

REAL TIME MEASUREMENT OF THE POSITION, DENSITY PROFILE AND CURRENT PROFILE AT TORE-SUPRA.

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At Tore-Supra, the plasma position, the magnetic axis, the density and the current profiles are calculated in real time, using data from magnetic probes, infrared interferometry and polarimetry. Measurements and calculations are performed by several VME microcomputers and the data are shared in a common memory (SCRAMNet bus). The infrared interfero-polarimeter has been upgraded to self-calibrate for a few seconds before each discharges. This provides more accurate data needed for the determination of the current profile shape. New powerful algorithms are used to compute profile shapes, and several control parameters are tested in order to feedback on LHCD power and/or the wave number spectrum.

1 - INTRODUCTION

Real time control of the current profile in a tokamak is a challenge for advanced scenarios of high performance discharges, since a large number of experiments on various tokamaks have demonstrated that current profile shaping leads to stable plasmas with improved energy confinement. At Tore-Supra, initial experiments have successfully been achieved, with a feedback on the LHCD power and/or the parallel wave index to reach desired values of the internal inductance l_i [1]. A global improved confinement was obtained when a large amount of non-inductive driven current was generated. A feedback control of the global current shape was then attempted for steady state discharges. But l_i is not sufficient to define the current profile, especially when reverse shear profiles are requested. A full computation of the current profile must then be attempted and further data are required to implement the algorithm. Local measurements of the current density such as Motional Stark Effect detection can be used, but these are not yet available on Tore-Supra. We therefore take advantage of the existing polarimetry and IR interferometry measurements which have been upgraded to deliver Faraday rotation angles and line integrated electron densities in real time.

The new generation of microcomputers and the associated new fast shared memory network (SCRAMNet) allows the sharing of data coming from individual diagnostics. In addition the development of new algorithms gives us the opportunity to calculate the plasma position as well as the density and current profile shapes fast enough for a real time control purpose. A feedback control of these profiles becomes then possible.

2 - PLASMA POSITION CONTROL.

The currents in the poloidal coils of TORE-SUPRA are controlled in real-time by a single matrix algorithm to produce the ohmic heating and the position control of the plasma. The nine coils (figure 1) are connected in parallel and associated with nine voltage generators. The main generator drives the central solenoid, mainly used for the plasma current control. The other eight drive the external coils to insure the plasma position control.

Using the magnetic measurements, the vertical flux and its derivatives are calculated on a reference surface by using the Grad-Shafranov equation in vacuum, and extrapolated in vacuum with a polar geometry using Taylor and smoothed spline expansions. The plasma edge is then located along 16 radial directions (22.5° spacing), by looking for points with equal vertical flux, and fixing the plasma to touch the wall/limiter at the first point of contact. These positions are compared to desired values (computed from the target plasma position defined by major and minor radii R and a , vertical position Z , elongation ϵ and triangularity τ), taking into account the toroidal field ripple. The 16 radial errors are converted to 9 voltages using a feedback matrix in a full P.I.D. control loop. These voltages are then applied to the generators. Finally, by including diamagnetic measurements, an iterative procedure is used to calculate global parameters of the actual plasma, position as well as q_ψ , β , l_i , V_{loop} .

The measured CPU time, using a 100 MHz PowerPC CPU in a VME crate, is around 330 μ s for the plasma position determination, and a convergence is reached after 8 ms.

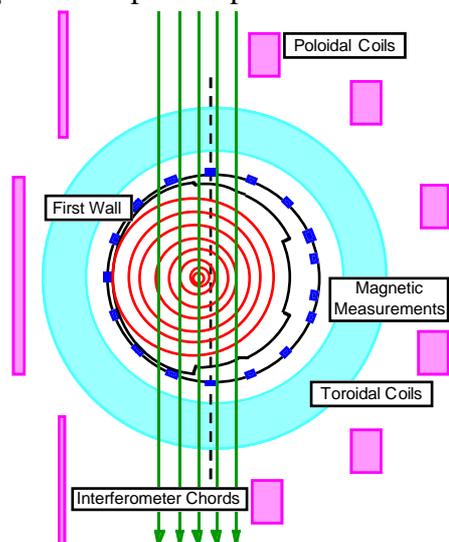


Figure 1 : Tore-Supra configuration

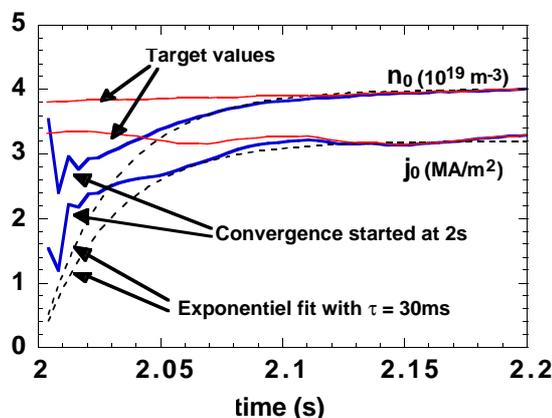


Figure 2 : Convergence of the real time profile calculations

It has been shown that a small oscillation with a characteristic time of 20ms ($\tau = 1/2\pi f$) is generated after an abrupt change of the plasma position [2]. This oscillation is directly connected to the time response of the poloidal system (12ms delay and 12ms integration times). A reduction of the delay has enabled us to double the gain of the P.I.D control loop leading to a better control of the plasma position.

3 - DENSITY AND CURRENT PROFILES.

The integrated line electron density is measured along five equally spaced vertical chords using a Mach-Zender interferometer (figure 1). The Faraday rotation created by the magnetic field induced by the plasma current is measured along the same chords. The laser beams are polarized parallel to the toroidal field before entering the plasma. After traversing the plasma, the two components of the polarization are separated, and the rotation angles are deduced from the formula :

$$\alpha_f(rd) = 2.615 \times 10^{-13} \times \lambda^2 \int n_e B_\theta dl$$

The zero rotation angle and the slope calibration are performed a few seconds before the plasma discharge to improve the accuracy. Using the plasma geometry, the location of the magnetic axis is deduced either from a formula fitting a large set of Tore-Supra shots, or by adjusting a feedback loop to better reproduce the maximum localization of the density distribution and the radius where the Faraday rotation vanishes.

For the profiles, a polynomial shape is assumed for both density (4th degree) and current (4th or 5th degree) distributions. With physical restrictions at the centre and the edge of the plasma (e.g. $j(a) = 0$), three free parameters remain for the density profile, and one (two) for 4th (5th) degree current distribution respectively. The time evolution of these parameters is determined by a linear iterative procedure : i) test profiles are assumed, ii) corresponding values of linear density and Faraday rotation angles are computed by integrating these profiles along the diagnostic chords using a toroidal geometry and assuming a circular poloidal section, iii) these values are compared to the measured values and the differences are used to correct the test profile parameters by means of a feedback matrix. For a given plasma geometry, this matrix is designed as the pseudo-inverse matrix of the 1st derivative terms of the rotation angles expressed as a function of the major radius R, with respect to each free parameter. These terms are corrected for the Shafranov shift and for the plasma location before to be used in the feedback loop.

This method takes advantage of the real time environment : one step of the convergence is achieved at each loop of the plasma position control program (4 ms). The measured CPU time is around 370 μ s for the two profile reconstruction. A convergence is reached with a characteristic time of 30 ms for both the density and the current profile computations (fig.2).

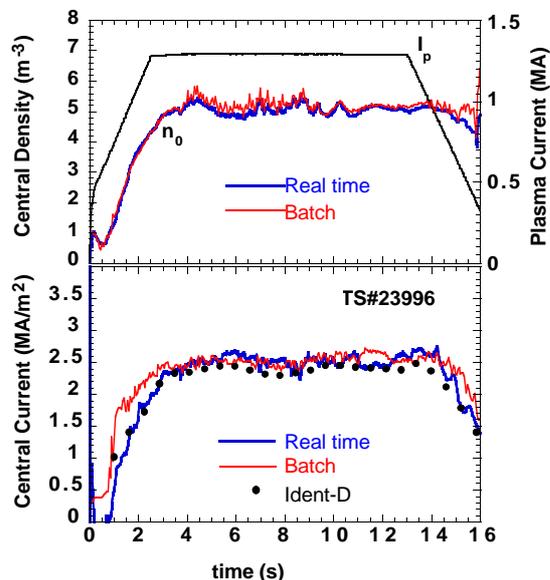


Figure 3 : Comparison of the central density and the central current obtained with several approaches.

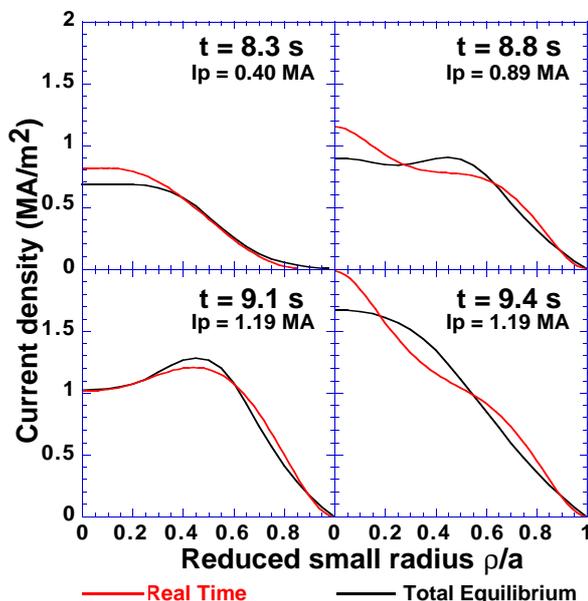


Figure 4 : Comparison between current profile as obtained during a fast I_p ramp-up (TS#25195) and the profile given by a total equilibrium code

Figure 3 shows a comparison of the central density and of the central current density obtained in real time, and calculated after the shot. A good agreement is reached, even during the density fluctuations generated by the ICRH heating between 4 and 9 seconds. The central current density also compares well with a full plasma equilibrium calculation (Ident-D code).

The measured integrated line density is well modeled by a 4th degree polynomial fit. An overall accuracy of $\pm 0.5\%$ is obtained for a broad set of Tore-Supra pulses, including shots with ergodic divertor, low and high density, ohmic and wave heating. For the Faraday rotation, the accuracy is $\pm 15\%$ using a 4th degree polynomial, and $\pm 10\%$ for 5th degree.

We have used this procedure on reversed shear profile experiments [3]. During a very fast current ramp-up, a transient hollow profile is observed both in real time and after a full equilibrium treatment (fig.4). The internal inductance calculated from the profile distribution agrees well with the measured value using magnetic probes.

Nevertheless, a spurious structure within $\rho/a \leq 0.5$ is observed (fig.4), due to the chosen polynomial parameterization. To avoid such a phenomenon, the profile can be described as a stack of disks, their thicknesses being adjusted using a minimization/regularization procedure with a Lagrange multiplier technique to constrain the most reliable data (I_p). Constraints on the 2nd derivative are included to avoid large oscillations in the profiles (regularization). Encouraging results have already been obtained on the plasma simulation code (CRONOS).

4 – CURRENT PROFILE CONTROL.

In order to control the current profile, a relevant variable, usable for feedback, has to be defined. This variable must carry a large part of the shape information and must be as robust as possible. In that sense, the central current density j_0 or the central safety factor q_0 which are too sensitive to the measurement accuracy are not robust enough. We have tested an integrated quantity given by the following normalized expression :

$$A_{ii} = \frac{\int_0^{a/2} B_{ii}^2 \rho d\rho}{\int_0^a B_{ii}^2 \rho d\rho}$$

where the integration is performed using a toroidal geometry. The inner inductance A_i measures the internal inductance carried by the plasma from the centre to the mid-radius.

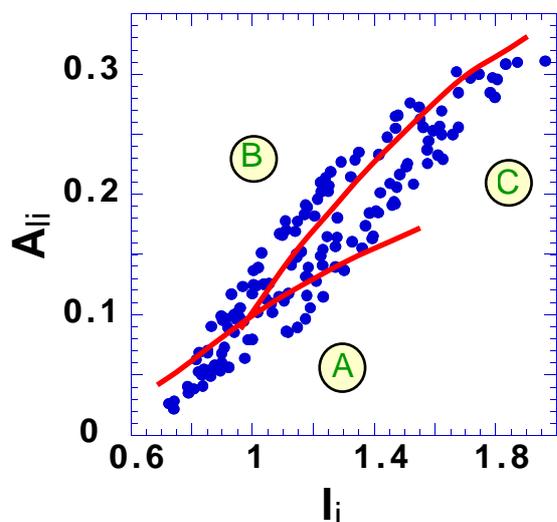


Figure 5 : Expected profile shapes. A : hollow profile, B : peaked with shoulder, C : peaked.

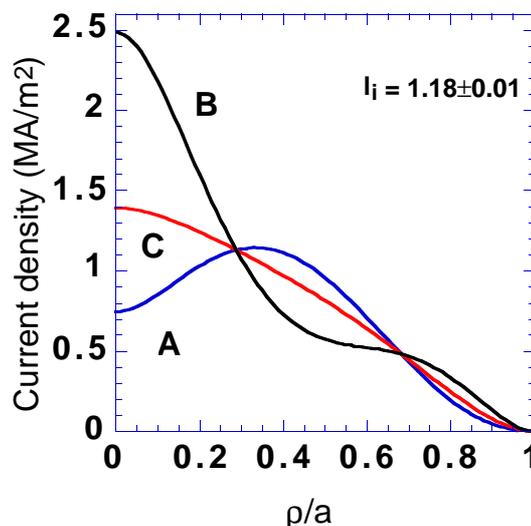


Figure 6 : Typical profile shape obtained with the 5th degree polynomial fit.

Figure 5 shows A_i as a function of the internal inductance l_i for a large set of current profiles (5th degree polynomial). For a given l_i , A_i classifies the profiles with respect to their shape. In particular, reverse shear profiles are well separated from peaked ones. For the same l_i , typical profiles are given in figure 6.

Figure 7 shows the time evolution of A_i and l_i for the shot TS#25195. At the beginning of the ramp-up ($t = 8.4-8.7s$), both A_i and l_i decrease : the profile flattened. At the end of the ramp-up ($t = 8.7-9.0s$) a minimum is reached for both A_i and l_i : a reversed shear profile is formed. At the beginning of the plasma current plateau, A_i starts to increase, although l_i stays constant : the current diffuses towards the center and A_i is sensitive enough to measure this evolution. Afterwards both quantities grow again : the additional heating is not strong enough to freeze the distribution and the current relaxes.

This quantity is promising to build a feedback control of the current profile. Nevertheless, other feedback variables based on the safety factor at various radii are also under investigation [4].

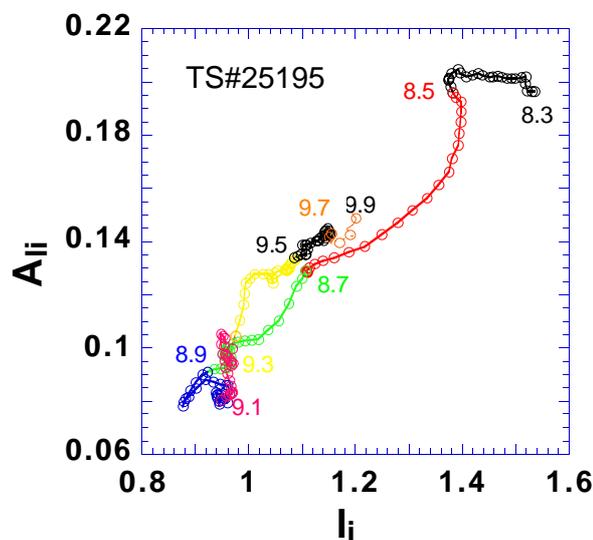


Figure 7 : Time evolution of l_i and A_i (see text) during the I_p ramp-up of the shot TS#25195.

5 - FUTURE PROSPECTS.

The on-line calculation of the density and current profiles is fully implemented and operational. The choice of a suitable variable associated with the internal inductance should allow a real time feedback control of the current profile shape in Tore-Supra in the near future. The full feedback loop will be tested in the next experimental campaign.

[1] T. Wijnands et al : Nuclear Fusion, Vol.37, No.6 (1997)p 777

[2] G. Martin et al : 19th SOFT Conf. on Fusion Technology, Lisbon (1996), p 917

[3] G.T. Hoang et al, Oral contribution to this conference.

[4] D. Moreau et al, Nuclear Fusion, Vol 39, No.5 (1999).