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Real time control of stationary states of the current profile on the Tore Supra tokamak

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1. Introduction : stationary control of 5 q-profile states

The present work reports on original Tore Supra experiments in which real time control of successive stationary states of the current profile has been achieved. These experiments involve a combination of Lower Hybrid Current Drive (LHCD) and Ion Cyclotron Resonance Heating (ICRH), using up to 8 MW of power with plasma durations up to 40 s (which represents about 20 resistive times). 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, it has been found that ICRH has 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 line averaged density and plasma current are $\bar{n}$ = 2.8 10^{19} m^{-3}, Ip = 0.6 MA. Those relatively low values of density and current (edge safety factor q_a ~ 8) have been chosen in order to be able to significantly modify the current profile with the available LHCD power.

The plasma current profile is controlled by varying the level of LH power, i.e. replacing part of the ohmic current by a non-inductive source with a different deposition. The safety factor profile can thus be varied at will from a sawtoothing monotonic one to a mildly reversed profile with q_{min} ~ 3/2 (FIG. 1). In this range, the q-profile evolves through five distinct states, characterised by specific MHD activity. Owing to difficulties in the interpretation of polarimetry measurements on Tore Supra, the q-profile cannot be determined in real-time to such degree of precision. Instead, the q-profiles states are detected by real time analysis of the electron temperature relaxations resulting from the MHD activity, observed on the central chords of the Electron Cyclotron Emission diagnostic. The MHD signature is indeed an accurate indicator of the q-profile characteristics, such as the presence of low order rational surfaces, q = 1 and q = 3/2 in this application.

The five q-profile states 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 refractive index $n_{//0}$ of the LH waves and the ICRH power. This explains the need of a real-time control algorithm 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.

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 ≤ P_{LH} ≤ 3.5 MW : a large MHD mode is triggered at q = 2 while qmin ~ 3/2 (in particular in the absence of ICRH), a deleterious state described as the MHD regime [P. Maget, G. Huysmans, J.F. Artaud, F. Imbeaux et al., Nucl. Fusion 44 (2004) 443]

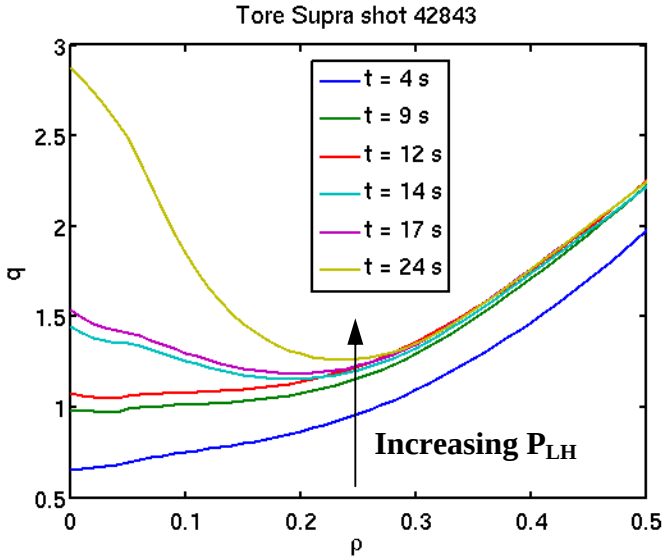

FIG 1 : q-profile states during discharge 42843 (zoom on the core ρ = 0 - 0.5 region) estimated by current diffusion simulation with the CRONOS code. State #1 at t = 4 s (dark blue). State #2 at t = 9 s (green). State #3 with T_e relaxations at t = 14 and 17 s. State #4 at t = 24 s, is stable with ICRH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

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 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 then used to distinguish between state 1 ($\Delta\tau_{crash}$ < 100 ms) and 3 (100 ms < $\Delta\tau_{crash}$ < 650 ms). State 5 is characterised by a strong deleterious MHD activity and detected when the Mirnov coil signal exceeds a given threshold. Conversely, 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. descreasing) P_{LH} means being in state 4 (resp. 2). These rules are not perfect or absolute however they provided, a robust detection of the q-profile state in our experiments.

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 a 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 Δt = 2 s is chosen as the minimum time needed for current relaxation between two levels of LH power. Therefore at the end of each P_{LH} plateau the current profile

has reached its stationary state. Unlike most current profile experiments carried out in present tokamaks that operate on transient states of the q-profile, we control here the stationary state of the current profile and vary the desired target during a single discharge. Such a strategy is possible thanks to the long pulse capability of the Tore Supra tokamak, where the duration of the discharge can be up to two orders of magnitude above the current diffusion time. The typical duration of our control experiments are ~ 30 s, while the estimated time step for current relaxation is $\Delta t = 2$ s.

4. q-profile control results

Several experiments have been carried out to demonstrate the capability of this control scheme to obtain a desired q-profile state and sustain it during a preset variation of another plasma parameter 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 is the maximum value of P_{LH} to be delivered by the system, limited to 4 MW for technical reasons. The plasma state is estimated continuously in real-time from the ECE diagnostic signals. 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.

In this short proceeding, we report only one example of a successful control of the plasma state 4. 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 heating 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 ($n_{//} = 1.8$ 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 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.

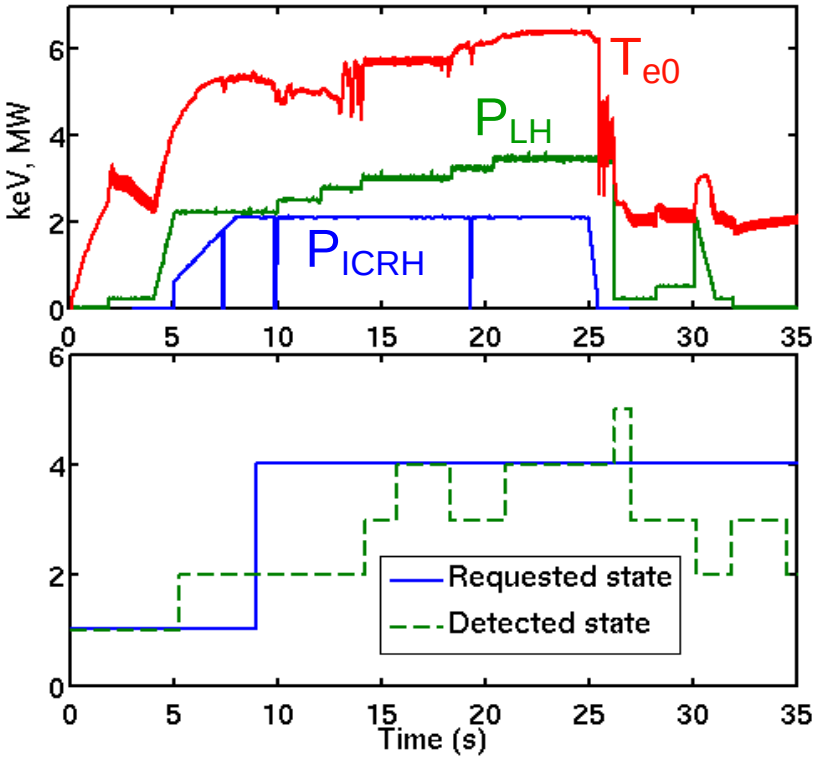

Figure 2 : Tore Supra shot 42843. Top : time traces of the central electron temperature (T_{e0}, red), LH power (P_{LH}, green), ICRH power (P_{ICRH}, blue). Bottom : time traces of the requested state (target, solid blue) and real-time detected state (dash green).

5. Perspectives

These experiments are a first example of current profile control on long plasma discharges with a high level of combined LH + ICRH power. During their preparation, new insight has been gained on the confinement properties and MHD characteristics of the non-inductive discharges, which will be used in the next years of Tore Supra with the CIMES project (upgrade of the heating systems). The main weakness of the control algorithm is the detection method : based on the time lag between two crashes of the electron temperature, it can get confused by accidental relaxations or is conversely blind to “soft” relaxations. In order to improve it, we are investigating the possibility to do a frequency analysis (via Fourier Transform) of the raw ECE signals in real time. The detection part could also be improved by using additional measurements such as polarimetry. Nevertheless, the control part has proven robust and effective – as long as the q-profile target can be reached with the available power. The LH power has allowed an efficient control of tiny details of the core q-profile detected by their MHD signature, even with varying external parameters.

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