Real-time Control of MHD Activity and steady-state current profile by non-inductive current drive in Tore Supra

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Abstract. Real time control is essential for many aspects of tokamak operation. A key parameter to control is the current profile, since both confinement properties and Magneto Hydrodynamic (MHD) activity depend on it in a quite sensitive way. Recently, two types of original real-time control experiments have been carried out on Tore Supra on this topic: i) Real-time control of successive stationary states of the current profile, characterised by their MHD activity. Multiple target stationary states could be requested and reached during the main heating phase of a single plasma discharge. ii) Real-time control of Electron Cyclotron antenna mirrors for destabilisation of sawteeth in the presence of fast ion tails produced by ICRH, using an improved ECCD positioning algorithm.

1 Stationary control of 5 q-profile states

1.1 Motivation and description of the experiment

Real time control is essential for many aspects of tokamak operation. In particular, there is a key requirement for the sustainment of enhanced confinement in advanced scenarios, which is a proper alignment of current and pressure profile [2]. One of the challenges for reaching a pure steady-state tokamak reactor is precisely to be able to maintain this alignment during the whole discharge and with as small recycled power as possible. This requires the development of efficient real time control schemes of the current profile during the stationary burn phase. In relation with this ultimate goal, the Tore Supra tokamak long pulse capability (superconducting toroidal magnets, actively cooled plasma facing components, large non-inductive current drive capability) has allowed a quite unique type of experiment where successive stationary states of the plasma current profile are controlled in real time during the main heating phase, on durations much longer (~ 10 to 30 times longer) than the resistive diffusion time.

The plasma current profile is controlled by varying the level of Lower Hybrid (LH) power, i.e. replacing part of the ohmic current by a non-inductive source with a different deposition. From the Fast Electron Bremsstrahlung measurements [3], in the parameter range of the experiments reported here, the LH power deposition profile is concentrated inside $\rho \sim 0.6$. It is peaked slightly off-axis (around $\rho \sim 0.2$), which is at the origin of the q-profile reversal obtained when replacing a significant part of the ohmic current by LH driven current. With the LH power available during the experiments (up to 3.5 MW injected with the main parallel refractive index $N_{//0} = 1.8$), the safety factor profile can thus be varied at will from a sawtoothing monotonic one to a mildly reversed profile with $q_{min} \sim 3/2$ (see FIG. 1). The experiments involve a combination of Lower Hybrid Current Drive (LHCD) and Ion

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Cyclotron Resonance Heating (ICRH), using up to 7 MW of power with plasma durations up to 40 s. Though ICRH is not directly used for current profile control, it has been included in these experiments as an additional challenge, i.e. to demonstrate q-profile control on long duration and high heating power. Furthermore, ICRH may have important effects in stabilising the MHD activity which plays a key role in these experiments. The toroidal field is B_T = 3.8 T, and the plasmas have circular poloidal cross-section with major radius R_0 = 2.4 m and minor radius a = 0.72 m. The nominal central line averaged density and plasma current are $\bar{n}$ = 2.8 10^{19} m^{-3}, Ip = 0.6 MA.

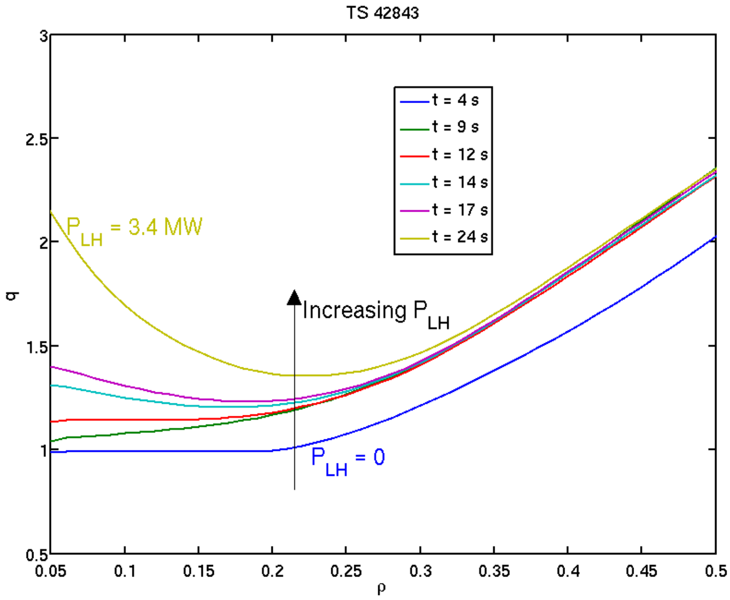

FIG 1: the 5 q-profile states as obtained during discharge 42843 (zoom on the core ρ = 0 - 0.5 region) estimated by current diffusion simulation with the CRONOS code [4] (taking into account the average effect of sawteeth). State #1 at t = 4 s (dark blue). State #2 at t = 9 s (green). State #3 with T_e relaxations at t = 14 and 17 s (light blue and purple). State #4 at t = 24 s (yellow), is stable with ICRH but leads to the MHD regime (state #5) when ICRH is switched off (for LHCD $n_{//0}$ = 1.8), see below.

In this range, the q-profile evolves through five distinct states, characterised by specific MHD activity. They are labelled from 1 to 5, this ordering corresponding to increasing LH power / fraction of non-inductive current. The LH power levels given here are indicative for the nominal conditions and vary with the density, plasma current, injected parallel refractive index $n_{//0}$ of the LH waves and the ICRH power. This is precisely the reason why a real-time control algorithm is needed that would tune the LH power P_{LH} in order to obtain the desired q-profile state.

- State #1 : $P_{LH} \leq 1.1$ MW : sawtoothing plasmas, monotonic q-profile with a q = 1 surface.
- State #2 : 1.2 MW $\leq P_{LH} \leq$ 2.2 MW : no visible MHD activity : sawtooth are stabilised by fast ion effects (ICRH) or absence of the q = 1 surface. The on-axis safety factor q_0 remains likely quite close to 1.
- State #3 : 2.3 MW $\leq P_{LH} \leq$ 2.9 MW : small or large relaxations of the electron temperature T_e, in relation with the q = 3/2 surface and low or negative magnetic shear. In fact state #3 covers both MHD-driven relaxations and quasi-periodic *Te* oscillations corresponding to the « O-regime »[1], which could be distinguished in future versions of the controller.
- State #4 : P_{LH} ~ 3.0 MW : high core electron temperature T_{e0} ~ 6.7 keV with no visible MHD activity, likely with q_{min} very close to 3/2.
- State #5 : 3.1 MW $\leq P_{LH} \leq$ 3.5 MW : a large MHD mode is triggered at q = 2 while qmin ~ 3/2 (either by increasing the LH power with respect to state #4 or by switching off the ICRH power), a deleterious state described as the MHD regime [5].

The q-profiles states are detected by real time analysis of the electron temperature relaxations resulting from the MHD activity, observed on the central channels of the Electron Cyclotron Emission diagnostic (ECE, see FIG. 2).

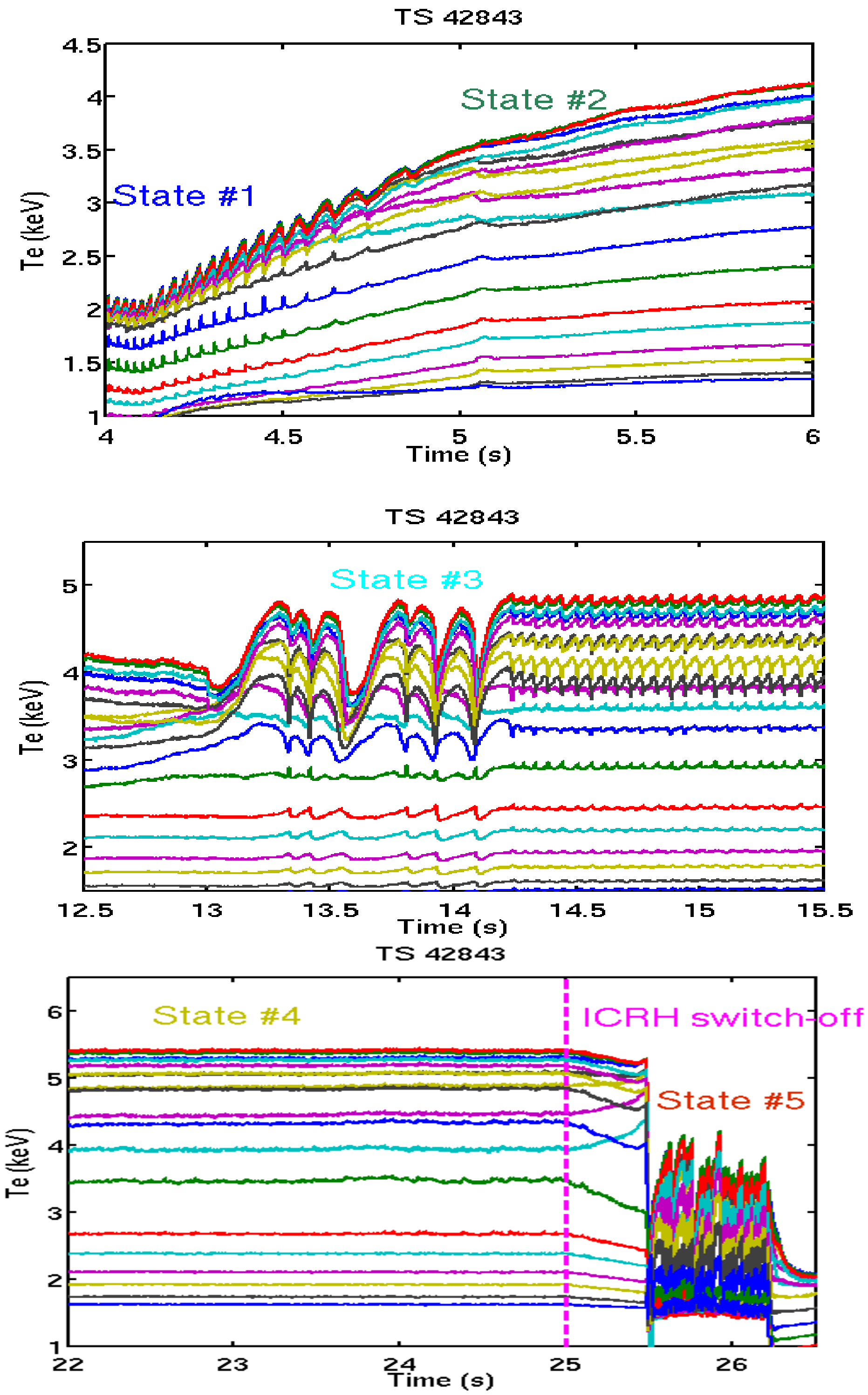

FIG 2: Dynamics of the core electron temperature as seen by the various channels of the ECE diagnostic during discharge 42843, in which the LH power was varied and the q-profile went through the 5 states. Top : LHCD power ramp-up and transition from a sawtoothing plasma (state 1) to a non-sawtoothing plasma (state 2). Middle : state #3 with various forms of T_e relaxations related to the q = 3/2 surface. Bottom : quiescent state #4, which is here metastable since the MHD regime state 5 is obtained by switching off voluntarily the ICRH power at t = 25 s.

1.2 q-profile state detection

The most delicate part of the experiment is the real-time analysis of the ECE signals to determine the q-profile state. The algorithm is based on the real-time detection of fast relaxation events (crashs) on the ECE channels and the period between two events. The inversion radius of the relaxations is also calculated in real-time but is not used by the control algorithm. The presence of crashes indicates states 1, 3 or 5. The period between two crashes $\Delta\tau_{crash}$ is primarily used to distinguish between state 1 ("short period" $\Delta\tau_{crash} < 100$ ms) and 3 ("long period" 100 ms $< \Delta\tau_{crash} <$ 650 ms). Unfortunately this simple criterion is not sufficient for the whole range of scenario studied here, e.g. the sawtooth period of a state 1 with significant ICRH power may exceed 100 ms. Therefore a more sophisticated state machine algorithm has been used to provide a robust detection of the q-profile state. State 5 is characterised by a strong deleterious MHD activity and detected when the Mirnov coil signal exceeds a given threshold. States 2 and 4 are characterised by the absence of fast T_e relaxations ($\Delta\tau_{crash} >$ 650 ms). The algorithm has to know the plasma state and P_{LH} history and a few additional rules to determine the current state unambiguously : i) losing the T_e relaxations from state 1 means being in state 2. ii) losing the T_e relaxations from state 3 with increasing (resp. decreasing) P_{LH} means being in state 4 (resp. 2). These rules are of course neither perfect nor absolute however they provided a robust detection of the q-profile state in our experiments.

1.3 Control strategy

In the absence of a "continuous" real-time measurement of the q-profile, the experiments aims at controlling the q-profile stationary state among the 5 characteristic states described above. The operator specifies in advance the desired q-profile state as a function of time (the "target"). Then the control algorithm adapts the LH power in real time to follow the target. Every Δt seconds, the controller checks whether the plasma is in the requested plasma state and, if not, modifies the LH power in the relevant direction. The LH power is modified by a fixed step ΔP_{LH}, which is a parameter of the control algorithm, typically chosen from 300 to 600 kW. A value of $\Delta t = 2$ s is chosen as the minimum time needed for current relaxation between two levels of LH power. The plasma state is estimated continuously in real-time from the ECE diagnostic signals as explained in the previous section. Since the q-profile states are labelled in increasing order of non-inductive current fraction (i.e. LH power), the actuator control scheme is quite simple :

- detected state < requested state → increase LH power of one ΔP_{LH} step
- detected state > requested state → decrease LH power of one ΔP_{LH} step
- detected state = requested state → keep LH power constant

The only exception to this rule is the reaction at the detection of state 5 (MHD regime). The control algorithm then reduces P_{LH} to a very low level (typically 200 kW) in order to change the q-profile drastically and go away from this deleterious regime.

1.4 q-profile control results

Several experiments have been carried out on Tore Supra to demonstrate the capability of this control scheme i) to obtain a desired stationary q-profile state and ii) to sustain it in spite of preset variations of other plasma parameters such as plasma density, ICRH power or total current. Successful experiments have been carried out featuring i) control of the presence/absence of sawteeth with varying plasma parameters, ii) obtaining and sustaining a "hot core" plasma regime without MHD activity, iii) recovery from a voluntarily triggered deleterious MHD regime.

All experiments begin with a startup phase of 10 s with a preset ramp-up of plasma current, density, ICRH and LH power. Then the control scheme starts and the LH power is modified every $\Delta t = 2$ s in order to reach the desired q-profile state, which is preset as a time-dependent target by the physicist. The only feed-forward parameter to the control algorithm is the maximum value of P_{LH} to be delivered by the system, limited to 4 MW for technical reasons. The duration of the experiment is limited only by the available flux in the poloidal field system.

Discharge #43106 (FIG. 3, left) shows a typical example of control of the q-profile around the q = 1 surface. Starting at t = 10 s with low LH power and a sawtoothing plasma (state #1), the target from t = 10 to 25 s is to reach the non-sawtoothing state #2. Then, from t = 25 s onwards the target is to come back to state #1. The control, when it is switched on at = 10 s identifies correctly the need to increase P_{LH}, as done with three successive steps. Having reached P_{LH} = 2 MW, the sawteeth disappear from the central ECE channels. This is again correctly identified and thus the LH power is kept constant. Then, as the target changes at t = 25 s, the control algorithm reduces the LH power of a single step and the sawteeth reappear. The requested and detected states then coincide, thus the LH power is kept constant until the end of the pulse. The slow decrease of the ICRH power starting after t = 13 s is due to overheating at the surface of one of the antennas, whose surface temperature is maintained at an acceptable level by the machine safety control algorithm by decreasing the ICRH power.

Discharge #43107 (FIG. 3, right) provides an interesting comparison to the previous shot, repeating the experiment with the same plasma current, density and initial LH power, also requesting a transition to state 2 but without ICRH power. Interestingly the transition to state #2 is obtained with less LH power than in the shot with ICRH (1.6 MW versus 2 MW), which was not expected. This shows the interest of having a real time control that adapts the actuator to obtain the desired MHD behaviour whatever the variations of the plasma scenario.

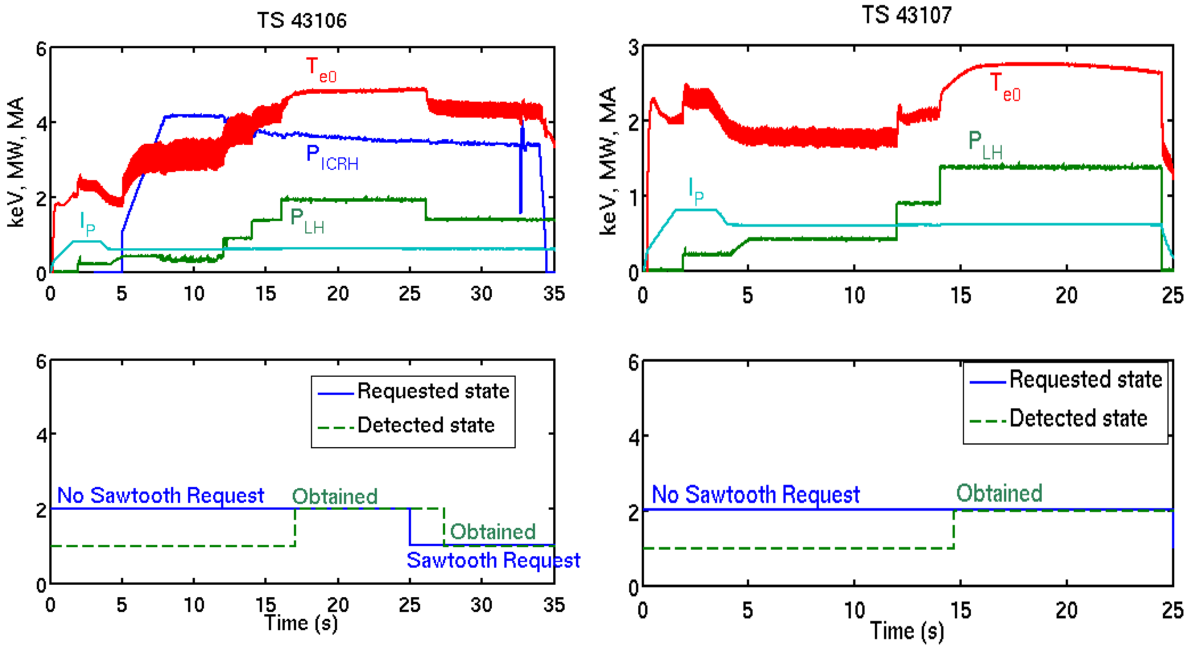

FIG. 3: Time traces of various quantities during Tore Supra discharges #43106 (with ICRH power, left) and #43107 (without ICRH power, right). Top : central electron temperature T_{e0} from the ECE diagnostic (red), ICRH power P_{ICRH} (dark blue), LH power P_{LH} (green), plasma current I_P (light blue). Bottom: requested target q-profile state (solid blue) and detected by the control algorithm q-profile state (dashed green).

Discharge #42843 (FIG. 4) is likely one of the most complete example of these control experiments, where the plasma goes through the 5 q-profiles states in a fully controlled way. The scenario of this experiment is i) to obtain a steady q-profile state #4 then ii) voluntarily trigger the MHD regime from this state and iii) let the controller apply its emergency strategy to depart from the MHD regime and recover a usable plasma discharge. The injected LH power spectrum has a central peak around $n_{//0}$ = 1.8. The first 10 s are the initialisation phase,

I_p, P_{LH} and P_{ICRH} are ramped up in a preset way. During this phase, the q-profile state detection is already active and correctly sees the transition from state 1 to state 2 at about t = 5 s (sawteeth disappear). The target for this shot is to obtain and sustain q-profile state 4. Thus the control algorithm starts increasing the LH power by steps from the onset of the control phase, i.e. t = 10 s. Between t = 10 s and t = 13 s, T_{e0} decreases while the LH power increases and the density remains constant. The reason is a degradation of the good core confinement that was obtained in state 2 (with a flat q-profile just above q = 1), small relaxations of T_{e0} start to appear though not detected by the algorithm. At about t = 13 s, the possibility of a high core confinement appears again, however T_{e0} is not stable yet and large relaxations occur, correctly detected as state 3. Meanwhile, the algorithm continues to increase P_{LH} since the detected state is still below the requested one. A quasi-quiescent phase appears then in a high core confinement state, with still very small oscillations of T_{e0} that are not detected and thus incorrectly interpreted as state 4. As bigger relaxations occur at t = 18 s, the control falls back in state 3 and increases again the LH power. A fully quiescent state 4 with high core confinement is then obtained from t = 21 s to t = 25 s. The control has reached the target and thus keeps the LH power constant.

Then a new event occurs : a preset switch-off of the ICRH power. During the preparation of these experiments, it has been observed that with this tuning of the LH initial refractive index ($n_{//0}$ = 1.8 for both launchers), state 4 is very close to degenerate into the MHD regime state 5. Such a transition occurs i) when increasing further the LH power (q_{min} becomes then too close to q = 3/2) or ii) when switching off the ICRH power. Here the control algorithm succeeded in avoiding case i), but we deliberately force the transition to the MHD regime by switching off the ICRH power at t = 25 s. As expected, the MHD regime occurs and is correctly detected. The reaction of the control algorithm is to reduce P_{LH} to a preset low level (200 kW). This induces a drastic change of the current profile, thus allowing the plasma to recover from the MHD regime and restart from a safe situation where the power can be progressively increased again. In spite of a wrong identification of the plasma state after the recovery (state 3 is detected while the plasma is sawtoothing in state 1), the algorithm tries again to increase P_{LH} by steps until the preset end of the heating at t = 30 s.

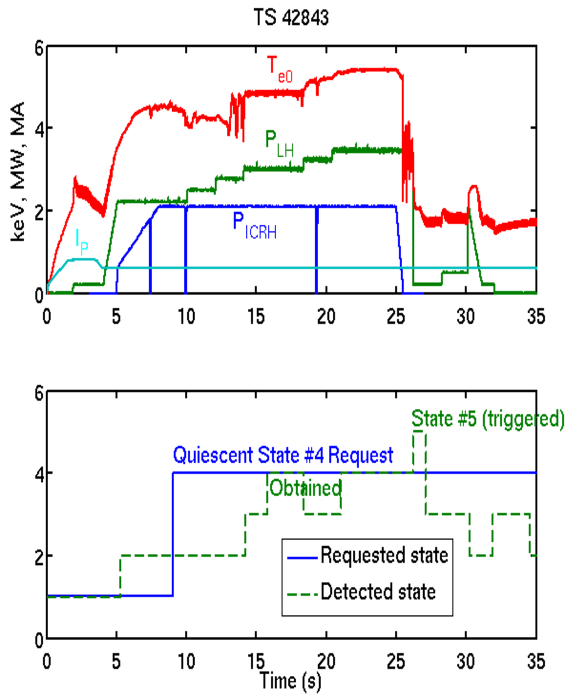

FIG. 4: Time traces of various quantities during Tore Supra discharge #42843. Same colour codes as FIG. 3.

1.5 Conclusion

The Tore Supra long pulse capability has allowed a quite unique type of experiment where successive stationary states of the current profile, characterised by their related MHD activity, are controlled in real time. Multiple target stationary states could be requested and reached during the main heating phase of a single plasma discharge. The control algorithm has proven robust enough to reach and sustain a desired q-profile state and recover it in spite of preset variation of other plasma parameters such as electron density, plasma current, ICRH power. This first demonstration is a preliminary step towards the control of a stationary burn phase in a reactor, though the reactor situation will be much more challenging (steady-state requirements, higher bootstrap current fraction, H-mode, self-heated burning plasma). Preparing steady-state burning plasma scenarios and the necessary current profile control algorithm should be a key objective for the rising generation of super-conducting tokamaks.

2 Real-time destabilisation of sawteeth by localised Electron Cyclotron Current Drive

Shortening of sawteeth through localised Electron Cyclotron Current Drive (ECCD), by increasing the magnetic shear near q = 1 have been achieved on various tokamaks [6][7]. Results from Tore Supra showing how sawtooth destabilisation using ECCD in the presence of central ICRH generated fast ions was achieved for the first time, were presented at the previous IAEA Fusion conference [8]. These experiments also demonstrated closed loop control of the sawtooth period for the first time. The control, which was achieved in the presence of central fast ions, used real time control of the the poloidal ECCD injection angle θ as actuator [9][10]. Feedback control of the sawtooth period using ECCD has also been achieved in TCV [11]. In the Tore Supra experiments the sawtooth period oscillated between two values. This oscillation was due to the fact that the sawtooth period switched abruptly between long fast ion stabilised sawteeth and short sawteeth with a period only slightly larger than the ohmic sawtooth period, when the ECCD absorption location was moved slowly across the q=1 surface [12] as illustrated in FIG. 5. When a sawtooth period between 70 ms and 30 ms was requested the controller made the sawtooth period oscillate between 70ms and 30 ms while maintaining the average value equal to the requested value.

As the aim of sawtooth control is to achieve and maintain short sawteeth, such an oscillation is clearly undesirable. To overcome this problem a new ‘search and maintain’ control algorithm was developed. Figure 2 shows the block diagram for this algorithm which proceeds in three stages. The initial ECCD injection angle θ_0 is chosen such that the absorption takes place in the outer plasma region indicated in light green in figure 1, outside the sawtooth destabilisation region which is indicated in orange. When the controller is activated the switch shown in FIG. 6 is in the bottom position and a simple PID controller tries to bring the sawtooth period to the reference value. If this value is in the unachievable interval, the sawtooth period will suddenly jump to a value below the reference value. When this jump is observed, the controller proceeds to stage two – the switch in FIG. 6 goes to the middle position - and the injection angles are held constant while the sawtooth inversion radius r_{inv0} and ECCD absorption location r_{ECCD0} are memorised. The distance between absorption and inversion radius which will result in reliable sawtooth destabilisation can now be determined as: $\Delta r_{ref} = r_{inv0} - (r_{ECCD0} - r_{margin})$, where r_{margin} is a small offset assuring that the ECCD absorption is fully inside the destabilising region when $r_{ECCD} = r_{inv} - \Delta r_{ref}$. After a short period the switch moves to the top position and the controller assures that the ECCD

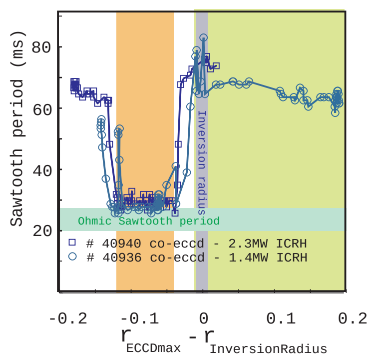

FIG. 5: Sawtooth Period as function of ECCD location

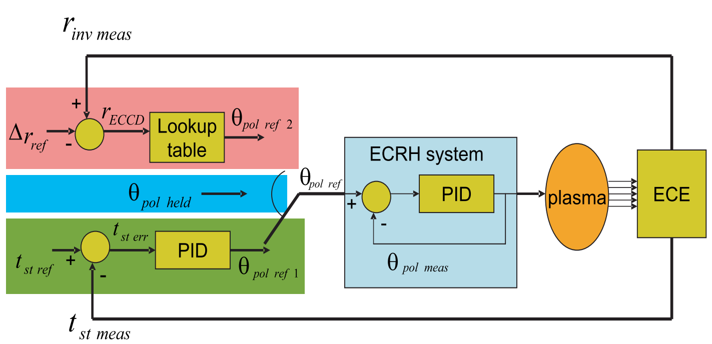

FIG. 6: Search and maintain controller bloc diagram showing the three step control.

location keeps following the evolution of the sawtooth inversion radius by setting $r_{ECCD} = r_{inv} - \Delta r_{ref}$. The sawtooth inversion radius and the sawtooth period are determined in real time inside the Electron Cyclotron Emission (ECE) diagnostic and the values are communicated to the central control computer which calculates the required poloidal injection angle. Similarly the ECCD absorption location is estimated in real time by the ECCD control computer. The latter estimation is based on look-up tables, pre-calculated using the REMA code, giving the absorption location as a function of the magnetic field and the injection angles [13] rather than a measurement of the actual absorption location. The absolute value of this ECCD absorption location estimation r_{ECCD} is rather imprecise but since the control algorithm starts by finding the correct absorption location, only small variations from the initial position are required when r_{inv} changes and for this purpose the pre-calculated translation from injection angles to absorption location is adequate. FIG. 7 shows a pulse in which this algorithm has succeeded in rapidly finding the ECCD location resulting in short sawteeth and subsequently maintaining the short sawteeth throughout the pulse. The colour coding in the figure corresponds to the colours used in FIG. 6 showing how the controller proceeds through the three phases. If the abrupt change in sawtooth period observed in Tore Supra is a general result in plasmas with significant fast ion pressures, as seem to be supported by observations on JET [14], direct feedback control of the sawtooth period is unlikely to be able to maintain short sawteeth in ITER. An algorithm of the type presented herein will therefore be required and the demonstration of its successful implementation on Tore Supra is promising for the use of a similar approach to prevent sawteeth from triggering NTMs on ITER.

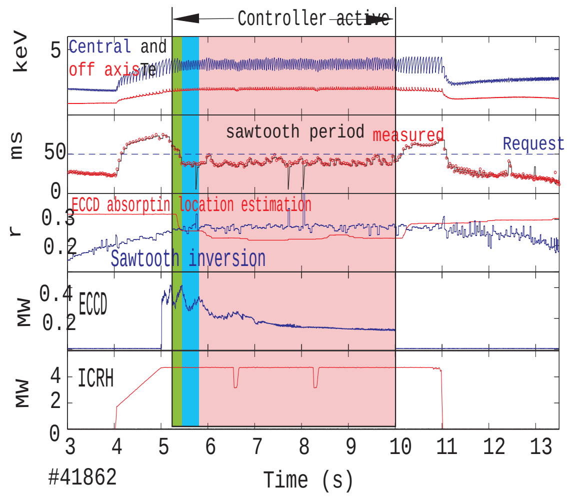

FIG. 7: Search and maintain control.

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