Physics and operational integrated controls for steady state scenario.

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Abstract: In recent campaigns, Tore Supra has focused its efforts on the physics optimisation and operation of stationary scenario with high input power (up to 8MW), duration of more than 60s and vanishing loop voltage (~80% of non-inductive current). For physics integration, Tore Supra has been equipped with a large number of new real time sensors. The control of the lower hybrid (LH) wave deposition profile width measured by the Hard X-ray camera has been achieved with the parallel index and power of the LH-wave using different type of control algorithms. The control of the current profile with the parallel index of the launched spectrum has been achieved in combination with loop voltage control using the central solenoid voltage as actuator. Temperature gradient has also been controlled and the effect of Electron Cyclotron Heating (ECH) on control assessed on temperature bifurcation phenomena. On the basis of the experimental power flux analyses, the seven infra-red cameras monitoring the five antennas and the toroidal pumped limiter have been used for setting up power load limit avoidance schemes and combined successfully to LH deposition profile and loop voltage control.

1. Introduction

Assembling the relevant physics features using integrated controls is expected to be a major challenge in the operation of ITER steady state scenario. The active and combined control of performance, power injection and extraction, fuelling and instabilities during relevant duration is mandatory for a reactor but are not yet demonstrated in today's fusion devices. This research also invokes novel techniques for controlling non-linear and sometimes competing physics phenomenon such as those related to pressure and current profile, confinement and radiation control or plasma instabilities.

ITER candidate scenarios such as the steady state advanced tokamak scenario or the hybrid regime [1] would be operated for duration exceeding 2000s with broad current density profile to optimise the plasma stability and create a wide region of improved transport. These requirements could be obtained by maximising the off-axis bootstrap current with the assistance of other current drive systems such as Electron cyclotron current drive (ECCD) and possibly lower hybrid current drive (LHCD) for controlling the detailed shape of the current density profile.

Active plasma profile control experiments have been achieved on several devices such as JET and then DIII-D. These experiments have demonstrated the possibility to modify the current profile either during the main heating phase [2] or in the current ramp up phase [3]. However, these experiments have been achieved in duration hardly exceeding the plasma resistive time [4]. For steady state scenarios it is essential to demonstrate that active current profile control is compatible with actively cooled plasma facing components protections on duration much longer than the resistive time and close to the thermal equilibrium time of plasma facing components (PFCs).

Using its long pulse capability and actively cooled plasma facing component system, Tore Supra can address these questions and develop advanced control methodologies for the physics and operational integration of plasma scenario using stationary scenario with high power and duration exceeding several minutes [5]. In recent experimental campaigns, Tore Supra has therefore focused its efforts on the physics optimisation and operation of stationary scenario with higher input power (>7MW), vanishing loop voltage (more than 80% of non-inductive current) with duration of typically 60s and above for the preparation and implementation of active profile control together with power heat load protection of PFCs.

This paper first presents a summarised overview of the plasma control capabilities operated in Tore Supra in the context of long duration stationary discharges. Active profile control experiments recently achieved in Tore Supra are presented using these tools as well as their associated control techniques. The potential of actuators such as lower hybrid power P_{LH} and its parallel index $n_{//}$ and ECCD power are also assessed in current profile control experiments on the so-called oscillation regime [6] and internal transport barrier (ITB). The next section introduces the analysis of the power load on plasma facing components in Tore Supra which then led to the integration of heat load limit avoidance schemes together with active profile control.

2. Overview of experimental setting for stationary long pulse control

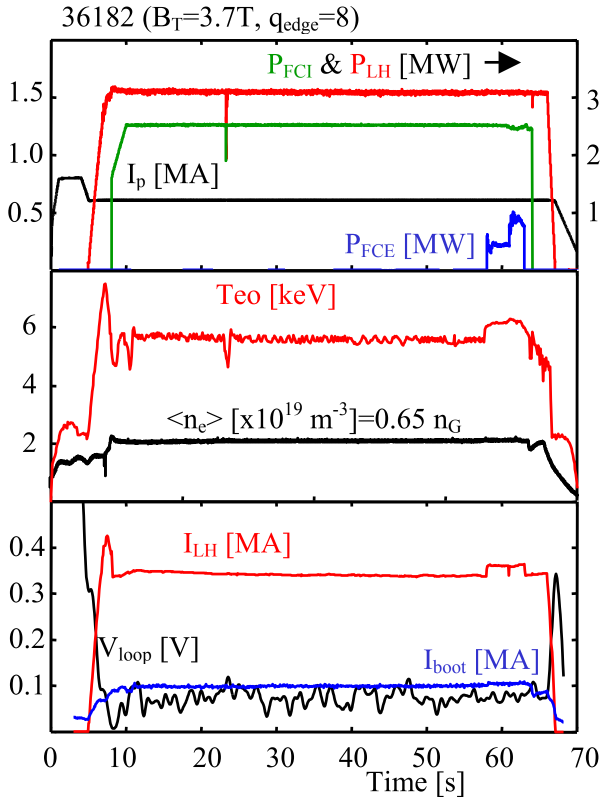


***Fig 1**: Typical stationary scenario used for profile control in Tore Supra with more than 80% of non-inductive current as inferred from the CRONOS code.*

Tore Supra (R=2.4m, a=0.72m) is equipped with three radiofrequency systems designed for long pulse operation. Three ion-cyclotron radiofrequency heating (ICRH) antennas between 42 and 63 MHz are able to provide up to 10MW of peak heating power within an envelope of 120MJ per antenna. Two Lower Hybrid couplers at 3.7 GHz are producing 4MW of peak coupled power and 3MW for duration of the order of 1000s with a controllable refractive parallel index spectrum varying from 1.7 to 2.3. In addition, two gyrotrons of the electron cyclotron resonance heating system (ECRH) at 118 GHz have been put back into service to produce typically 500 kW for a maximum duration of 5s. This system is also equipped with steerable mirrors in both poloidal and toroidal directions which have been used at fixed position for the experiments reported in this paper.

In 2004 and 2005 campaigns, Tore Supra has produced discharges with input power close to 8MW for duration of 60s and more (fig 1). In terms of power extraction, Tore Supra is now going towards a domain of operation with higher conducted and convected power flux through the last closed flux surface (fig 2). On-going power upgrade of LH klystrons is aiming at reaching longer duration and loss power flux compared to the ITER scenarios [7].

This type of discharges has been the workhorse scenario for the combined implementation and operation of profile control techniques and heat load limit avoidance schemes on PFCs. These limiter discharges (Ip=0.6MA, B_T=3.7T and a line average density of 3.5$10^{19}$ m^{-3} i.e. 65% Greenwald density) have been selected to combine both lower hybrid (LH) current drive (between 3 and 3.5MW) and ion cyclotron resonance heating (ICRH) coupling (from 2.5 to 3.5MW) at the same time. They show a central electron temperature close to 6keV and Te/Ti=1.8. The q profile is above unity in the plasma core and close to reversal. This type of plasma is suitable to minimise the loop voltage to typically less than 0.1V, making possible discharges of duration longer than 60s (typically 10 resistive times) and giving enough flexibility for combining current profile control with LHCD or ECCD. There is a remaining ohmic current of typically 100kA peaked in the plasma centre which tends to reduce the magnetic shear reversal. This appears to help in preventing plasma instability such as double tearing modes [8] which would otherwise degrade the discharge performances. The resonance position of ICRH has been chosen to minimise the loss of fast ions by the two effects driven by the significant ripple present in Tore Supra [9], namely, the direct losses of ions trapped in local mirrors of the toroidal field and the stochastic drift of large banana orbits.

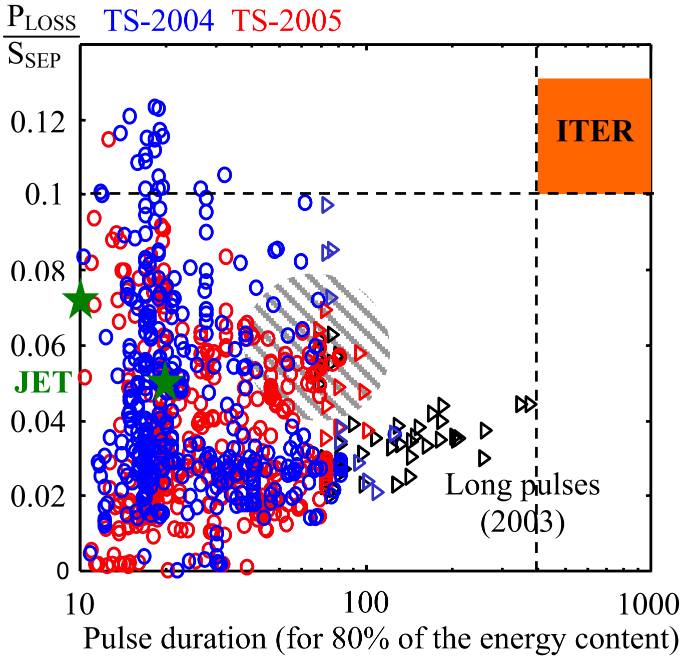


***Fig 2**: Operation domain of Tore Supra stationary discharges with combined active profile control and PFC limit avoidance schemes (shaded zone). P_{LOSS}=P_{TOT}-P_{RAD} and S_{SEP} is the surface of the separatrix. Typical Tore Supra resistive time: ~5s.*

Given the relatively modest β_N (=0.8) and poloidal beta β_p (=0.9) the bootstrap current fraction does not exceed 20% of the total current. In this sense, these discharges are far from the properties required for an "advanced tokamak" discharge which should feature a much stronger kinetic pressure with β_N of 3.5 and above. However the combination of profile control schemes with the off-axis LH power, long duration with respect to the resistive time (factor 10) and convected and conducted power level through the separatrix are making these regimes close to what is expected in a steady state regime.

The two current drive systems (LHCD and ECCD) are the main actuators for current profile control experiments. Their efficiency is mainly depending on plasma conditions such as plasma density, current and temperature. To produce reversed magnetic shear q profiles with 3 to 4MW of LHCD, feedback control experiments are carried out at modest current (Ip<0.7MA) and line average density below 3 10^{19}m^{-3}.

In addition, key new real time sensors have been installed on Tore Supra for the physics integration of steady state scenario. The hard X-ray emission (HXR) diagnostic (59 detectors distributed in two cameras) has been equipped with real time capabilities for the monitoring of the LH deposition. This system is capable of discriminating the energy of the bremsstrahlung emission in 8 different energy channels. For the real time measurements of the LH-deposition profile the 60-80keV energy channels from the horizontal camera are used since this energy is characteristic of the non-thermal HXR emission produced by the LH wave [10]. The HXR profiles are determined every 16ms in real time by a tomographic reconstruction based on a superposition of Bessel functions [11]. The Electron Cyclotron Emission (ECE) in X-mode is another key real time diagnostic for profile control. The 32 available real time channels have a radial resolution of 2.5cm and are not affected significantly by non-thermal emission for radii between 2.4 and 2.8m [12]. From the real time temperature data the normalised temperature gradient ρ^*_T ($=\rho_s.T/\nabla T$) is also inferred in real time and can be used as a sensor for the control of internal transport barrier [13].

For PFC protection, Tore Supra is equipped with a comprehensive thermographic system of seven endoscopes [14] monitoring the five antennas and the actively cooled toroidal pumped limiter (TPL) with a total of eight cameras. As required for steady state operation the endoscope envelopes are actively cooled. The system record infrared images every 20ms with a spatial resolution of the order of 9mm and supplies the maximum value of the luminance in 16 predefined areas on PFC where the heat load is expected to be critical at high power. The primary purpose of this system is to prevent any damage to the actively cooled PFCs by long duration plasma.

Associated with these diagnostic capabilities, real time computations and the shared memory network capabilities have also been enhanced. A newly installed central controller provides a convenient platform to test novel algorithm techniques linking actuators and sensors for profile and global parameter control.

3. Active profile control experiments at low loop voltage.

a. Control of the LH-power deposition profile

Preliminary profile control experiments have been achieved at moderate plasma density (~2.510^{19} m^{-3}) without ICRH power and loop voltage of about 50mV. At this density, the LH power is an efficient actuator to modify the current density profile. With a normalised β_N of 0.4 and a poloidal beta β_p of 0.4, the bootstrap current is negligible (<10%), therefore, the non-inductive component is almost entirely produced by the LH-power. With 2.5MW, 90% of the plasma current is driven by the LH-wave.

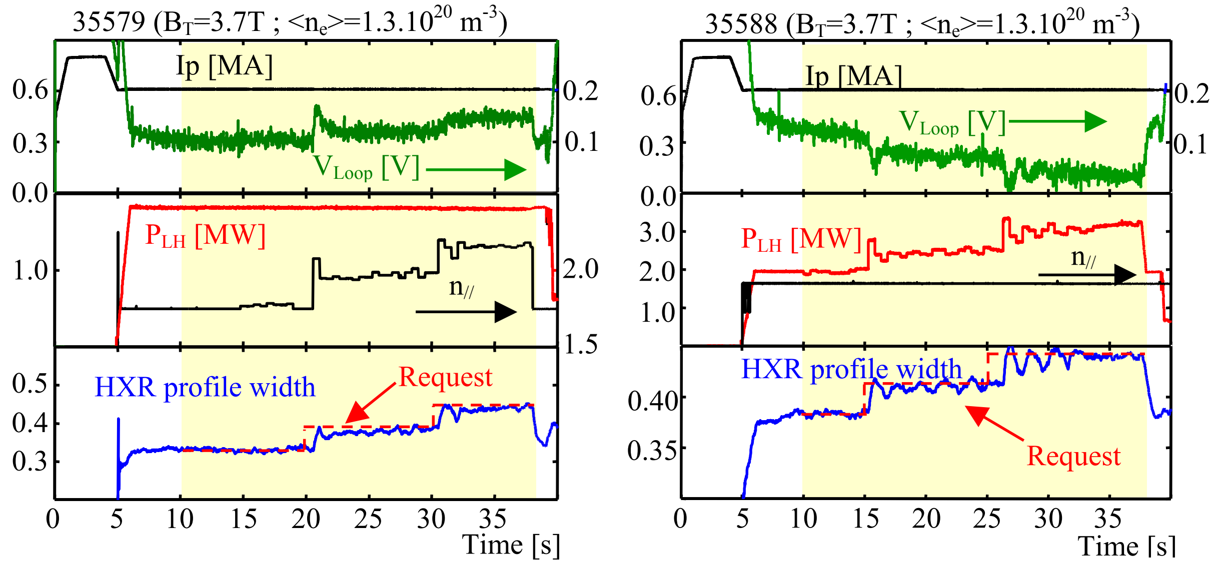


***Fig 3a and 3b**: Control of the hard X-ray profile width using $n_{//}$ (left) and P_{LH} (right) as actuator from 10 to 38s. Note that V_{loop} behaves differently in the two cases.*

In past experiments, the dependence of the current profile with the parallel index $n_{//}$ of the LH wave has been identified [15]. It was shown that the q profile broadens as the parallel index is departing from its peak value of 1.83 where the spectrum of the LH wave is the most directional. In the present experiment the broadening of the deposition of the LH-wave is directly controlled by the parallel index of the LH-wave. The control of the LH deposition profile is made using as sensor the HXR profile width defined at half maximum of the profile using the 60-80keV energy band. This experiment has been achieved with a proportional-integral (PI) controller with a requested HXR width varying in two increasing steps (fig 3a) with the objective to broaden the q profile. The gains (G_P=2000 and G_I=200) have been determined from dedicated open loop experiment. During the control phase (10 to 38s), the loop voltage also changes as a result of the loss of current drive efficiency when the parallel index increases. This implies that the ohmic current is also modified and participates to the changes of the overall q profile. Indeed, q profile measurements (internal inductance and central q_o inferred from infrared polarimetry) are indicating that the total current does not broaden significantly. In another experiment the HXR width is controlled by the LH-power as actuator (fig 3b). It appears that the effect of increasing the LH power tends to broaden the LH deposition profile. In this experiment, the loop voltage is this time decreasing and the ohmic current therefore decreasing. These two preliminary experiments demonstrate the feasibility to control the LH deposition profile width using P_{LH} and n// separately. However, they also indicate that the remaining ohmic current component is still playing a role in the resulting q profile particularly in the plasma centre where it is maximum.

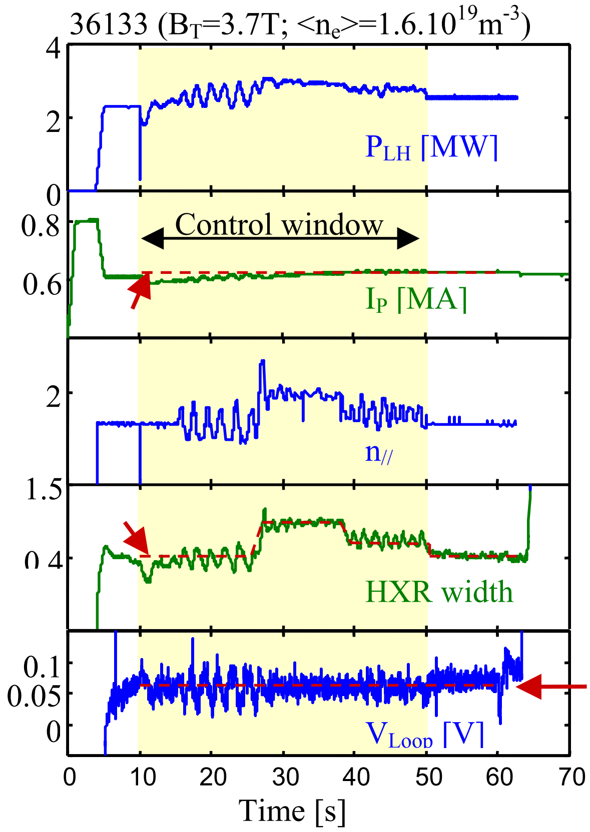


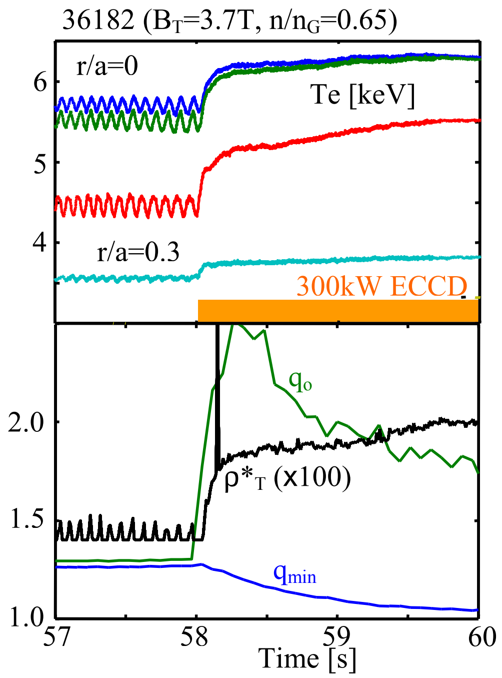
***Fig 4**: Triple control of Ip by P_{LH} (box 1 & 2), HXR width by n// (box 3 & 4) at constant loop voltage using the voltage of the primary circuit. (Arrows: the requested waveform).*

To minimise this effect, the next experiment has coupled the feedback control of the HXR width with the control of the poloidal flux using the scheme routinely used in Tore Supra experiment: Ip controlled by P_{LH} and flux consumption (V_{loop} fixed at 60mV) by the main poloidal field amplifier voltage. This scheme therefore guaranties that the current profile is broadened (as confirmed by q profile measurements with infrared polarimetry and the CRONOS analysis) while keeping a constant flux consumption (fig 4). This “triple control” scheme worked successfully, using the same gain parameters than those adjusted for the experiments shown in figure 3a and 3b and three different steps of the HXR width lasting about 10s each (~2 times the resistive time). This demonstrates that the deposition profile can be robustly controlled consistently with the remaining ohmic current.

b. Interaction between current density and temperature bifurcation.

In the absence of deleterious MHD instability and moderate plasma density with 2.5MW of LH power, the q profile is generally reversed above unity. In Tore Supra, this often triggers the onset of a central electron internal transport barrier (ITB) inside r/a=0.3 [16] and sometimes the so-called O-regime characterised by non-linear temperature oscillations [6].

When increasing the LH-power in previous experiments, transition to a higher temperature regime is sometimes observed. For the control of enhanced performance, this has motivated the use of the LH power as an actuator to reproduce these transitions using the normalised temperature gradient ρ^*_T as a sensor. Using this parameter, active control of the temperature gradient has been attempted successfully with the LH power as actuator using a proportional integral controller. By increasing the LH-power request, this experiment did produce a temperature transition as expected. The bifurcating nature of these temperature transitions is strongly linked to the magnetic shear. Therefore, a more sophisticated algorithm



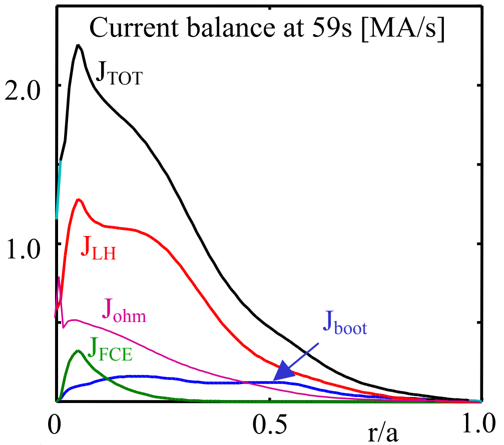


Fig 5a (top): *Temperature oscillations suppression with ECCD.* ***Fig 5b (bottom)****: current balance at 59s from the CRONOS code.*

invoking both temperature and current profile would be required as this has been attempted in similar experiments in JET [2].

Present experiments have also reproduced the O-regime on several occasions. Simulations of past experiments with the CRONOS code [6] have shown that the interplay between the electron temperature (Te) and the LH-current is a plausible candidate for this oscillating behaviour which could also be regarded as an incomplete ITB transition driven by the dependence of transport with the magnetic shear. From this initial physics study, the current profile looks the most promising control parameter for stabilising this behaviour. This was first achieved by modifying the peak value of the parallel refractive index n// of the LH wave which resulted in a frequency change of the oscillation and even a complete suppression of the oscillation leading to a complete temperature transition. This experiment confirms that the LH-current does play an important role in the onset of this behaviour and could be therefore used as an actuator in future feedback control experiments.

Similar tests have been carried out using pre-programmed ECCD power. This tool can induce local modification of the current profile. In previous experiments, it was shown already that co-ECCD deposited at r/a=0.22 could trigger the O-regime [17]. In the present experiment, the opposite has been observed: 300kW of co-ECCD deposited at r/a=0.06 in an O-regime can trigger transition to a fully developed ITBs (fig 5a & 5b). This suggests that the ECCD even at moderate power (<500kW) can be also used as an efficient actuator for controlling the O-regime giving good prospects for future active control experiments of improved confinement regime with the current profile.

4. Integration of profile control and power load limit avoidance schemes

At higher density (~3.510^{19} m^{-3}), the ICRH coupling conditions are improved and more than 3MW of ICRH and 3MW of LHCD (~400MJ for 60s) can be launched producing a central electron temperature reaching 4 to 5keV (see fig 1) while keeping the flexibility of actuators (P_{LH} and $n_{//}$) for current profile control.

During these stationary discharges the most critical components are the RF antennas and LH-launchers where hot spots or overheating of larger areas can be observed with the infrared diagnostics. The heat flux sources (fast electrons generated by the launchers, large orbit ions, radio-frequency sheath effect) and the deposition location on PFCs of these power loads have been identified by combining the IR diagnostics and calorimetric measurements from the cooling circuits of the antennas and launchers [18, 19]. All these information (see table below) are inserted in the controller that selects the appropriate way of action so as to keep the temperature below the operational limits of the component [20]. In this process, it is assumed that each object is a black body (i.e. the background contribution is neglected).

Location of heat load	**Interaction**	**Physics mechanism**	**Controller action**
LH-launcher side limiter	LHCD→LHCD	Fast e- generated in front of LH-launcher	Reduce Power of the responsible LH launcher
LHCD wave guide	ICRH→LHCD	Fast ion generated by the IC wave	Reduce total P_{ICRH}
ICRH antenna side limiter	LHCD→ICRH	Fast e- generated in front of LH-launcher	Reduce total P_{LH}
ICRH antenna screen	ICRH →ICRH	Fast ions produced by RF sheath effect	Reduce power of the ICRH responsible antenna

This is justified when the material observed by the camera is made of carbon or CFC. To prevent overheating of a component the additional power is varied between 0% down to 75% within a temperature range chosen below the technological limits of each area of interest. This limit avoidance has been put in action throughout the discharges and combined with the control of the LH deposition profile presented in section 3. A larger temperature limit acting as an interlock causes a plasma stop in case this avoidance scheme fails.

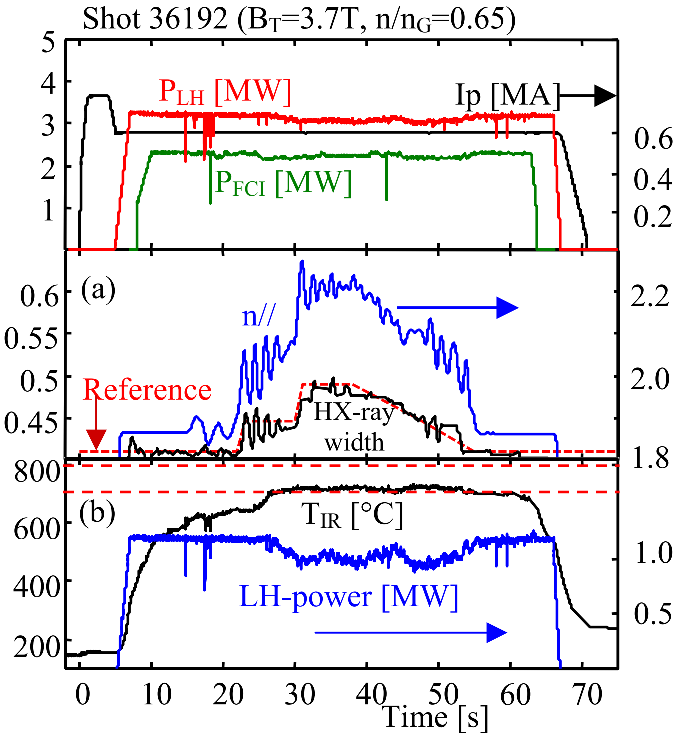
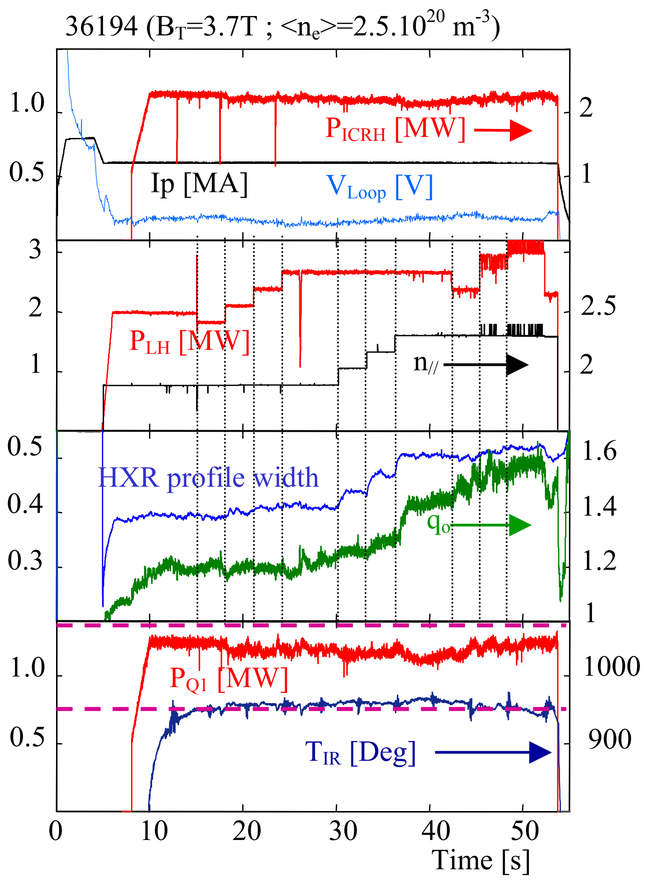


Fig 6: Combined control of the LH deposition profile (a) combined with Infra-red limit avoidance of PFCs. In (b), the IR avoidance limit scheme acts on one LH-launcher as the temperature reaches its limit of 700deg.

These experiments address more particularly the complex non-linear coupling between physics requirements for achieving the requested plasma performances within technologic constraints. As the parallel index is modified (fig 6) by the profile controller, the LH reflected power on the launcher increases. This causes a temperature increases on one of the launcher and the LH power is modulated by the limit avoidance scheme. The HXR width is reached despite the LH power modulation produced by the protective action.

Finally, the IR limit avoidance of PFCs has been also used successfully together with the control of the LH-power deposition width by both $n_{//}$ (fig 7a) and P_{LH} using a so-called “search optimisation” algorithm. This algorithm searches the maximum of HXR width by making steps of both actuator one after the other. Recent simulations using the CRONOS code have used this algorithm and demonstrated its efficiency for the optimisation of fusion performance for ITER scenarios [21]. The optimisation of the HXR width leads to a broadening of the q profile: the internal inductance drops from 1.16 to 1.10 and the central q increases from 1.2 to 1.6 as inferred from infrared polarimetric measurements and confirmed by the CRONOS current balance analysis. The total ohmic current remains roughly constant as shown by the evolution of the loop voltage. This is achieved while the ICRH power is being modulated as the temperature of one ICRH antenna septum reaches the limit of 950 deg caused by RF sheath mechanism [19] as shown on figure 7b.



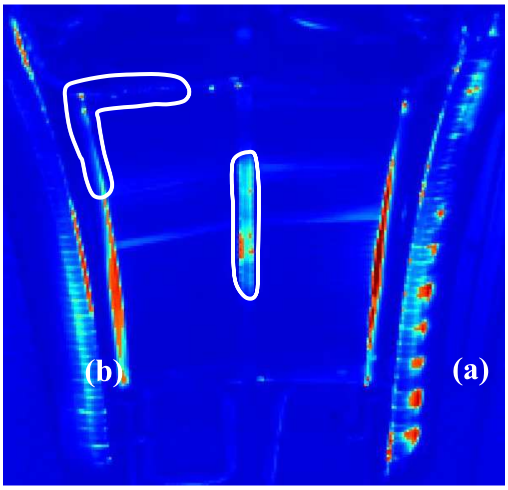


***Fig 7a** (left): Combined control of the LH deposition profile with both $n_{//}$ and P_{LH} using the "search optimisation" algorithm and IR avoidance scheme. **Fig 7b** (above): IR image of the ICRH antenna. The masks show the area from where T_{IR} is issued in figure 7a. The other hot zones are originating (a) from fast electrons generated by the LH launchers and (b) from carbon deposits.*

These plasma control experiments are showing that optimising current drive deposition to get a broad q profile is feasible and can be compatible with power handling limits on long durations. They are pioneering the integration work that will be required on ITER stationary scenario when combining several types of control such as global performance control, profile control, plasma instability control and Beryllium PFC components limits.

5. References

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