Real time Plasma Feed-Back Control:
An overview of Tore-Supra achievements

G. MARTIN, J. BUCALOSSI, A. EKEDAHL, C. GIL, C. GRISOLIA, D. GUILHEM, J. GUNN, F. KAZARIAN, D. MOULIN, J.Y. PASCAL, F. SAINT-LAURENT
Association Euratom-CEA, CEA Cadarache, 13108 Saint Paul Lez Durance, FRANCE
E-mail: martin@drfc.cad.cea.fr

Abstract. Stable and reliable fusion plasma operation requires increasingly advanced control systems. This is especially true for steady-state operation in advanced modes, when several parameters are to be simultaneously optimised: e.g. the current profile, which has been related to the formation of internal transport barrier, and the density, which plays a crucial role both in the fusion power and in the plasma wall interactions. At a more technological level, good management of the power entering and leaving the plasma is required, by efficient additional heating coupling, and with a full control of radiation and convection losses and distribution to the first wall elements. For these goals, several feed-back mechanisms have been developed with success on Tore-Supra, in the past four years. Most of them are based on software, implemented in a set of micro-computers connected through a VME network.

Within the world fusion community, Tore Supra main goal is the production of thermonuclear grade plasmas over long duration, ultimately toward steady-state. It requires efficient ways to control plasma parameters, usually through feedback loops. This paper presents some of the most relevant results obtained on Tore Supra in the recent years.

1. Tore Supra Plasma Control Network

With its near circular shape, the Tore Supra plasma is not subjected to fast global instabilities such as VDE’s (vertical displacement events), observed on more elongated machines. The control loops, needed to maintain the plasma parameters, are operated with response times of a few milliseconds, and have therefore been realised by software implemented in microcomputers. A fast dedicated network has been built, connecting together several units, each in charge of a specific aspect of the plasma control. The sharing of information in real time insures a global and coherent function of the sub-units. A schematic representation of this feedback network is shown on figure 1, where only the four active computers have been identified: magnetic field, density, ion cyclotron and lower hybrid waves controls. Additional units only provide informations on the plasma, with no mean of retroaction, except through one of the four active units.

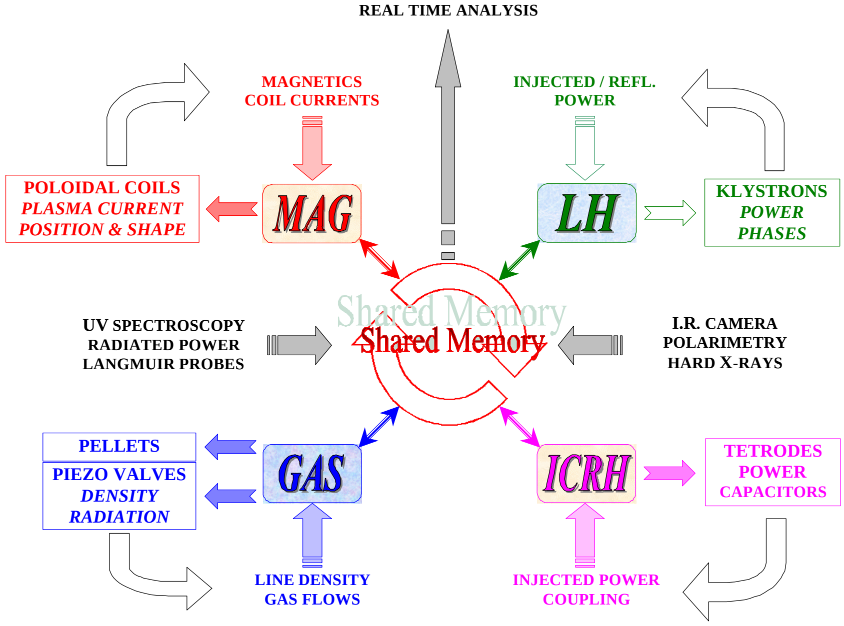


Figure 1. Tore Supra feedback network.

2. Position of the Plasma

Accurate positioning of the last closed plasma surface is required for power flux control and coupling of radio-frequency waves. Precision of a few millimetres is required, a value smaller than the characteristic length of power decrease in the scrape-off layer. For example, in Tore-Supra quasi-circular plasmas, a small triangularity of ± one centimetre, as shown on figure 2A, will change the power load peaking on the toroidal pumped limiter (TPL) leading edge by a factor more than two, above the technological limit of this actively cooled component. Such precise shaping control is obtained with a high quality set of magnetic probes, connected to very low drift integrators. A fast algorithm is used to determine the plasma shape in less than half a millisecond, allowing a fast feed-back through the poloidal coil currents [1]. The typical response is plotted on figure 2B, where the feedback gain was progressively increased: errors between observed and programmed values for the main radius R and vertical position Z are within 2 mm. A small oscillation around 12 Hz is observed, which increases as expected with the feedback gain.

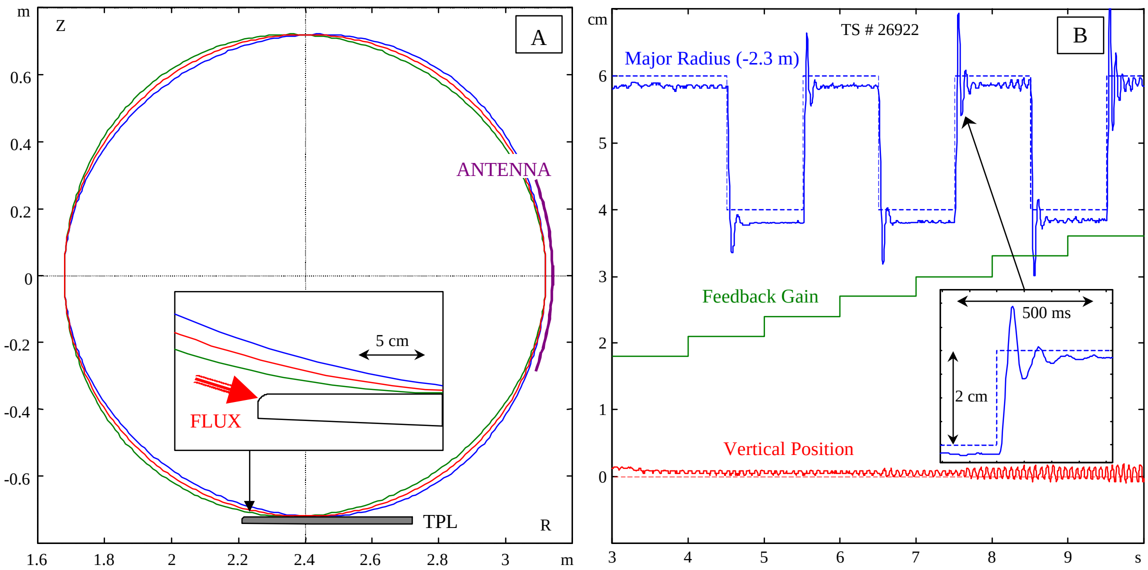


Figure 2. Plasma Position Feedback: A) Triangularity Control; B) Dynamic Response.

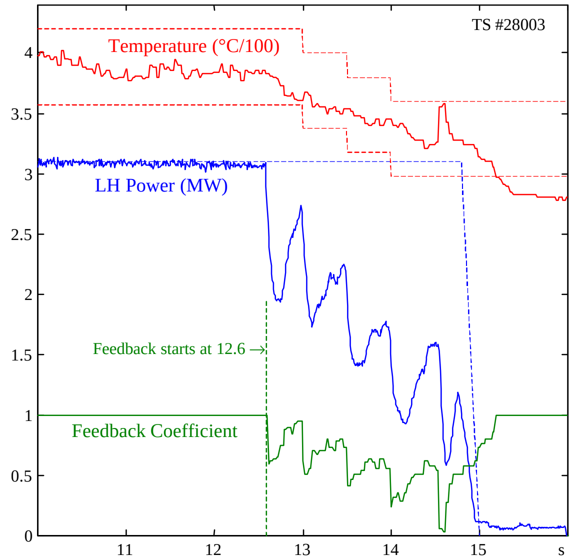
3. Temperature of the First Wall Elements

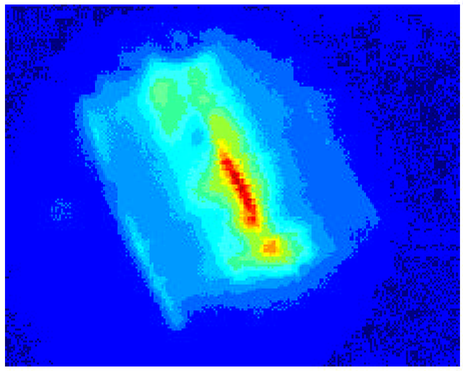
Whatever the quality of the magnetic control, the surface temperature of the first wall elements can rise unexpectedly, either due to some failure of the control, or due to the presence of an anomalous power peaking (e.g. with fast particle beams sometimes observed on Tore-Supra). A real-time analysis of an infrared camera view is coupled to the main additional power control unit. Temperature limitation though power modulation has been experimentally demonstrated during a few pulses, and will be installed as a routine safety feature in the future. An example is shown on figure 3, where the surface temperature of the main outboard limiter is used to limit Lower Hybrid waves (LH) power. The feedback loop is validated at 12.6 seconds, and the temperature is constrained to stay within a limited range: for this, a coefficient between 0 and 1 is applied to the pre-programmed power (dashed line).

4. Radiation Control

Power can be removed more uniformly from the plasma edge by radiation, thus limiting peaking factors. More than an order of magnitude of safety can be gained on the power load to the components, and radiation of a high fraction of the plasma power is envisaged for ITER. This loss channel is usually controlled by a density rise, and/or by impurity seeding. When the density level is imposed by other considerations (e.g. fusion power or current drive efficiency), impurities must be used. This has been tested on Tore-Supra [2], with the feed-back of the impurity fraction (e.g. neon in deuterium) on a radiation bolometer, as shown on figure 4A. A mixture of deuterium and neon is injected to reach a stable radiated fraction around 85%.

Another scheme, in which a “detachment criteria” (DoD) is defined by a ratio of bolometer channels (edge and central), exhibits slow oscillations, as shown on figure 4B. These are mainly attributed both to the slow response of the gas injection and pumping, and to a fast change in the fuelling efficiency close to the detachment. It has been discarded for the detachment controls based on Langmuir probes analysis, described below.





IR vue of the Outboard Pumped Limiter

Figure 3. Control of the Outboard Limiter Temperature with an Infrared Camera.

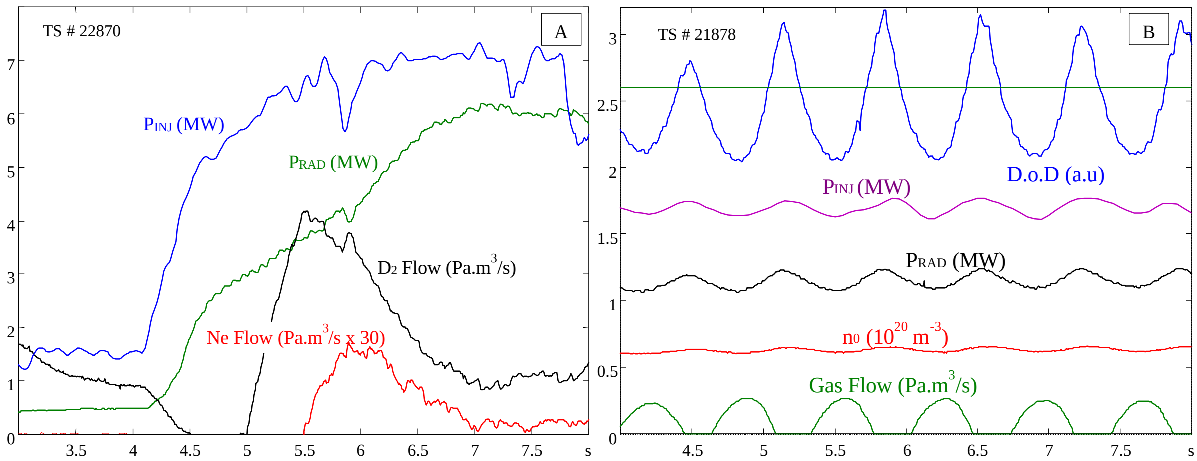


Figure 4. Radiation Fraction Control through Bolometric Measurements.

5. Plasma Detachment

When the radiated fraction approaches one hundred percent, the plasma detaches itself from the wall. Although this high radiation regime is favourable for the power extraction (no conducted power to the limiter), it is usually not compatible with the coupling of the RF waves, and tends to be prone to disruptions. Measurements with Langmuir probes in the scrape off layer show that, just before the detachment, the electron temperature decreases to a value which is always around 12±2 eV [3]. A real time analysis of probe voltage-current characteristics is performed, to extract the edge temperature, and this value is used to control either the edge density or the impurity content, and to operate as close as possible to the detachment, but with a still good coupling for the ICRH antennas. An example is shown on figure 5, where the edge temperature is maintained as close as possible to 14 eV, by limiting the amount of injected gas. When ion cyclotron waves (ICRH) are injected, the density is allowed to increase, to keep the edge regime close to the detachment value. The disruption probability is strongly reduced with this edge temperature control, compared to similar plasma operation in these high radiation regimes.

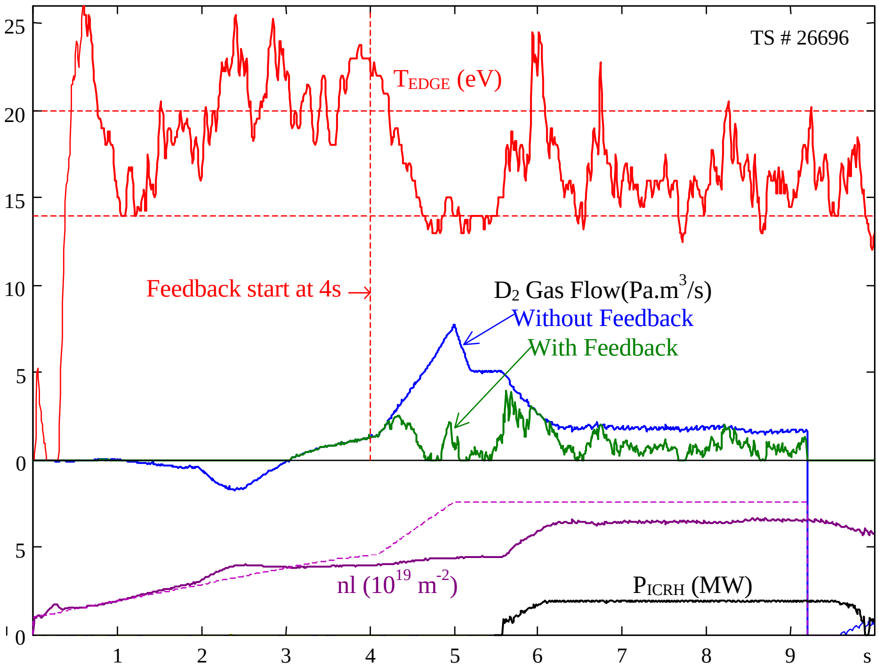


Figure 5. Control of the Edge Temperature, close to the Detachment Limit.

6. Injected Power Optimisation

On a Tokamak, steady state operation cannot be achieved with the ohmic current drive alone, which is intrinsically transitory. Additional heating, such as Lower Hybrid waves (LH), is required to drive the plasma current. To keep the control of the plasma current value, a new scenario has been developed. The main ohmic generator is driven as to keep the vertical flux constant, and the LH power is modulated to insure the control of the current. Two such tests are represented on figure 6: first without the LH power (TS #17018), and then with a steady control of the current by the LH system (TS #17970). Small steps were programmed in the current waveform, to evaluate the robustness of the feedback loop.

Long plasma pulses require stable and reliable operation of the additional power sources. This stability is increasingly difficult to maintain since power levels are close to the sources limits. Specific algorithms have been developed and tested to optimise the power availability. The required power level, dictated by a feed-back on the plasma current and/or density, is shared in real time among all the klystrons, as a function of their capability to inject the power. Lower power level are requested from the less conditioned tubes.

7. Profile Control

Optimisation of tokamak configuration, toward the so-called advanced scenario, requires the shaping of the profiles. This entailes first a fast and reliable determination of the density and current profiles. This is done at Tore-Supra with a real-time analysis and inversion of five interfero-polarimeter cords. Several algorithm have been tested, and compared to off-line full equilibrium codes: a reliable profile can be determined within a few milliseconds, presently limited by the precision of the Faraday angle measurement. The second step is to modify these profiles. On most tokamaks, the broadening of the current, which provides reversed shear operation, is obtained using fast current ramps, and is therefore not available in steady-state. On Tore-supra, preliminary tests of a feed-back of the LH wave spectrum index on the current profile have been performed, in a true steady-state regime, i.e. with full non inductive current drive. In this experiment, shown on figure 7, the phase between the 8 klystrons connected to the LH launcher was tuned in real time to modify the launched parallel index, with a feedback on the internal inductance l_i, used as a global parameter to evaluate the current profile broadening. The performance was mainly limited by the available power.

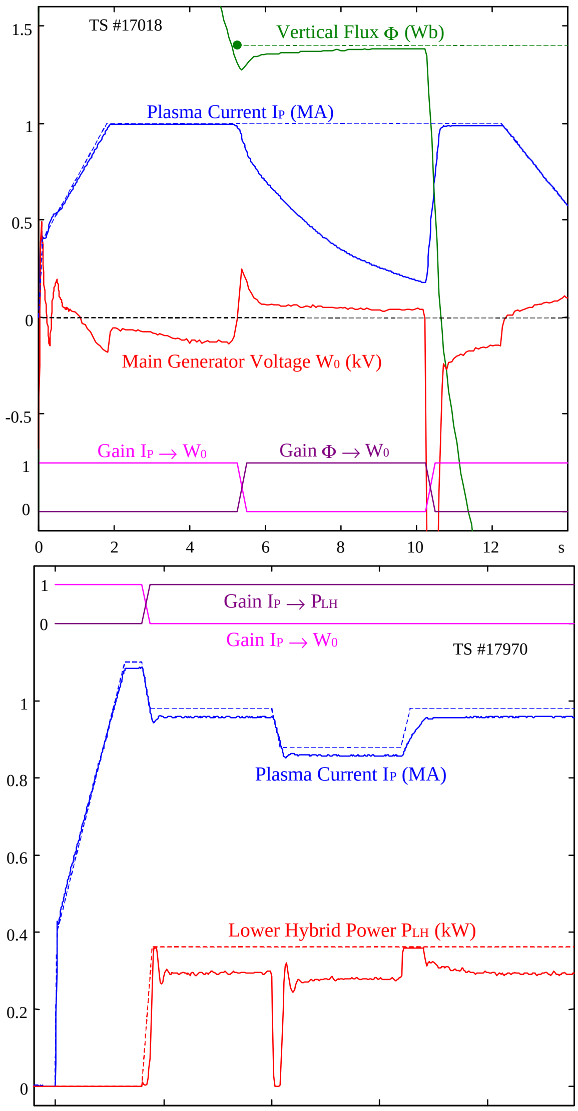


Figure 6. Plasma current Control with Lower Hybrid waves

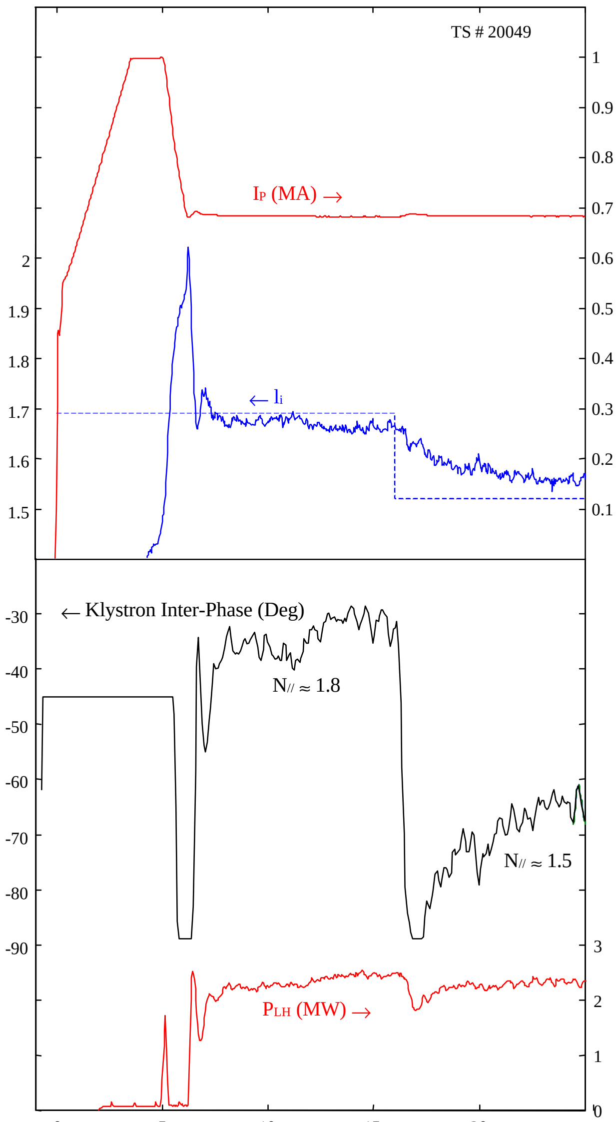


Figure 7. Feedback Control of the Current Profile with the LH parallel Index $N_{//}$

8. Summary

Tore Supra has been equipped with a versatile feedback network. It allows a full control of many global plasma parameters: position, shape, density, in and out power fluxes, … Further developments are under way toward more advanced controls, e.g. for the current profile. All these tools will be used in the future to realise high performance plasmas in steady-state regimes.

[1] T. Wijnands, G. Martin, “An advanced plasma control system for Tore Supra”, Fusion Technology **32** (1997) 471-486
[2] C. Grisolia, “ Feedback control of highly radiative plasmas in Tore Supra”, J. Nucl. Mater. **275** (1999) 95
[3] J. Gunn & al., “Improvement of density control by feedback on Langmuir probe signals in Tore Supra ergodic divertor experiments”, Plasma Phys. Control. Fusion **42** (2000) 557-568.
[4] T. Wijnands & al., “Plasma feedback control for stationary enhanced performance operation of Tore Supra”, Proc. of the 24th EPS conf. on Controlled Fusion and Plasma Physic, Berchtesgaden (1997).