described in this paper, in a limiter configuration with toroidal magnetic field 1.47T, plasma current 280kA, elongation 1.4 and electron density 10^{19} m^{-3}. The sawteeth have a period ~2.5ms in the Ohmic phase. The current redistribution time is ~300ms and the central value of the safety factor is approximately between 0.60 - 0.75 in these shots, calculated from post-shot equilibrium reconstruction.

2.3. Model of the sawtooth instability

In order to build a real time control system, it is essential to have a model of the sawtooth response to movements in the EC launcher injection angle which can be used to develop and test the control algorithm. Figure 2 shows a plot of the sawtooth period in response to feedforward sweeps of EC deposition across the q = 1 surface. One EC beam was used to modify the shear as shown in Figure 1. As well as modifying the local current profile, movement of the EC beam causes a redistribution of the global plasma current on a slower timescale, which manifests itself as hysteresis in the peak of the sawtooth period when the EC beam is swept across the q = 1 surface in the subsequent reverse direction. Off-axis deposition broadens the global current profile, shrinking the q = 1 surface, whereas core deposition peaks the current profile, moving the q = 1 surface to larger radius.

The response of the sawtooth period to changes in the launcher position is non-linear. Away from the q = 1 surface, there is very little change in the sawtooth period as the launcher moves. In the vicinity of the q = 1 surface, the period changes rapidly in response to movements in the launcher position.

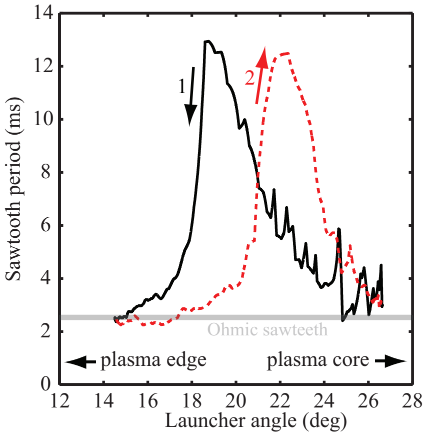

Figure 2. Feedforward launcher scans (pulse 35807) to sweep the EC deposition across the q = 1 surface in both directions. The peak in the sawtooth period shifts due to redistribution of the global plasma current profile as the EC deposition becomes either more centralised or off-axis. Also shown is the approximate period of sawteeth in Ohmic plasmas ~ 2.5ms.

The result of the feedforward sweep was used to generate a lookup table of the launcher angle vs sawtooth period. The hysteresis effect was included as an approximate temperature profile dependency, which was modelled as a function of the mean launcher position over the previous 0.5s in time. The time of 0.5s was selected as it matched well simulations of the feedforward launcher sweeps and is of the same magnitude as the current redistribution time on TCV (~300ms).

The experiments in this paper concentrated on controlling the sawteeth using co-current ECCD/ECRH deposition outside the q = 1 surface (ie small angles shown in Figure 2).

2.4. Measuring the sawtooth period

The first calculation the control system should undertake is to find the observed sawtooth period by detecting each sawtooth crash. This must be reliably detected over a wide range of sawtooth periods, crash sizes and sawtooth shapes. This is especially critical if the sawteeth become very small as several missed detections will result in the algorithm calculating an unrealistic large sawtooth period and subsequently the system could become unreliable or even unstable. The algorithm used throughout these experiments was based upon finding large negative derivatives in the soft x-ray intensity. A band pass filter (100-500Hz) operates on the mean of a few line integrated core soft x-ray signals from the TCV soft x-ray DMPX diagnostic [16] (see Figure 1). A sawtooth crash is detected when the filter output exceeds a critical value as shown in Figure 3. In order to detect both large and small sawteeth, with minimal missed/fake crash detections, the critical value is dynamic in response to the immediate time history of sawteeth. For example, if the previous sawteeth were small, the critical level was reduced. The sawtooth period was then calculated by taking the running mean over three successive crashes. This method was found to be reliable over a wide variety of sawteeth with only very occasional errors in the detection.

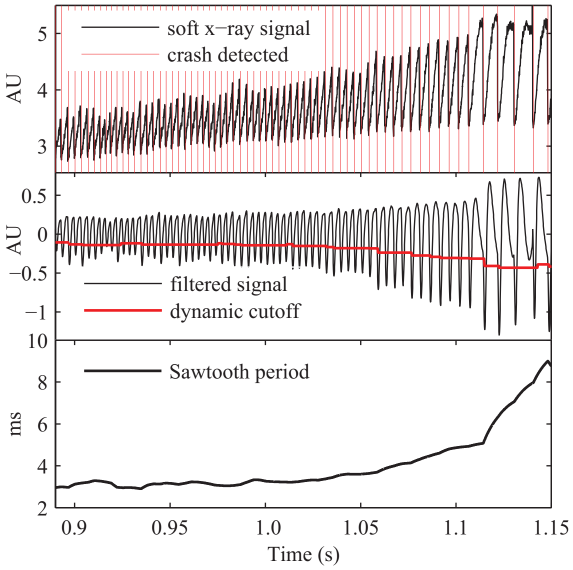

Figure 3. The sawtooth crash detection and period calculation algorithm. A band pass filter operates on the soft x-ray signal (top) and a sawtooth crash is detected (top) when the filtered signal (middle) passes a dynamic cutoff level. The period (bottom) is taken as the mean over the previous three sawteeth.

2.5. Controller setup

Ideally the control algorithm should know the position of the $q = 1$ surface together with the launcher injection angle required to deposit EC at and around this location. This would require a real time equilibrium reconstruction including current profile measurement to find the $q = 1$ surface. Real time ray-tracing using electron temperature and density profile data would be required to calculate the required injection angle. Although the real time equilibrium reconstruction is under development for TCV, real time ray tracing is not yet possible.

The algorithms developed in this paper rely exclusively upon the detected response of the sawtooth period to movements of the launcher and required the deposition to be targeted off-axis, outside the $q = 1$ surface (or more accurately outside the peak in the sawtooth period). In this case the controller moves the launcher to larger angle in order to increase the sawtooth period and to smaller angle for a shorter period, although alternatively, the deposition could be targeted for the plasma core in which case the controller gains would be reversed. As there is no information on whether the EC deposition is inside or outside this peak, it is important that the deposition does not cross the peak, as the controller could become unstable. In this situation, the sawtooth period will decrease with increasing launcher angle and the controller will continue to request an increasing launcher angle, until either the deposition coincides with the $q = 1$ surface on the other side of the plasma, or a limit to the launcher angle is reached. This was prevented by selecting a target sawtooth period somewhat less than the peak period and by ensuring the controller gains were not too large. A more advanced control algorithm could detect the derivative of the sawtooth period to launcher angle in order to prevent the system becoming unstable.

The central philosophy of these algorithms was to generate sawteeth of a pre-determined period. This target reference period may vary in time, for example step changes in the target period midway through the shot were used to demonstrate the sawtooth period was indeed controlled.

Two control algorithms were developed, simulated, tested and compiled using Simulink and the Real-Time Workshop Embedded Coder. The first was a typical linear PI controller, described below, as well as an alternate two-speed controller. Examples of the performance of each algorithm are presented in the results section.

2.5.1. Linear PI control

The first algorithm used a linear proportional-integral controller as shown in Figure 4. The detected sawtooth period is subtracted from the target period to generate the error signal. This is multiplied by a gain (the P term) and/or integrated (I term) in the PI controller and the output summed with the feedforward launcher angle to generate the target angle signal. This is passed through a digital 8Hz low pass filter which is required to prevent stress on the launcher motor and mechanical systems. The typical feedforward angle used in these experiments was between 15 and 17deg. Although this system was able to obtain and maintain the target sawtooth period (see results of Figure 5), it required careful selection of the P and I gains, and typically went unstable, oscillated or was unable to obtain the target if the target period was changed for a subsequent pulse, due to the change in open loop gain. An example of such behaviour is shown in Figure 5 of the results section 3.1.

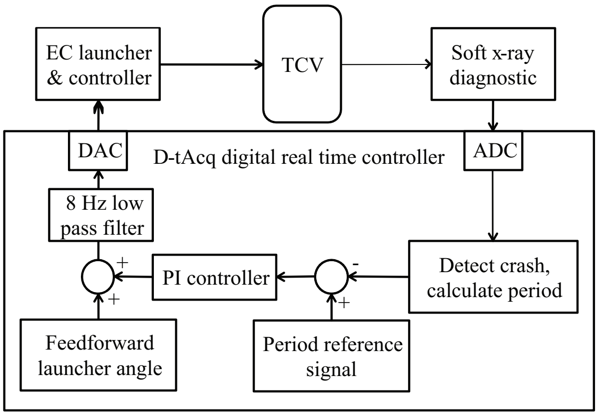

Figure 4. Block diagram of the PI sawtooth controller.

2.5.2. Dual speed control

To improve the performance of the controller, an improved algorithm was developed, relying heavily on the model of the plasma response obtained from the feedforward launcher sweeps (Figure 2). In order to be able to track both the slow movement of the $q = 1$ surface over the current redistribution time and the fast changes in period due to deposition near the $q = 1$ surface, a simple algorithm was designed with gain scheduling to allow the controller to switch between two effective gains, to move the launcher at 2 speeds depending upon the following conditions:

1) Fast (20 deg/s) if the sawtooth period < 4 ms.
2) Fast if the sawtooth period > 4 ms and controller requests a sawtooth period < 4ms.
3) Slow (2 deg/s) otherwise.

The other properties of this control algorithm are:

4) Launcher is held at constant angle if the observed period is within +/-0.5ms of the target.
5) Requested launcher position is passed through an 8Hz low pass filter to prevent stress on the launcher motor and mechanical systems.

As before, the controller relies upon maintaining the EC deposition off-axis, outside the position where there is a peak in the sawtooth period (ie roughly outside q=1) or it could become unstable. Simulations before the experiments provided confidence that the algorithm would work effectively and not cross this limit.

3. Results.

3.1. PI Controller

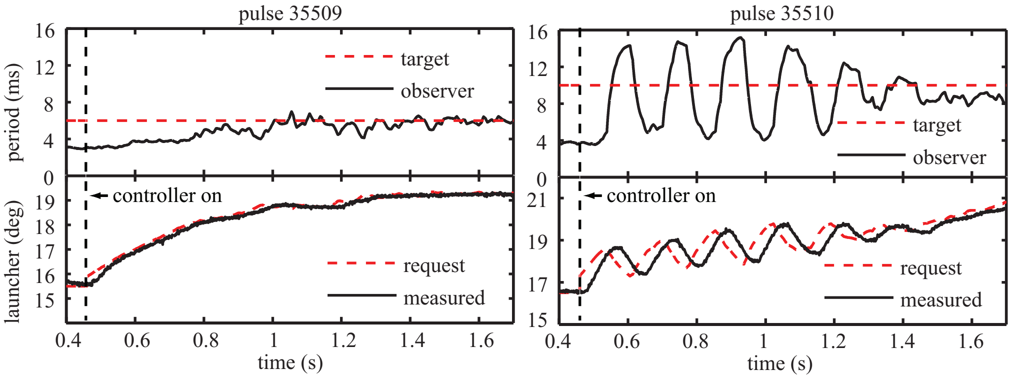

Figure 5. Two cases of PI control. The target was 6ms sawteeth in pulse 35509 (left) and 10ms in the subsequent pulse 35510 (right), with no change in the controller gains. The controller was successfully able to obtain and track the target at 6ms, however for the subsequent pulse with the same PI gains and a target of 10ms, the controller oscillated heavily.

The PI controller was able to track target reference periods as shown in Figure 5 left, where a target period of 6ms sawteeth is obtained within ~500ms. Figure 5 right shows the same control algorithm operating on the subsequent plasma shot, with the same gains and feedforward launcher angle but with a larger target period of 10ms. In this case the launcher oscillates as the gain is now too large due to the increased open loop gain. This necessitates optimisation of the gains for each change in the target period signal. Clearly a controller is required which is robust to changes in the target period. The performance of a more effective, two speed controller using gain scheduling is described in the following section.

3.2. Two speed controller

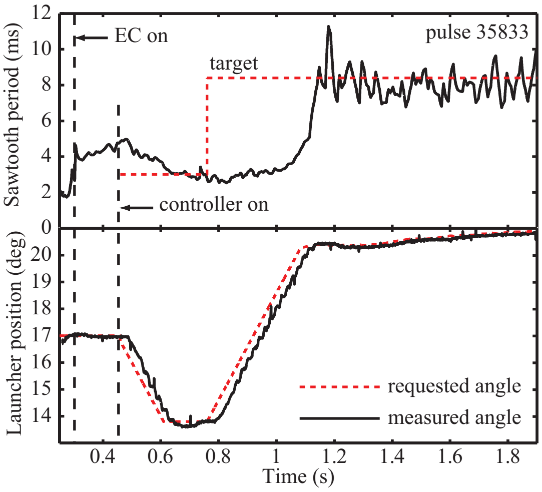

Figure 6: This controller drives the mirror at two speeds depending on the conditions described in 2.5.2. In this case a target sawtooth period of 3ms is obtained soon after the controller is activated. A step to 8.5ms is also successfully achieved and tracked.

This controller drives the launcher at either a fast (20 deg/s) or slow (2 deg/s) speed, depending on the conditions listed in section 2.5.2. The initial target sawtooth period of 3ms is obtained ~0.1s after the controller switches on. The target step to 8.5ms is then obtained in ~0.4s. The behaviour of the controller is described below:

1) The controller activates with a target period of 3ms. The detected period is ~5ms and therefore the launcher is driven to a smaller angle at 20 deg/s.
2) The target of 3ms is obtained at ~0.6s and the launcher is requested to remain stationary.
3) The target period is changed to 8.5ms at t=0.75s. The launcher is moved, at high speed to larger angle. Hysteresis is noticeable as the period remains at 3ms until the launcher has moved to a considerably larger angle than earlier. This is due to the initial EC switch-on leading to a narrowing of the $q = 1$ surface. As the mirror is stationary from 0.6s, the $q = 1$ surface will be moving further away from the deposition and therefore the launcher must move several degrees before the deposition is again close to the $q = 1$ surface.
4) At approximately t=1.1s, the sawtooth period becomes longer than 4ms and the launcher velocity is reduced to 2 deg/s.
5) 8.5ms sawteeth are obtained at approximately t=1.15s.
6) The sawtooth period is held roughly constant at 8.5ms for over 0.5s.

4. Conclusion & discussion

The ability to control sawteeth using real time steerable EC launchers has been demonstrated. We have shown the sawtooth period can be tailored to follow a pre-determined signal. The controller was able to track changes in the target sawtooth period despite the non-linearity of the plasma response and movement of the $q = 1$ surface. It is important to build control algorithms using models of the plasma response that include effects such as the movement of the $q = 1$ surface due to the EC beam deposition location.

The algorithms required EC deposition to be maintained off-axis, outside the position where there is a peak in the sawtooth period. If this location could be determined in advance, using calculations of the current profile and EC beam deposition, the response time of the controller could be improved. The possibility of the controller becoming unstable would also be removed. A more advanced control system could include the ability to control multiple EC beams using real time information from multiple diagnostics, designed using coupled sawtooth and transport codes to provide more accurate models of the plasma response.

ITER will rely on the ability of EC systems to control MHD activity in the plasma, particularly NTMs and sawteeth, using its launchers to direct the EC deposition. This work has demonstrated some of the key techniques necessary for MHD control using EC launchers.

Acknowledgments
We would like to thank O. Sauter and J. Graves for useful discussions.

This work was funded by the European Atomic Energy Community under an intra-European fellowship (Euratom) and in part by the Swiss National Science Foundation.

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