New real-time profile controls for steady state operation on Tore Supra

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1) Introduction

During last years, the main focus of tokamak worldwide experimental activity has been the preparation of ITER scenarios. As the research progresses, the integration of steady state advanced tokamak scenarios requires nowadays the control of more and more plasma parameters and profiles. The Tore Supra tokamak is well-suited to address these points and to develop advanced methodologies for the physics and operational integration of plasma scenarios using stationary discharges on several minutes pulses [1] and multi-Megawatt power levels.

In order to address the issue of the integration of several control schemes in steady state, many efforts have been made to equip Tore Supra with a large number of new real-time systems. The growth of collected data and the possible complexity of the control algorithms also required a new real time central controller which has been tested for the first time during the 2005 campaign. This paper reports recent technical and scientific achievements made on Tore Supra in this domain. After a brief introduction to the Tore Supra real time control network, recent real-time sensor processing developments are presented. Practical control scheme experiments are then described leading to the integration of several control schemes in a steady state scenario ensuring safety aspects of plasma facing components.

2) Tore Supra real-time system

The existing real-time control network of Tore Supra is described in [1]. The sharing of information relies on the SCRAMnet (Shared Common Random Access Memory network) reflective memory, which provides communications between real-time processors. Recently, PC units have been used for real time computation.

Sensors have been also recently included: hard X-ray (HXR) emission diagnostics (59 line of sights) have been equipped with real time hardware. Associated to these raw data, real time treatments and computations have been developed and validated such as the tomography inversion of the HXR line integrated measurements which allows the reconstruction of the Lower Hybrid current drive (LHCD) power deposition profile each 16ms [2]. This real-time information is of prime interest in Tore Supra where the LHCD system is the main source of non inductive current, in particular during long discharges at zero loop voltage. The real-time HXR reconstruction can thus be used to control indirectly the current density profile. The 32 channels of the Electron Cyclotron Emission (ECE) [3] are also available in real-time. In order to control the plasma performance, the real time computation of the normalised electron temperature gradient [4] is performed each millisecond. But using feedback control algorithms, in particular during high performance pulses may require the full power available leading to the problem of temperature safety of the in-vessel components. In order to ensure the safety of the plasma facing components, six infra red cameras are monitoring the toroidal pumped limiter, the 3 ion cyclotron resonance heating (ICRH) and the 2 LH launchers. Critical areas subject to strong heat flux have been identified on each infrared views [5] and the role of the private power or RF launchers cross interaction effects for each area has been determined. A real time algorithm infers the surface temperature of these elements each 20ms. A feedback controller decides then which RF system has to reduce its injected power and by which amount.

3) Real-time profile controls

With its toroidal pumped limiter, Tore Supra has demonstrated its capability of producing routinely long steady state discharges (up to 6 minutes) using LHCD as the main source of non-inductive current [6], [7]. These discharges characterised by low loop voltage are lasting several resistive times and are therefore suitable for testing feedback algorithms on the current profile. During the last experimental campaign efforts have been made to control the width of the LH deposition profile. This constitutes one mean to wider the current profile and reach higher performance regime when internal transport barriers (ITB) are triggered. The shape of the current profile is indeed a key point in the ITB formation and location [8].

Preliminary experiments have been performed at reduced plasma density (~2.5 10^{19} m^{-2}) with LH-wave as main actuator to control the HXR width deposition profile. The LH power or refractive parallel index $n_{//}$ are used independently to achieve the proportional-integral (PI) controls (Fig.1-2) as suggested in [9]. The optimum proportional and integral gains of the controller were determined from dedicated open loop experiments. The LHCD current generation efficiency decreases (as $n_{//}$ reaches higher values) at constant LH power P_{LH} (Fig.1) and a direct consequence is the increase of the loop voltage (V_{loop}). On the contrary (Fig.2), at constant $n_{//}$, V_{loop} decreases when P_{LH} rises. The possibility to control the LH power deposition profile has been clearly demonstrated in both cases. The actuator n// seems nevertheless more adequate than P_{LH}. This might be partly explained by the fact that when P_{LH} varies, the confinement and the deposition of the wave changes. The time evolution of the LH and ohmic deposition profile obtained from the CRONOS [10] code can be seen in Fig.3. It confirms the broadening of the LH profile.

In this scenario the bootstrap fraction was low and consequently HXR reconstruction gives a direct estimation of the total current profile provided ohmic current is cancelled. Control of the current profile with the n// index, combined with zero loop voltage control by the ohmic coils and control of the plasma current by the LH-power (Fig.4), has been achieved thus demonstrating that these controls can be run in a compatible and robust manner. The chosen scenario was exempt of any kind of MHD activity and with the association of low density and 2.5MW of LH power the safety profile was reversed above unity. This sometimes triggers in Tore Supra the onset of a central electron internal barrier (ITB) inside r/a=0.3 and sometimes the so-called O-regime characterised by non linear temperature oscillations [11]. In view of controlling enhanced performance discharges, the active control of the maximum of the normalized electron temperature gradient profile (max (ρ^*_{Te})) using LH power as actuator has been successfully achieved with a PI controller (Fig.5). The chosen target was time dependant. At the beginning of the control from 19s up to 33s, the rising target is perfectly tracked through a small increase of the LH power. Then at t=33s an MHD event occurs, perturbing the control. The tracking error cannot be compensated due to the limitation of the available LH power. A redistribution associated to a relaxation of the profile then occurs, triggering later at t=34.5s an improved confinement mode, characterised by a strong rise in central temperature and thus of the max(ρ^*_{Te}). The target at that time is exceeded and without control this could have led to a disruption (as seen on previous pulses without control). The LH power is then reduced by the feedback control but with a delay of a few seconds due to the effect of the integral gain (integration of the previous tracking error). The proportional gain that we chose was maybe a little bit too high and explains why the control around the targets oscillates then a bit up to the end of the control window.

At higher density (~3.5$10^{19}$m^{-3}), the ICRH coupling conditions are improved and more ICRH power and energy can be launched (400MJ for 60s). In order to determine the best actuator for controlling the current density profile a new search optimisation control algorithm [12] based on the empirical maximisation of a global quantity has been applied to the HXR width. The algorithm finds by itself the way to maximize the HXR width by changing each 3s the values of the actuators n// and P_{LH}, following of the constant preset steps of variation (see Fig.6). From this experimental result, it is clear that at higher density n// is much more efficient in controlling the width and thus the current density profile than P_{LH}. This can be explain by the effect of electron collisionality process (P_{LH} is less efficient when the collisionality is high).

At such high densities where more power can be injected, an other important point for steady state operation is the protection of the plasma facing components. Real-time analysis of infrared cameras signals provides the surface temperature of twenty areas identified as critical for safety. In case of overheating, modulation of the power sources is performed. An example of integrated control is shown in Fig.7 where the control of the HXR width using n// as actuator is combined to the heat load protection of PFCs components through a limitation of the LH power. The control starts at 20 s and each temperature is constrained to stay within a limited range: for this, a coefficient between 0 and 1 is applied to the pre-programmed power. These experiments provide a first successful attempt to address the complex non linear coupling between physics requirements for achieving the requested plasma performances and technologic constraints such as local power load, RF coupling and radiative events. This integrated control is in line with the work that will be needed on ITER to insure global parameter control, current and pressure profile and MHD control while keeping the tokamak in a safe state.

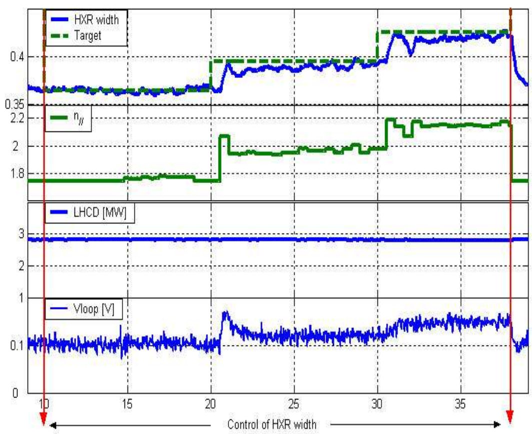

Fig.1.Feedback control of the HXR width with n// as actuator (PI control) while keeping the LH power constant (#35579, BT=3.6T, Ip=0.6MA, Nl=2.5$10^{19}$m^{-2})

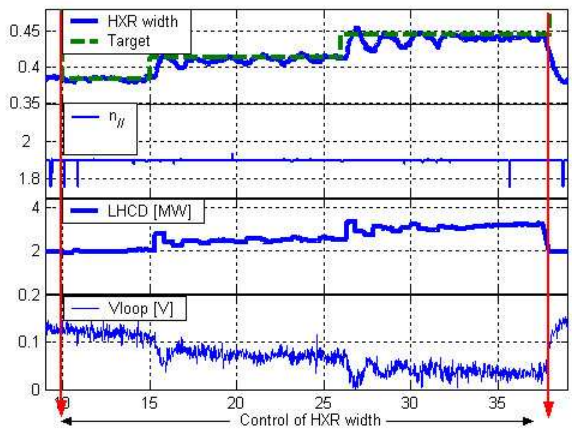

Fig.2.Feedback control of the HXR width with PLH as actuator (PI control) while keeping the n// index constant (#35588, BT=3.6T, Ip=0.6MA, Nl=2.5$10^{19}$m^{-2})

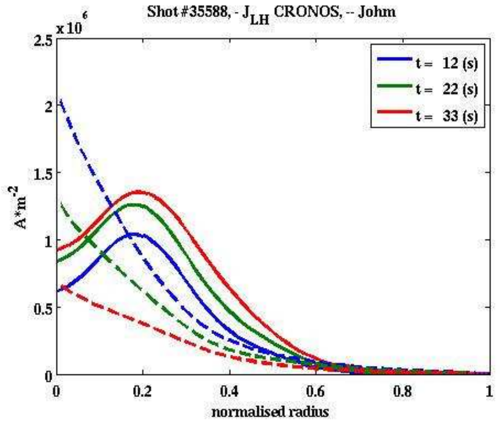

Fig.3 Cronos simulation of shot #35588. Time evolution of LH current density and ohmic current profiles during the control phase. Broadening of the LH profile is clearly seen while P_{LH} increases.

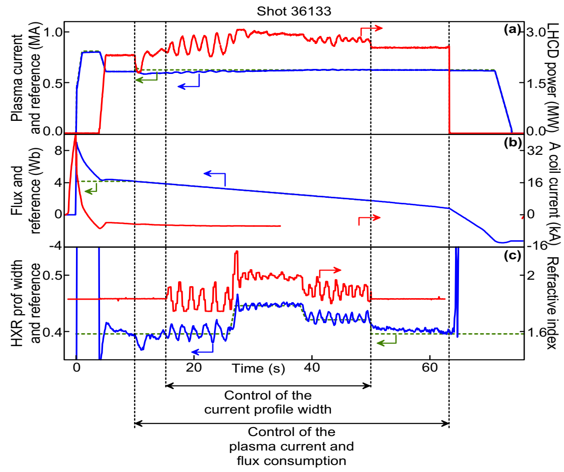

Fig.4 Feedback control of Ip with LH as actuator at fixed vertical magnetic flux consumption (Vloop=60mV) while the HXR width is controlled with n//. #36133 B_T=3.6T, I_P=0.6MA, nl=3.5 $10^{19}m^{-2}$.

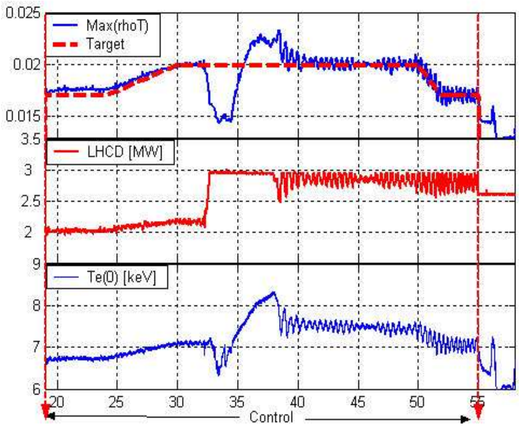

Fig.5 Feedback PI control of the maximum of the ρ^*_{Te} with LHCD power as actuator. Control start at 19s and ends at 55s. #36175 B_T=3.6T, I_P=0.6MA, nl=2.5 $10^{19}m^{-2}$. Central electron temperature Te(0) is also shown.

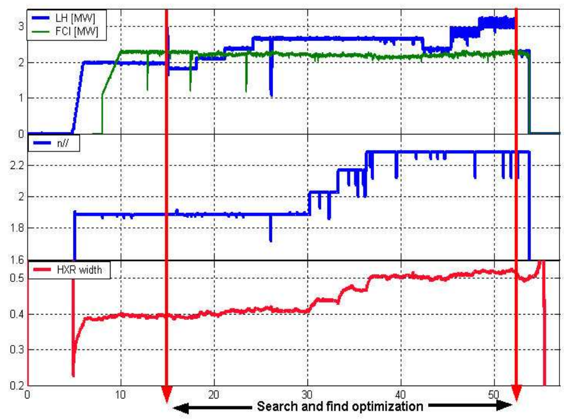

Fig.6 Search and find optimization control. The HXR width is maximized with LH and n// as actuators. Predefined LH power and n// steps are applied until the HXR width is no more maximised. #36194, B_T=3.6T, I_P=0.6MA, nl=3.5 10^{19} m^{-2}.

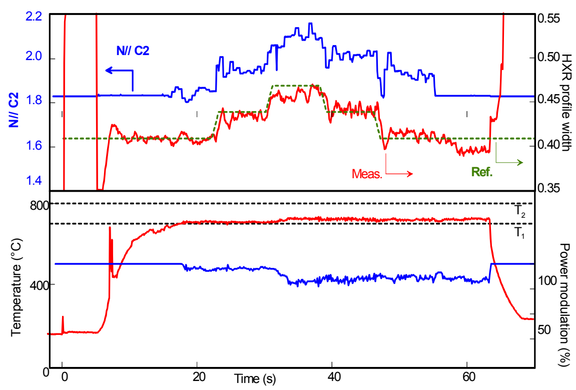

Fig.7 Example of compatibility between feedback controls: (Top) control of HXR profile width using LH refractive index, (Bottom) Temperature limitation decreasing the LH power.#36191, B_T=3.6T, I_P=0.6MA, nl=3.5$10^{19}m^{-2}$. Control starts at 19s and ends at 55s.

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