Real Time Control of Fully Non-Inductive 6 Minute, 1 Gigajoule Plasma Discharges in Tore Supra

D. van Houtte, G. Martin, J. Bucalossi, F. Saint-Laurent and the Tore Supra Team

Association EURATOM-CEA, CEA/DSM / Département Recherche Fusion Contrôlée,
Centre de Cadarache, F-13108 Saint Paul Lez Durance Cedex, FRANCE,

e-mail contact : Didier.van-houtte@cea.fr

Abstract: The experimental programme of Tore Supra has been devoted in 2003 to study simultaneously heat removal capability and particle exhaust in steady-state fully non-inductive current drive discharges. This required both advanced technology integration and steady-state real time plasma control. In particular, an improvement of the plasma position within a few millimetres range, and new real time cross controls between RF power and various actuators built around a shared memory network, have allowed Tore Supra to access a powerful steady-state regime with an improved safety level for the actively cooled plasma facing components. Feedback controlled fully non-inductive plasma discharges have been sustained in a steady-state regime up to 6 minutes with a new world record of injected-extracted energy exceeding 1 GJ. Advanced tools, experimental results and brief physics analysis of these discharges are presented.

1. Introduction

The Tore Supra experiment explores the high injected energy domain and holds, for more than 8 years, the record of injected and extracted energy in a tokamak (figure 1): 1min, 180 MJ in 1992 [1]; 2 min, 280 MJ in 1996 [2]; 4min, 740 MJ in 2002 [3]; and now 6min, 1,07 GJ in 2003 [4]. To reach such an injected energy record, it is necessary to implement on the device simultaneously:
i) A strong toroidal magnetic field in a large volume, usually provided by room temperature copper coils. On Tore Supra, it is operated at 3.4 Tesla using the NbTi super-conducting coils cryogenically cooled at 1.8 K [5],
ii) A strong toroidal current usually induced by a transformer, inherently pulsed. On Tore Supra, it is generated by injecting up to 5 MW of Lower Hybrid (LH) waves at 3.7 GHz delivered by two, launchers with a parallel index spectrum which can be changed between 1.5 and 2.5. The cooling

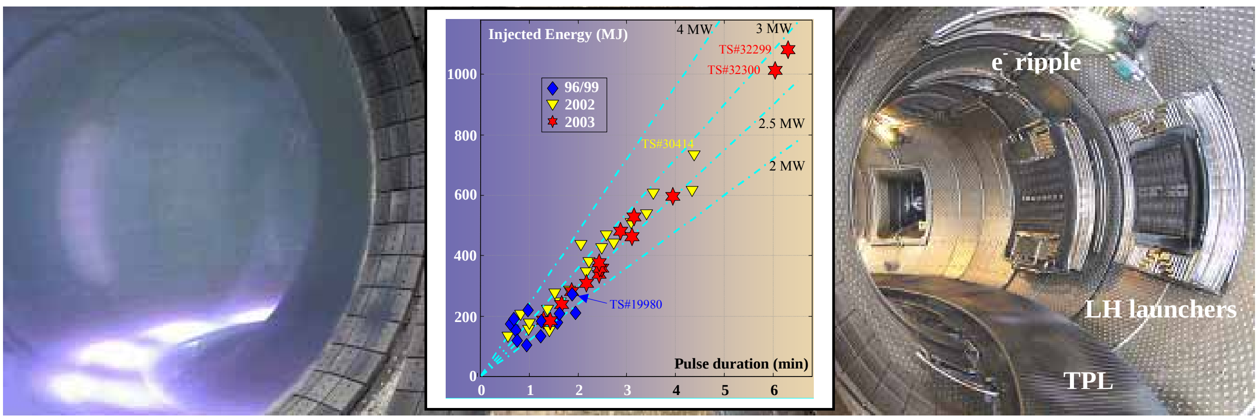

Fig 1: Interior of the vacuum chamber with plasma (on the left) and without plasma (on the right). The graph represents the Tore Supra long-pulse high-energy operation domain: the blue diamonds correspond to results obtained prior to the installation of the CIEL components and the yellow triangles and red stars to those obtained afterwards

loops of the LH generators have been recently improved by adding a 75 m^3 water tank into the loop. This tank, together with a heat exchanger, allow to continuously maintain the water inlet of LH generators at sufficiently low temperature (approximately 30°C) and to operate the LH generators during approximately 1000 sec,

iii) Actively water cooled plasma facing components. Tore Supra is now equipped with limiters close to the plasma, made with carbon fibre composite (CFC) tiles bonded on copper alloy tubes, which have the capability to remove up to 15 MW of convected power (peak power density 10 MW/m^2) [6]. Almost 100% of the wall has been covered with steel panels filled with a primary high temperature pressurized water loop (120°C, 30 bars, 980 m^3/h). They include bumpers, ripple protections and inner vessel protection panels, on the upper part, the outboard limiter and RF antenna protections, in the middle part and the toroidal pump limiter sectors on the lower part. A secondary loop, coupled to a heat exchanger, removes the thermal energy through cooling towers.

iv) An active particle control. New particle injectors have been installed on Tore Supra in 2003:

- a new pellet injector, built by PELIN Laboratory and based on a screw extruder coupled to a fast valve for pneumatic acceleration. It has the capability to inject continuously hydrogen/deuterium pellets of adjustable size (2-6 x 10^{20} atoms) at frequency higher than 10 Hz, velocity between 100 and 900 m/s, with a very high level of reliability. Pellets can be injected from four different poloidal locations,
- a new a pneumatic pulsed Supersonic Molecular Beam Injector was developed and successfully used. This technique is based on the fast expansion of a small volume of gas at pressure (typically 5 bars) through a Laval nozzle into the plasma chamber.

A feedback loop on the frequency of the injectors has been successfully implemented to control the plasma density. The Toroidal Pumped Limiter, located at the bottom of the vacuum vessel, is used for scrape-off layer pumping, and can remove up to 4 $Pa.m^3/s$ of deuterium or helium with turbo-molecular pumps,

v) A real time controller and continuous data acquisition system.

2. Real time control operation

With the main goal of a continuous operation, the Tore Supra Data Acquisition System (DAS) has been upgraded. The supervision system, storage and timing tasks are now continuously running. To avoid too many accesses to the central database, a large memory cache on the local servers, updated every second, is used for data frames as well as discharge parameters. Thus plasma analysis can immediately start at a quasi real-time level. For the 6 min 18 sec 1 GJ record discharge, the stored data was 541 MB, corresponding to an average data flow rate of 1.4 MB/s.

To control the plasma in advanced regimes (not only the plasma position and density, but also its energy content, its temperature and current distributions…) and for long-duration plasma discharges, it is necessary to real-time react on several additional heating systems using information coming from different plasma diagnostics. The sharing of information, not only some measured quantities but also computed parameters, becomes an essential issue. Therefore a fast dedicated network (cf. figure 2) has been built (using SCRAMNet® boards from SYSTRAN Corporation), connecting together the various control units.

2.1 Plasma discharge equilibrium control

An improvement of the control of the plasma position and shape within a few millimetres range, together with a new real time cross-controls between the injected LH power [7] and various actuators built around a shared memory network, have allowed Tore Supra to access in 2003, a powerful steady-state regime. The equilibrium stability was maintained during the whole discharge

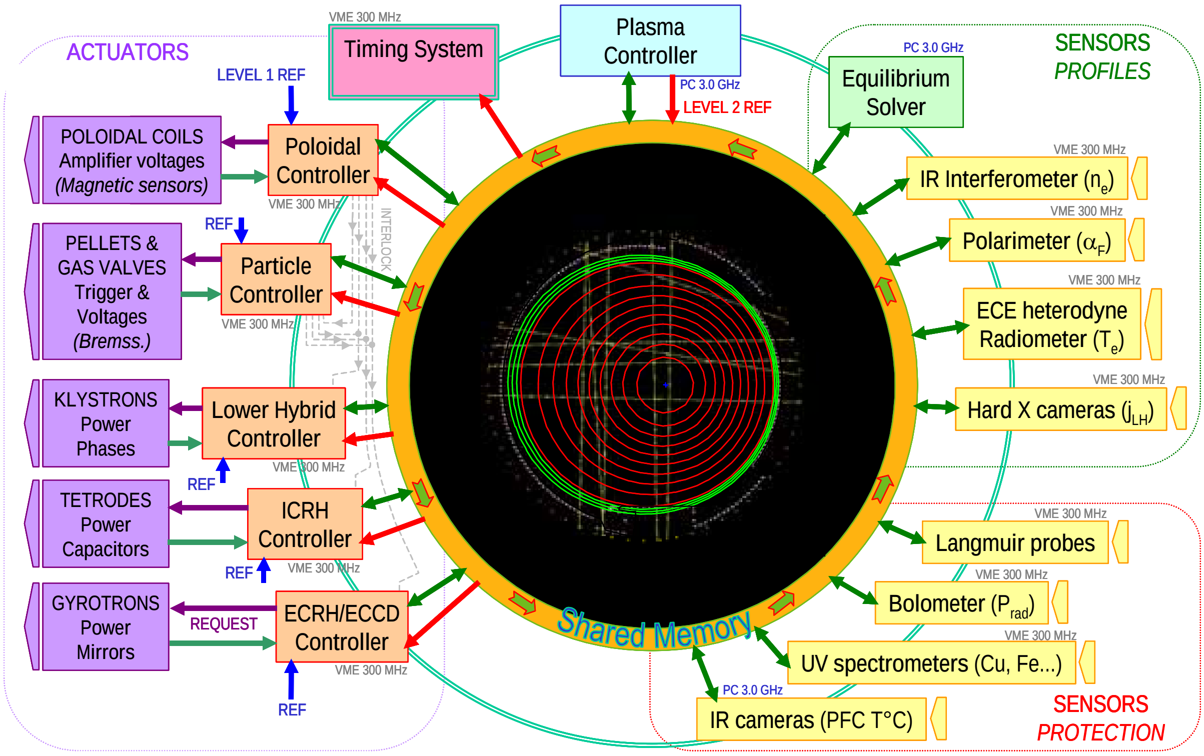

Fig 2: Central real time control system with the various actuators and the associated control loops, the diagnostics giving the plasma parameters and protection signals, the solver dedicated to real time equilibrium reconstruction, the central controller and the shared memory network using the SCRAMnet technology.

due to new integrators for the magnetic measurements used to control the plasma position and shape. Very low drift integrators [8] have been used and an almost perfectly circular plasma could be maintained for several hundred of seconds as shown in the figure 3. Small drifts, correlated with slight changes in the magnetic sensor orientation - at the level of a few micro-radian - were observed during some short discharges but were corrected for the longer ones. This real time control loop solves the electromagnetic equations in vacuum from magnetic coil sensors up to the plasma boundary. The calculated boundary is then compared with the request and a feedback PI controller acts on the magnetic poloidal field power amplifier voltages to adjust the poloidal field coil currents

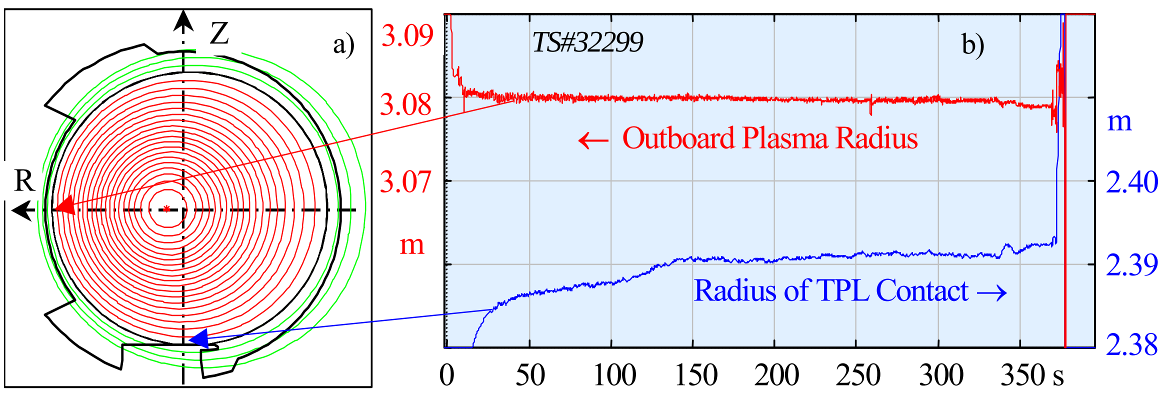

Fig 3: a) Magnetic surfaces at a given time

b) Time evolution of the outboard plasma radius and Toroidal Pumping Limiter contact radius

The control loop time is 2ms, regulated by a central megahertz clock. The typical CPU time (VME PowerPC unit at 300Mhz) is 1.8 ms, including data reading and saving (0.4 ms), calibration (0.2 ms), boundary solver (0.9 ms), feedback (0.2 ms) and safety control (0.1 ms). A new full real time, C++ fast solver, plasma equilibrium reconstruction using a finite element method is now routinely available on Tore Supra [9].

2.2 Plasma current control

During previous long pulse operation, the plasma duration was limited by the ohmic flux consumption, because a residual low loop voltage still existed in the plasma, with its intrinsic limitation on the ohmic heating transformer available current swing. Starting in 2003, plasmas were obtained in a rigorously zero loop voltage regime. After an initial ohmic heating ramp-up and flat top phase lasting a few seconds, the vertical flux was kept constant by the main poloidal field (PF) power supplies, providing no loop voltage at the plasma edge and leading to a slow current decrease until the plasma current was stabilized at 500 kA with a feedback control of the current on the LH power at a level close to 3 MW corresponding to a LH current drive efficiency of 0.073×10^{20} Am^{-2}/W. To enable stable and reliable long pulses with a pure radio-frequency (RF) induced current drive regime, it was necessary to overcome some arcing in the lines of the RF system. This led to a short transient in the power, which irremediably induces a fall of the plasma current and could terminate the discharge. Figure 4 shows such effect. An arc in the launcher (seen by the copper content of the discharge), causes an immediate decrease of the plasma current. However, the RF system was able to over-drive the current by injecting more power and thus recovering initial value. In spite of a small transient modification of the plasma characteristics, the discharge could be maintained.

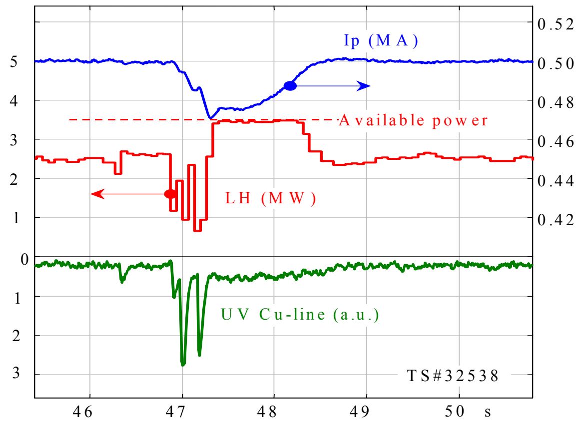

Fig. 4: Time evolution of plasma current, LH power and Cu-line impurity during a real time feed back of LH power on the plasma current for recovering a transitory LH power failure.

2.3 Particle control

Before upgrading the PFCs, most of the high power long discharges experiments exhibited an uncontrolled density increase over time due to outgassing from uncooled and poorly conditioned in-vessel components, when the injected energy exceeded about 150 MJ. As it is shown in figure 5, the plasma density is kept perfectly constant at its feedback controlled value for the whole discharge. The overall plasma impurity content (carbon, oxygen, metallic impurities such as Fe, Ni and Cu) is quasi stationary during the discharge, corresponding to an effective charge Z_{eff} close to 1.7. The radiated power corresponds to about 23% of the total injected power. During these discharges, about half of the injected particles are recovered in the pumps and the other half is implanted into the wall

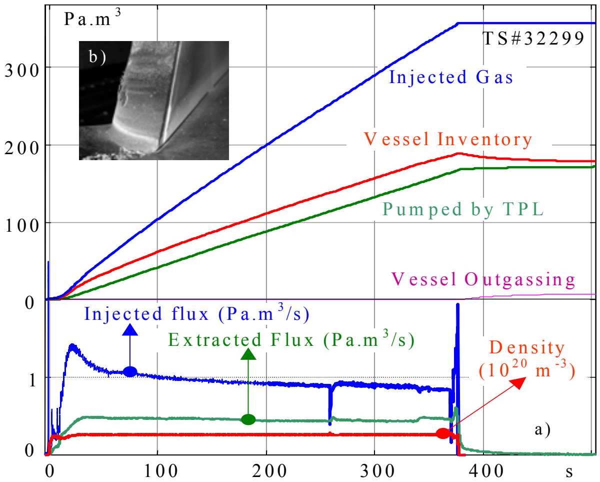

Fig 5: Particle balance between limiter and wall. Time history of gas injection, vessel inventory, outgassing and pumping a) and Carbon deposit observed on the neutraliser plates at the entrance of the pumped limiter b)

without any indication of saturation, even after two successive 6-minute discharges. Co-deposition of deuterium with eroded carbon, coming from erosion of PFC by the plasma, is expected to play a major role, as indicated by the observation of deuterium-graphite concretions growing on thermally insulated in-vessel areas [10] (see inset on figure 5). Additionally, loose carbon flakes were observed.

2.4 Heat control

In these discharges, the injected power is removed continuously from the vessel by the water loop, and all components within the torus reach a stable surface temperature after a few seconds, as shown in figure 6. Even inertial components, which are only submitted to low thermal fluxes in Tore Supra, reach a radiative equilibrium after 200 seconds, e.g. point IRP-2 in figure 6. These inertial components, which have been installed to protect parts between toroidal magnetic field coils from electrons trapped in the magnetic ripple wells, will be replaced in 2005 by actively water cooled components. A complete energy balance of the plasma by calorimetric measurements, is now possible due to the extensive instrumentation of PFCs, coupled to a continuous data acquisition. Recovery of the power by the pressurized water loops is illustrated on figure 6. Water enters the six modules of the TPL at 121°C, and goes out around 124°C. The 3°C increase corresponds to the removal of 250 kW by each module (water flow of 77 m^3/h, or 20 kg/s). A good toroidal repartition is observed and was optimised by a slight tilt of the limiter: 2 mm over its 5 m diameter. The 1°C increase of the inlet temperature after 1 ½ minute is due to the return of the water after a full turn in the loop composed of the pump, the machine itself and the heat exchanger connected together by more than 80 m of pipes. Repartition of the injected energy between the various components, as measured by the calorimetry of the water is also shown on figure 7. About 98% of the energy is accounted for with roughly ½ on the TPL (7 m^2), ¼ on the first wall panels (75 m^2 with the bumpers) and ¼ shared between the outboard limiter and antennas. The largest part of the last ¼ is absorbed by the LH launcher C3 which provided more than 70% of the injected power and are mainly related to HF losses in the launcher itself. About 3% are lost through fast electrons (100 keV), trapped in the magnetic ripple wells and impinging port and part edges between toroidal magnetic coils.

Real time control of main in vessel components is performed with an infrared camera and water cooled endoscopes, located in vertical ports. The surface temperature is analysed in real time in several zones, defined on the IR images prior to the shot. The IR thermographic system has been designed to oversee the entire surface of the TPL and five RF antennas. Each endoscope (2.5 m

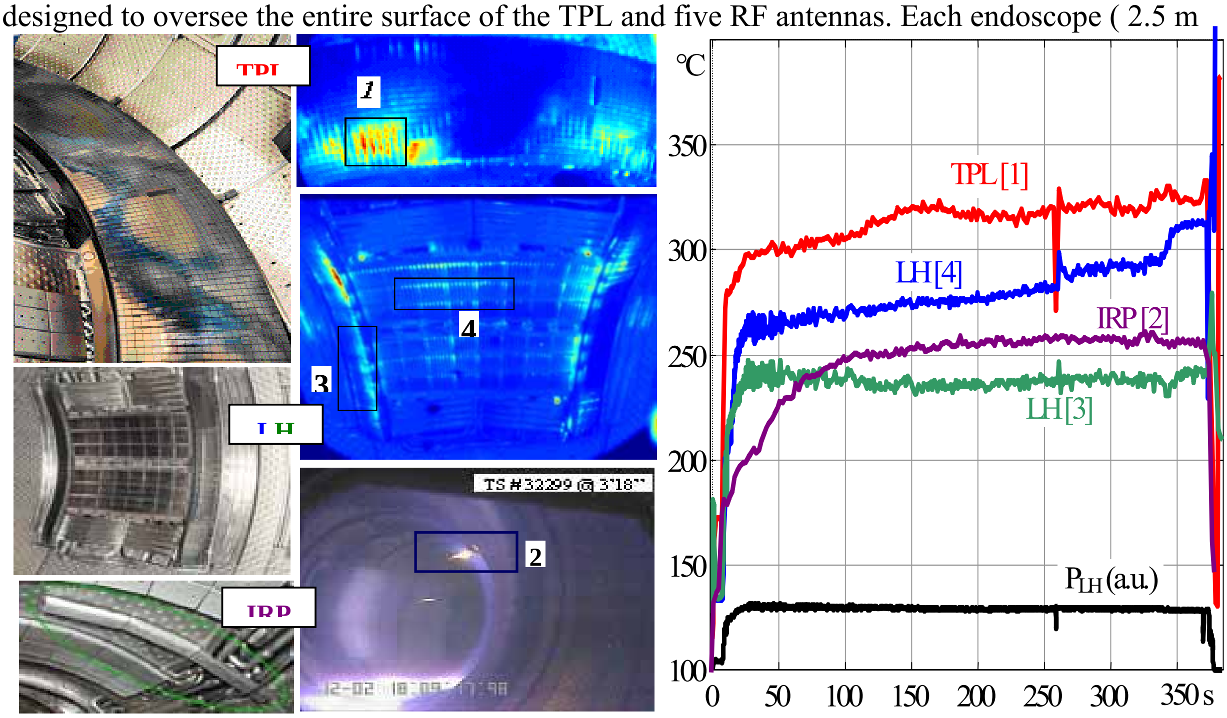

Fig 6: Time evolution of LH power and surface temperatures of actively cooled TPL, C3 LH launcher and inertial e ripple limiters

long) is equipped with 3 viewing lines: 2 IR cameras able to survey 2x35° of the TPL and 1 RF antenna). New generation digital cameras are used for real time control against overheating. The system resolution is about 9 mm, allowing to control the surface temperature of the smallest PFC elements (20 mm) with an error < 10%.

3. 6 mn, 1 GJ plasma discharges

As indicated on the figure 8, after an initial ohmic heating ramp-up and flat top phase lasting a few seconds, the vertical flux was kept constant by the main poloidal field (PF) power supplies, providing no loop voltage at the plasma edge and leading to a slow current decrease until the plasma current was stabilized at 500 kA with a feedback control of the current on the LH power at a level close to 3 MW corresponding to a LH current drive efficiency of 0.073×10^{20} Am^{-2}/W. With regard to the LH current drive efficiency, the maximum value was found for an $n_{//}$-spectrum peaked at 1.7, which was chosen for these long pulse experiments. The C2 reflection coefficient remained constant and equal to 4% during almost the whole discharge. On the contrary, the C3 reflection increased slightly from 4% to 7%. The exact origin of such a drift is not entirely understood, but might be due to small and slow (thermal time-constant several minutes) changes in the length of the wave guides.

The main plasma characteristics of the fully non-inductive 6 min, 1 GJ discharges are shown in figure 7: R = 2.42 m; a = 0.71 m, B_T = 3.4 T, Ip = 0.5-0.7 MA, $\langle n_e \rangle = 1.5\times10^{19}$ m^{-3} with deuterium gas. The plasma discharges were characterized by an ionic temperature $T_i(0)$ = 1.5KeV, a high electronic temperature $T_e(0)$ = 4.6 KeV, and a poloidal beta β_θ= 0.7.

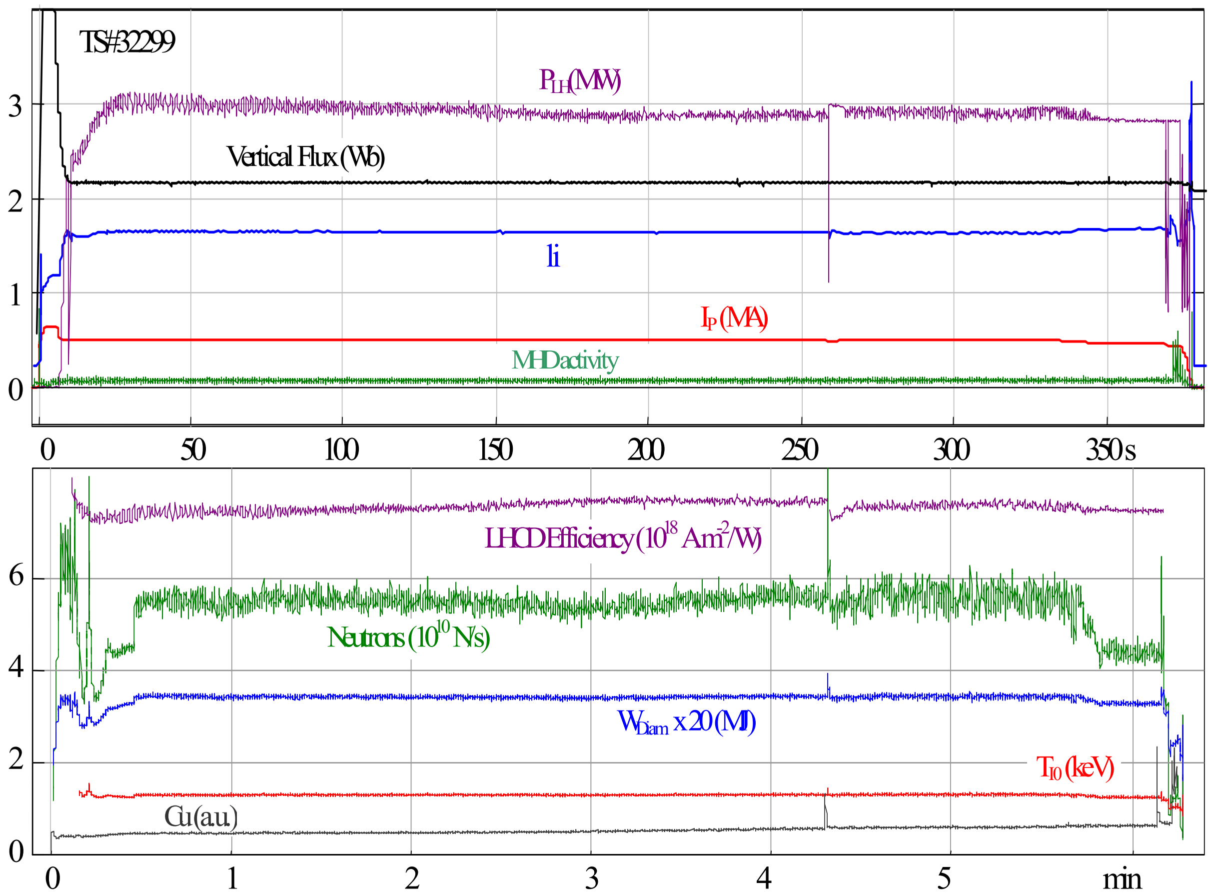

Fig 7: Time history of parameters: LH power, vertical flux, internal inductance, plasma current, MHD activity, LHCD efficiency, neutron flux, diamagnetic energy, ionic temperature and Cu impurity

These high safety factor (q_{edge}=8.6) discharges exhibit peaked current profiles. These were inferred by the relatively high value of the internal inductance (1.65) and on the very central localisation of fast electrons as seen by the hard X-ray (60-80 keV) radiation diagnostic, which are representative of current profiles in non-inductively driven current regimes (figure 8). The toroidal magnetic field value was set to avoid MHD instabilities in the plasma driven by the LH waves. No saw-tooth activity was observed, as the central safety factor remained between 1.5 and 2. The neutron flux remained constant during the discharge, confirming that the density, temperature and light impurity content did not change. A peaked electron temperature profile regime with a hot central core is rapidly obtained in these discharges, which exhibit an L-mode confinement, possibly associated with a so-called Lower Hybrid Enhanced Performance. An energy confinement time of about 65 ms corresponding to a 35% improvement with respect to L-mode ITER scaling for the thermal energy ($H_{ITER97-L}$=1.35) is obtained. Such an improvement of core confinement is correlated with a non monotonic q-profile calculated with the CRONOS code [11] and corresponding to a central reverse shear configuration. In spite of the presence of a double q=2 surface, no unstable MHD mode of the m=2 type is excited as it is usually the case when the current is fully driven by LH waves.

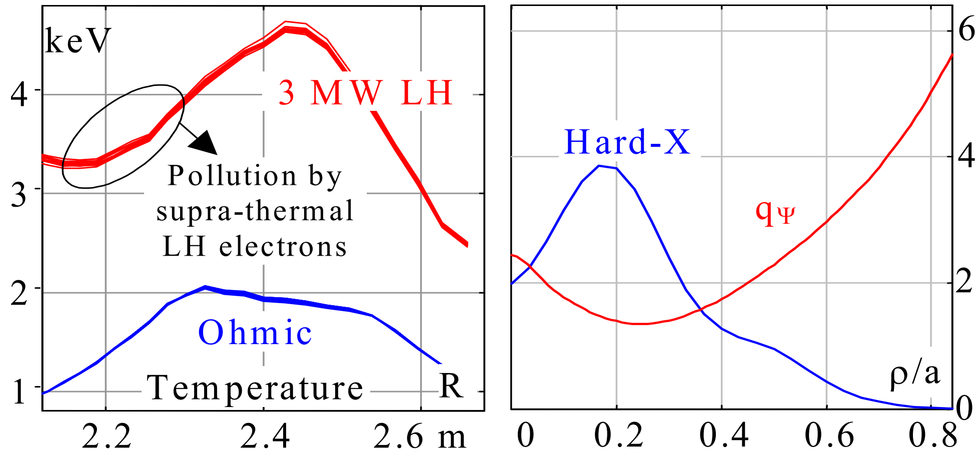

Fig 8: Zero loop voltage plasma main characteristics

4. Conclusion

The upgrade of the PFCs and the use of real time feedback control systems allowed for a significant increase of both the injected-extracted energy, up to 1.07 GJ with LH power alone, and duration of fully non-inductive plasma discharges up to 6 min 18 sec. The LH Current Drive showed its capacity to drive all the plasma current in an MHD stable way during several minutes and accurate balances of energy and particles were made: a reverse shear MHD stable configuration has been maintained with LHCD during 6 minutes. No indication of saturation, even after two successive 6-minute discharges has been observed.

Tore Supra can now explore the physics and technology of very long discharges, a multi-GJ energy at moderate injected power, multi-minute duration domain. The next major challenge for the Tore Supra team will be to upgrade, in coming years, the heating and current-drive systems in the framework of the CIMES project, in order to operate the tokamak at a higher injected power, up to 15 MW for 1000s.

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