PLASMA POSITION CONTROL AND CURRENT PROFILE RECONSTRUCTION FOR TOKAMAKS *

F. Saint-Laurent[#], S. Bremond, P. Moreau,
Association Euratom CEA, CEA/DSM/IRFM Cadarache, 13108 Saint-Paul-lez-Durance, France.
B. Faugeras, J. Blum, C. Boulbe,
Laboratoire J. A. Dieudonné, Université de Nice-Sophia-Antipolis, F-06100 Nice, France

Abstract

In large size tokamaks, plasma performances in term of internal temperature, radiated power, stored kinetic energy are growing year after year. A precise control of the plasma position is a key issue in order to avoid damages on the first wall of the device. Such a control is essential when high-power long-duration plasmas have to be performed as on the Tore Supra tokamak. The current carried by the plasma can be localized using magnetic measurements (pick-up coils) outside the plasma. The plasma boundary can thus be identified and controlled on real time in less than a few milliseconds.

In order to get information on the current distribution inside the plasma, more sophisticated calculation must be performed. The 2D Grad-Shafranov equation describing the force balance between kinetic pressure and Lorentz force in an axisymmetric toroidal geometry must be solved. Such a solver has been successfully implemented in C++ and installed on Tore Supra device. It is fast enough to enable a real time equilibrium reconstruction.

Because magnetic measurements are no longer sufficient to constrain the solution when detailed information on current distribution inside the plasma are mandatory, other measurements must be introduced as external constraints in the solver. A few examples of such an implementation will be discussed.

INTRODUCTION

In the field of fusion plasma studies, the Tore Supra tokamak explores the way of high-power long-duration plasma discharges. When operating such discharges, the first wall, located inside the vacuum vessel in front of the plasma, must sustain the huge heat flux (10 MW/m2) released by the high temperature plasma following both convection and radiation processes. Dedicated high heat flux components have been manufactured and are currently used. Nevertheless some of these components are not designed to sustain a direct contact with the plasma.

Real-time identification and control of the plasma boundary and position are thus mandatory to safely operate the device. The control takes advantage of the current carried by the plasma. The magnetic field induced by this current can be measured outside the plasma by pick-up coils and toroidal flux loops. From these measurements the plasma boundary can be reconstructed, assuming an axisymmetric geometry and no current flowing between the plasma boundary and the sensors. In present days tokamaks the shape of the plasma boundary is routinely identifiable in real-time in less than a few milliseconds.

Such a procedure provides precise information for plasma boundary but only poor information inside the plasma itself. It can be improved by solving the 2D Grad-Shafranov equation (GS) which describes the axisymmetric plasma equilibrium and thus identifies the non-linear distribution of plasma current. The GS equation describes the balance between Lorentz force j × B and the force ∇p due to kinetic pressure, together with the quasi static form of the Maxwell equation (Ampere's theorem and conservation of magnetic induction). The GS equation reads:

$$-\Delta^*\psi = rp'(\psi) + \frac{1}{\mu_0 r}(ff')(\psi) \qquad (1)$$

Where,

$$\Delta^* = \frac{\partial}{\partial r}\left(\frac{1}{\mu_0 r}\frac{\partial .}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu_0 r}\frac{\partial .}{\partial z}\right). \qquad (2)$$

$\psi(r, z)$ is the poloidal magnetic flux function, r and z are the two remaining cylindrical coordinates, and μ_0 is the magnetic permeability of the vacuum. The right hand side of (1) represents the toroidal component j_φ of the plasma current density which is governed by p', f and f' functions.

Solving (1) with given boundary conditions from magnetic measurements is a free boundary problem in which the plasma boundary is free to evolve. This is an ill-posed problem which needs a dedicated algorithm to be solved.

ITERATIVE ALGORITHM

The goal of a real-time equilibrium code is to identify the plasma boundary together with the flux surface geometry outside and inside the plasma, and finally the current density profile.

Let Ω be the domain representing the vacuum vessel of the Tokamak, and $\partial\Omega$ its boundary. In Tore Supra the plasma boundary is determined by the contact with a limiter D. Thus the boundary is associated to the last closed magnetic flux surface. The region Ω_p containing the plasma is defined as

$$\Omega_p = \{\mathbf{x} \in \Omega, \ \psi(\mathbf{x}) \geq \psi_b\}$$

where $\psi_b = \max_D \psi$.

Magnetic measurements provide both Dirichlet condition $\psi = h$, using toroidal flux loops, and Neumann condi-

tion $\frac{1}{r}\frac{\partial \psi}{\partial n} = g$, using pick-up coils. The Ω domain boundary is chosen to be closed to the sensor localization.

To solve equation (1) with these boundary conditions, the main difficulty consists in identifying the functions p' and ff' in the non linear source term of (1). An iterative strategy involving a finite element method to solve the direct problem (1) and a least square optimisation procedure to identify the non linearity using reduced basis has been implemented.

At each time step determined by the availability of new measurements, the method consists in constructing a sequence $(\psi, \Omega_p, p', ff')^n$ converging to the solution $(\psi, \Omega_p, p', ff')$. The procedure can be described as following:

- Starting guessing $(\psi, \Omega_p, p', ff')^o$ from the previous time step.

- Optimization step: computation of $p'(\psi^n)^{n+1}$ and $ff'(\psi^n)^{n+1}$ functions using a least square procedure and including Neumann boundary conditions as external constraints. The cost function takes into account the accuracy of each measurement. The p' and ff' functions are decomposed on a basis (cubic splines, polynomials,…) which reduces the problem to finding a few free parameters (typically 5 to 10)

- Direct problem step: solve (1) to compute ψ^{n+1} and Ω_p^{n+1} using the p'^{n+1} and ff'^{n+1} functions previously calculated and Dirichlet boundary conditions.

- Check for convergence.

As a consequence of the ill-posedness of the identification of p' and ff', a Tikhonov regularization term must be added to the cost function.

Further technical details on the solver implementation and its numerical resolution can be found in [2].

In order to meet the real-time requirements (the execution time for one sample must be faster than 100 ms), the Equinox code [1] has been designed and implemented in C++. The code relies on tokamak specific software providing flux values on the first wall of the vacuum vessel. By means of least-square minimization of the difference between magnetic measurements and the simulated ones the code identifies the source term of the non linear GS equation (1). The finite element solver uses triangles mesh, the calculation being limited to the vacuum chamber. Recently the code has been upgraded to improve the treatment of the external constraints in the optimization phase of the algorithm [2].

The code has been used off-line to test the convergence either using Tore Supra or JET geometry. The algorithm is found to be very effective and to converge after about 10 steps [2].

REAL TIME IMPLEMENTATION

For real time application the solver is implemented on a PC under Windows XP OS, using Visual C++ compiler. The CPU is a Pentium4 at 2.8Ghz (without Hyper Threading) mounted on a socket 478 asustek P4G8X mother card, with ATI 9700 pro AGP graphic card and 2x512 Mo

SDRAM. The real time interface is built using the OpenGL library [3]. The package is standalone and no external library is needed.
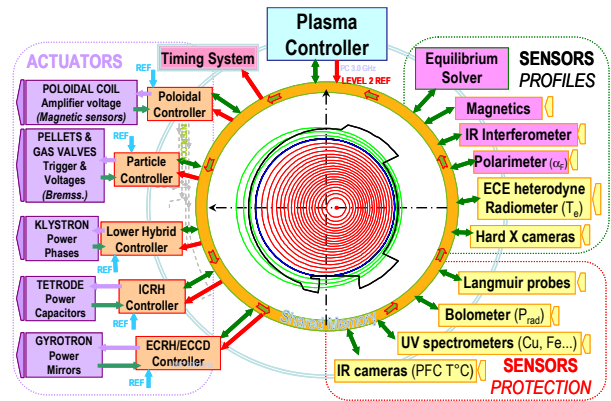

Figure 1: RTC network implemented on Tore Supra.

The time stamp of samples and the synchronisation with the central timing system of Tore Supra plasma control system are ensured by a National Instruments PCI-6601 card associated to a National Instruments PCI-6533 card. Finally a SYSTRAN Corp. PCI 150+ card connects the node to the real time central (RTC) network based on a shared memory ring (SCRAMNet® at 150MHz) [4].

The RTC network is sketched in fig.1. Each node of the network can access the data provided by the other nodes. This arrangement enables us to include information from any diagnostic as external constraints in the equilibrium solver.

The actual implementation on Tore Supra is routinely used since 2004. It uses the magnetic measurements only. The triangle mesh is made of 412 nodes (60 nodes on boundary). A set of 114 magnetic measurements is used as inputs in the solver. The fig.2 is a snapshot of the real time display.
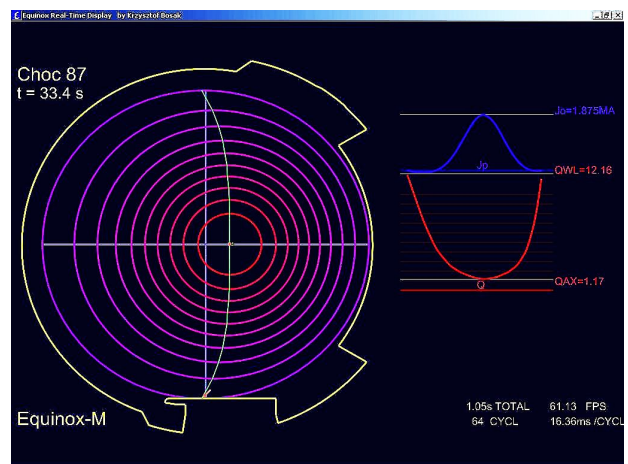

Figure 2: snapshot of Equinox real time display.

The picture shows a poloidal section of the plasma. The first wall is drawn using yellow colour. Isoflux contours are displayed in red to violet, following the flux relative value. Central dot indicates the magnetic axis of the

plasma. The arrow on the bottom of the picture shows the contact localization and green line draws the Shafranov shift of isoflux surface which is related to the kinetic pressure and internal inductance (ie current profile) of the plasma. On the right hand side the current profile and the safety factor profile calculated in the equatorial (mid) plane are displayed.

Solver outputs are the isoflux contour lines, the localization of magnetic axis, several global plasma parameters (kinetic energy, internal inductance, Shafranov shift…) and many profiles: plasma current - safety factor - pressure - *p'*, *f* and *f'* functions. These results are both sent to the Tore Supra database and written in the buffer of the shared memory to be used by actuators of the RTC system.

After a convergence phase of about ten loops at the plasma breakdown, the algorithm is forced to perform one iteration/sample only for reducing computation time. The accuracy is still preserved because the problem is quasistatic and only minor variations of measurements are recorded from sample to sample. With this restriction 8 ms are necessary to find the equilibrium solution and 8 ms are spent to the display in a 1024*768 size window. We found that the plasma boundary is recovered within a few millimetres accuracy when compared to the initial plasma control system which solves (1) without the right hand side term.

USE OF EXTERNAL CONSTRAINTS

External magnetic measurements are no longer sufficient to constrain the solution when detailed information on current distribution inside the plasma are mandatory. Other measurements must be introduced as external constraints in the solver: several diagnostics can provide useful information on local magnetic field inside the plasma:

- *polarimetric measurements*: this measurement gives the value of the integral along a family of chords C_i

$$\int_{C_i} \frac{n_e}{r} \frac{\partial \psi}{\partial n} dl = \alpha_i.$$

$n_e(\psi)$ is the electronic density which is approximately constant on each flux line, $\frac{\partial \psi}{\partial n}$ is the normal derivative of ψ along the chord C_i.

- *interferometric measurements*: they give the values of the integrals

$$\int_{C_i} n_e \, dl = \beta_i.$$

The optimization step is thus modified to include these constraints in the cost function to be minimized. Weighting factors are added to take into account the experimental accuracy of the measurement. A n_e dependent term is also included into the Tikhonov regularization term to guaranty smooth variations of electronic density.

Figure 3 is an example of the numerical equilibrium reconstruction performed off-line, where these measurements have been included as constraints. The yellow lines represent the localization of the chords C_i.

Of course the CPU time needed for the convergence is larger (roughly 80ms) but remains acceptable for real time application. Faster computer can also be used.
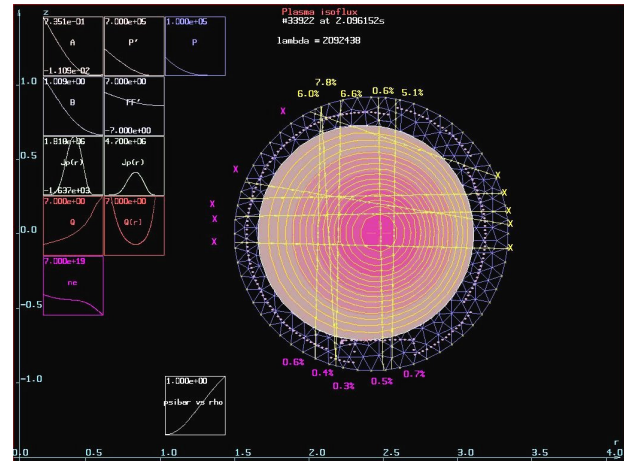

Figure 3: Off-line Equinox analysis including magnetic, Infra-Red interferometry and polarimetry measurements.

FUTURE WORK

The Equinox solver including magnetic, interferometry and polarimetry constraints has already been extensively used for the off-line analysis of JET tokamak plasma discharges [5]. Its implementation in the Tore Supra real time environment is scheduled next year.

This implementation will enable us to actively control the plasma current profile using a feedback on the additional heating systems. Such a control is strongly mandatory to sustain advanced plasma confinement regimes. For example it has been found that an internal transport barrier can improve the confinement. Such a barrier can be generated and sustained by acting on the current profile.

These new controls are an active field of research in the controlled fusion plasma community.

REFERENCES

[1] K. Bosak, *Master's thesis University of Wroclaw, Poland, (2001),* http://panoramix.ift.uni.wroc.pl/~bosy/mgr/mgr.pdf.

[2] J. Blum et al, ICIPE 2008: 6th Int. Conf. on Inverse Problems in Engineering, Dourdan : France (2008).

[3] OpenGL library, http://www.opengl.org/.

[4] F. Saint-Laurent et al. "Machine protection and advanced plasma control in Tore Supra tokamak" *Proceedings of ICALEPCS07, Knoxville, Tennessee, USA (2007).*

[5] D. Mazon et al., proceeding of the 48th IEEE Conference on Decision and Control Shangai (China), December 2009.
.