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Plasma Position Control and Current Profile Reconstruction for Tokamaks

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Abstract

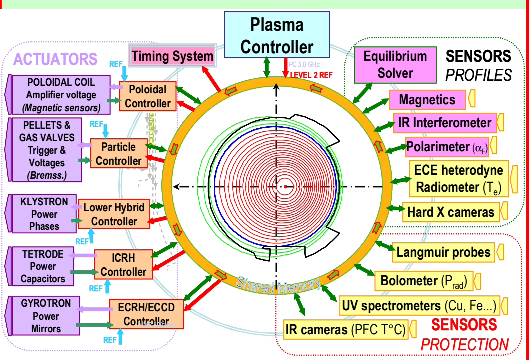
In large size tokamaks, plasma performances in term of internal temperature, radiated power, stored kinetic energy are growing year after year. A precise control of the plasma position is a key issue in order to **avoid damages** on the first wall of the device. Such a control is essential when high-power 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. 2 sets of constraints have been implemented:

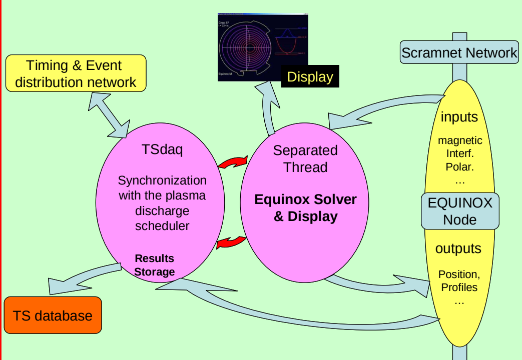
- **Infra-Red Interferometry measurement** giving line integrated electron density
- **Polarimetry which measures Faraday rotation effect** provides information on line integrated magnetic field.

Real Time Implementation



- PC under Windows XP OS
- Visual C++ compiler and OpenGL library for RT interface
- Pentium4 at 2.8Ghz (without Hyper Threading)
- Socket 478 asustek P4G8X mother card,
- ATI 9700 pro AGP graphic card
- 2x512 Mo SDRAM.
- **standalone package**

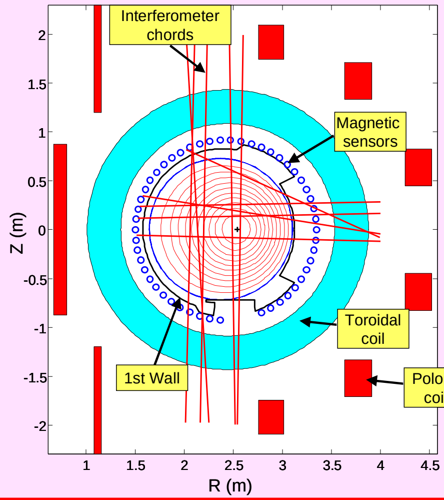
- RT network: shared memory ring SCRAMNet® (Systran corp.) at 150MHz
- Time stamp of samples and Synchronization with the timing ssystem: National Instruments PCI-6601 & PCI-6533 cards.
- Connection to the RT network: SYSTRAN Corp. PCI 150+ card



Performance: (with magnetics only)
- **8 ms to solve the GS equation**
- **8 ms for displaying**

In operation since 2004

Poloidal View of Tore Supra Tokamak & Used Measurements



Magnetic measurements:
- 51 pick-up coils: local B_θ
- 6 toroidal flux loops

Integration of inductive magnetic sensor voltage
- 51 pick-up coils: local B_r
- 2 poloidal flux loops

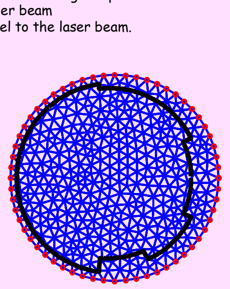
Infra-Red interferometry measurements: 10 chords crossing the plasma
- Modification of the optical length by the plasma free electron density
- Used in association with polarimetry measurements to deduce magnetic field

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

Infra-Red polarimetry measurements: 10 chords crossing the plasma
- Faraday rotation effect of a polarized IR laser beam
- Measure the magnetic field component parallel to the laser beam.

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

Tore Supra Mesh used for Real Time Equinox solver
412 nodes, 762 P1 triangle elements,
60 nodes on boundary
(**Black**: TS first wall)
Boundary mesh is chosen to be closed to magnetic sensor localisation.



2D Grad-Shafranov Equation

Grad-Shafranov equation:
- Axisymmetric geometry ⇒ **2D equation** (r and z cylindrical coordinates)
- balance between **Lorentz force j × B** and the **∇p force due to pressure gradient**

& quasi-static form of Maxwell equations

$$-\Delta^*\psi = rp'(\psi) + \frac{1}{\mu_0 r}(ff')(\psi) \quad \text{where} \quad \Delta^*. = \frac{\partial}{\partial r}\left(\frac{1}{\mu_0 r}\frac{\partial .}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu_0 r}\frac{\partial .}{\partial z}\right).$$

- $\psi(r, z)$ is the poloidal magnetic flux function,
- r and z cylindrical coordinates,
- μ_0 is the magnetic permeability
- p' pressure gradient distribution
- f = r B_φ and f' its derivative
- prime derivative is with respect to ψ

The right hand side (non linear) of GS equation represents the toroidal component j_φ of the plasma current density which is governed by p', f and f' functions (null outside the plasma).

Solving GS equation 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.

GS equation is solved numerically using finite element method.

Ω domain of the vacuum vessel; decomposed in P1 triangle mesh. ∂Ω its boundary
Ω_p plasma boundary $\Omega_p = \{\mathbf{x} \in \Omega,\ \psi(\mathbf{x}) \geq \psi_b\}$ where $\psi_b = \max_D \psi$ (limiter configuration).

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

Iterative Algorithm

➊ Starting guessing (ψ, Ω_p, p', ff')° from the previous time step.

➋ Optimization step: computation of $p'(\psi^n)^{n+1}$ and $ff'(\psi^n)^{n+1}$ functions using a **least square minimization** 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 find a few free parameters (typically 5 to 10)

➌ Direct problem step: solve GS equation 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.

➍ Check for convergence

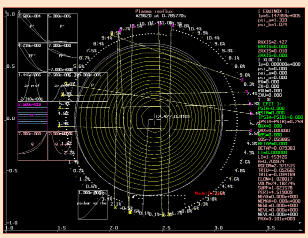
Tikhonov regularization term added to the cost function (ill-posed problem)

Boundary conditions & Constraints:
From magnetics:
- toroidal flux loops ⇒ Dirichlet condition $\psi = h$
- pick-up coils ⇒ Neumann condition $\frac{1}{r}\frac{\partial \psi}{\partial n} = g$

Boundary constraint

Other Constraints: Interferometry & Polarimetry

Real Time & Off-Line Results

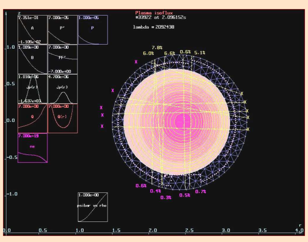


Display variation to magnetic measurements, and comparison with EFIT equilibrium solver

2 types of Off-line Display (GIF/EPS picture)

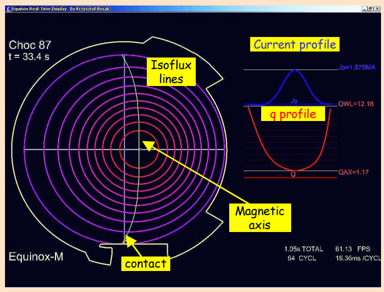
- Microsoft Visual C++ compiler. Also available for Linux (GNU gcc, Kai KCC) and SunOS (DEC CXX and GNU gcc-g++)
- Interface with Tore Supra Database: MATLAB® script
- Standalone interface for GIF or EPS picture generation.
- Capability for comparing results with other equilibrium solvers (EFIT), and RT results
- Optional display of the mesh, variation to measurements...
- Display of profiles:
  - p' and ff' functions
  - pressure, flux (psibar), plasma current, safety factor
  - density (when interferometry constraint is used)
- Generation of result: text and matlab files

Use Interferometry and polarimetry data as external constraints.



Display variation to interferometry measurements, and comparison with EFIT equilibrium solver

Real-Time Equinox Display Snapshot



Real Time Display using OpenGL library (8ms/frame)
- Isoflux contour lines (color ranges with the flux value)
- Current profile in equatorial plane
- Safety factor profile in equatorial plane
- Magnetic axis and Shafranov shift (information on plasma pressure)

Solver Outputs

- Isoflux contour lines
- Plasma boundary position & shape (barycentre, minor radius, ellipticity, triangularity)
- Magnetic axis localization, Shafranov shift...
- Kinetic energy, internal inductance

Profiles :
- Current, safety factor
- p' function and pressure
- f' and f functions