New TORE SUPRA steady state operating scenario

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1. Introduction

Operation for times larger than the time required to reach full equilibrium conditions in plasma wall interaction (several minutes) is one of the main goals of TORE SUPRA. This operational regime can only be achieved with a non inductive plasma current. Lower Hybrid Waves (LHW) are used for this purpose. Steady state plasma control has been successfully achieved at TORE SUPRA by developing a new plasma control system which not only allows a better control of the plasma shape and position, but is also able of feedback control on some global plasma equilibrium parameters like the safety factor at the plasma edge $q_\Psi(a)$, the loop voltage V_l and the plasma current ramp rate dI_p/dt. Its capability to control the current drive and operate TORE SUPRA plasma discharge in steady state regime has been demonstrated.

2. Plasma Shape and Position Control

The design of the poloidal field system of TORE SUPRA [1] is particular in the sense that it fulfils in a single set of coils ohmic heating, radial and vertical position control of the plasma. In this way, the total installed power and the total weight of the conductors is minimised. The poloidal field system is constituted of 9 coils, associated with 9 power generators, allowing the control of the plasma boundary at 9 points. They are located on 9 axis directed towards the coils, the eigen axis of the system (see figure 1). The plasma control system makes use of the magnetic measurements of the poloidal field B_θ and the vertical flux on the vacuum vessel. The position of the plasma is identified through the isoflux method along the 9 axis. Differences between the measured points and programmed ones are then converted into generator voltages aid of a 9X9 transfer matrix.

During plasma operation, the required plasma shape and position are parametrised by 4 parameters: major radius R, vertical position Z, elongation ε and small radius a, obtained consistently with the contact between the plasma and one of the movable limiters or the inner wall. At each step of the control algorithm, the required plasma shape $\{R,Z,a,\varepsilon\}$ is translated into 9 control points $\{\rho_i\}$ along the 9 eigen axis, by using simple trigonometric formulas.

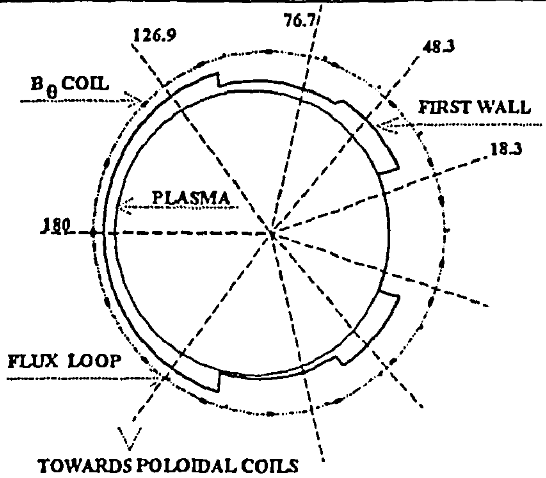

Fig 1: Geometry for Position Control

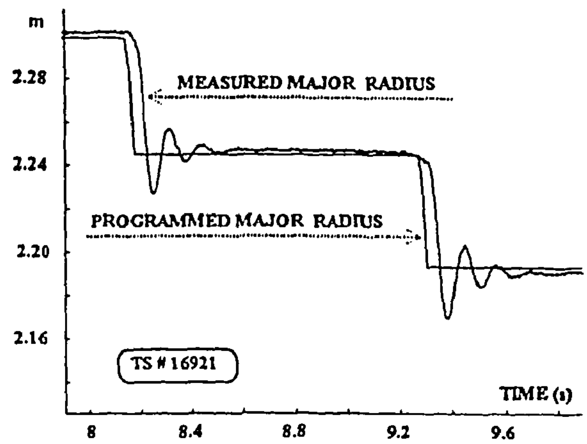

Fig 2: Plasma Position Control

3. Real-Time Determination of Equilibrium Parameters

If the forward mapping, from $\{R,Z,a,\varepsilon\}$ to $\{\rho_i\}$, is straightforward, the inverse mapping is more difficult to perform in real time. Due to its non-linearity, it requires the use of a Multi Layer Perceptron Neural Network [2]. This network fits an ellipse characterised by its central position $\{R,Z\}$ and its two axis $\{a,b\}$ on the 9 plasma positions $\{\rho_i'\}$, determined for the generators voltage control. A typical result for the major radius R has been plotted on figure 2, along with the programmed value. The small oscillation around 11 Hz shows the characteristic time response of the feed-back loop.

More sophisticated parameters are then calculated:

↳ The safety factor at the edge: $q_\Psi \equiv \frac{1}{2\pi}\int_0^{2\pi}\frac{\partial\varphi}{\partial\theta}d\theta = B_{T0}R_0\sum_{i=1}^{9}\frac{\rho_i\Delta\theta_i}{R_i\Psi_i'}$. Preliminary tests have been performed to control its value, either by varying the plasma current or the plasma position. An example is plotted on figure 3: the plasma current has been modified by the pilot, and the feed-back system has changed the major radius to keep the safety factor close to a constant value (6.5).

↳ The two first Shafranov momentum [3], which are integrals of the poloidal field on the measurement surface, i.e. the vacuum vessel. They allow the determination of the stored energy in the plasma via the equilibrium field: $\beta+l_i/2$

↳ The kinetic energy (β) can then be separated from the magnetic energy (l_i) with the use of a diamagnetic loop surrounding the plasma. This second parameter will be used in a near future for current profile control algorithms, in particular during current ramp-up.

4. Feed-back Control during L.H.W. Current Drive

The new plasma control system has the capability to control the iron core flux evolution, by modulating the main poloidal generator. It allows in particular to run constant flux plasmas, a necessity for very long discharge (true steady-state), provided that some non-inductive current drive is used (L.H.W on TORE-SUPRA). In contrast with constant current mode operation for which the typical decay time of the iron core transformer system is very long, this zero loop voltage (constant flux) operating mode allows OH current to decrease with a time constant of about 4 sec.

In this kind of scenario, the plasma current is able to take any arbitrary value, depending on plasmas parameters and the LHW current drive efficiency. As the plasma current intensity has a large effect on the current profile and plasma performances it cannot be allowed to vary outside a limited range and one must control precisely its value. Therefore, a second proportional feedback algorithm was install to control the pulse amplitude of the injected LHW power to keep the plasma current constant rather than the usual opposite (i.e. constant rf power but varying current) (see figure 4).

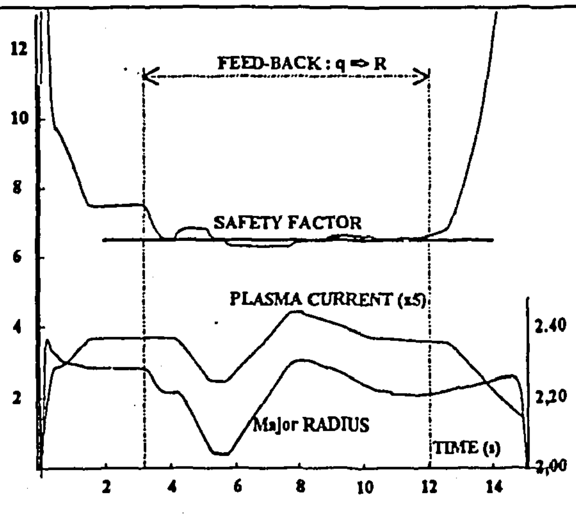

Fig 3: Control of the Safety Factor

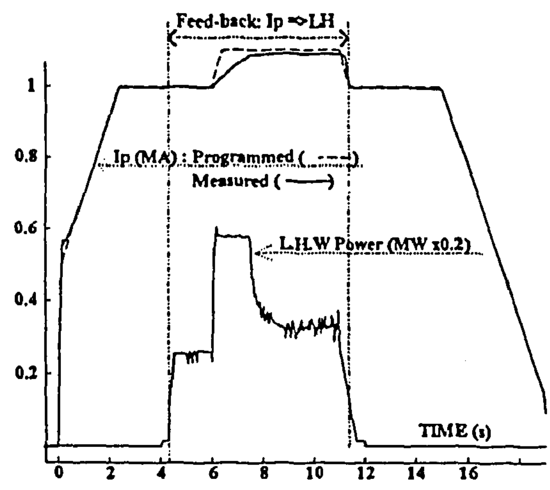

Fig 4: Control of Ip with LHW Power

Thanks to this new plasma control system which has proven a versatile tool, fully non inductive steady state regimes for the first time in a large tokamak could be maintained for up to 15 seconds without indicating any operational limit [4].

We have put in evidence during these experiments the need for an extra margin in the available LHW power to cope with temporary losses of current drive efficiency and/or plasma confinement. On the other hand during full Lower Hybrid Current Drive (LHCD), after the few seconds needed by the profile to evolve from its ohmic to LHCD shape, a strong MHD activity arises very often and degrades subsequently plasma performances. For some LHW spectra, however, no MHD activity appears, indicating potential stable LHCD current profile (figure 5).

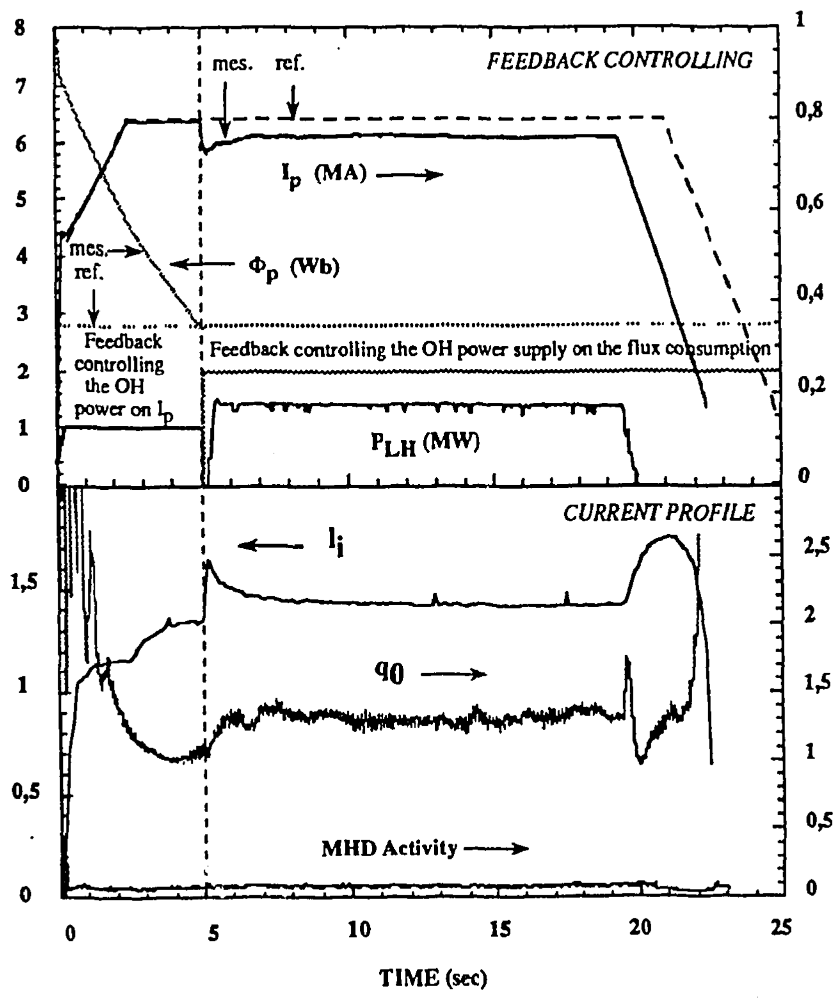

Fig 5: Full Lower Hybrid Current Drive Plasma

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[3] SHAFRANOV, V.D.,Plasma Physics, vol. 13 pp757, Pergamon Press 1971.

[4] KAZARJAN-VIBERT, F. et al, This EPS Conference.