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PERFORMING REAL-TIME RECONSTRUCTION OF THE MAGNETIC FLUX OF THE FTU TOKAMAK IN AN RTAI VIRTUAL MACHINE USING MULTI-POLAR CURRENT MOMENTS

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Abstract

An important topic in plasma equilibrium study [1] and control in a tokamak is to find out and reconstruct the magnetic iso-flux surfaces by using plasma boundary condition. This can be done by using the multipolar moments method which results from the homogeneous solution of the Grad-Shafranov equation. The equilibrium code ODIN [2] is based on the above described technique and is used to reconstruct the magnetic flux and the equilibrium in the Frascati Tokamak Upgrade (FTU) experiment. The real-time reconstruction of the magnetic field map is important to compute quantities necessary to control the plasma. In this paper we discuss the real-time implementation of ODIN in an RTAI virtual machine and as result of the real-time implementation, we will show the time evolution of the reconstructed magnetic iso-flux surfaces.

Key words

Plasma equilibrium/control, Grad-Shafranov, RTAI, Iso-flux, ODIN code.

1 Introduction

In other works [2], [3] the relations between the multipolar moments and the magnetic flux have been discussed. The goal of our research is to provide a procedure that implements in real-time the existing equilibrium code ODIN, which is currently working (off-line) at FTU. In this paper we will first give a brief explanation of the plasma current/position control scheme and of the Grad-Shafranov equation, then we will show the proposed real-time ODIN algorithm implementation. This implementation amounts to pre-computing a number of constant parameters before the experimental pulse (shot) and then evaluating key quantities in real-time, based on the magnetic measurements available from the plant and acquired by the real-time acquisition boards during the experiment [4]. The developed real-time algorithm will be shown to be effective by running it in real-time on an RTAI virtual machine with characteristics of Pentium II@1.5 GHz using a Linux Kernel 2.4.18 patched with RTAI 24.1.10, whose operation exactly coincides with the operating conditions of the real-time control system during the FTU experiments (see [5] for a specification of the underlying architecture). Finally, we will present time evolution of the magnetic flux reconstruction as a result.

1.1 Frascati Tokamak Upgrade (FTU)

FTU is a medium size, compact, high-magnetic-field tokamak and is provided with three additional heating systems (LH, ECRH and IBW), two pellet injection systems, one shooting along the major radius, one shooting along a vertical chord in the high field region and a complete set of plasma diagnostics. The current FTU feedback control system is in charge of the real-time control for the gas density regulation and the plasma position/current feedback. The control system architecture is composed of a measurement subsystem, a controller unit, and several different actuating devices.

1.2 The Plasma Boundary

The plasma boundary is defined as the outermost closed iso-flux surface contained inside the device. The shape of this boundary is generally referred to as the plasma shape. Unfortunately, the plasma shape cannot be directly measured, and for control purposes it must be estimated in real-time using indirect measurements of the magnetic flux and field. One of the available methods for plasma boundary estimation is based on equilibrium reconstruction. Equilibrium codes, such as ODIN and EFIT calculate the distributions of flux and toroidal current density over the plasma and the surrounding vacuum region that best fits the external magnetic measurements (in a least squares sense), and that, at the same time, satisfy the MHD equilibrium equation (the solution of the Grad-Shafranov equation).

Table (1) FTU Tokamak Main Parameters

FTU Parameters	Value
Plasma major radius	0.935 m
Plasma minor radius	0.31 m
Maximum Plasma Current	1.6 MA
Toroidal Magnetic Field	8.0 T
Toroidal Field flat-top duration	1.5 Sec
Toroidal Field Energy	160 MJ
Poloidal Field Energy	200 MJ

2 The Plasma Position and Current Control

To maintain the plasma column in the center of the vacuum vessel and to control the movement of the plasma in the horizontal and vertical directions in a tokamak, a set of poloidal field coils which is placed symmetrically with respect to the tokamak equatorial plane is compulsory. The plasma cross-section of FTU is not elongated (circular). Due to this reason the vertical stabilization is an easier task as compared to the elongated case. In the FTU control system, two SISO PID controllers are used to control the plasma position and current (Fig.2 and 3).

2.1 The Plasma Position and Current Feedback System

Four sets of windings named respectively T, H, V, and F coils [6], [7] generate the poloidal magnetic fields required for the plasma position/current control in FTU. The T winding regulates the plasma current, the V coil generates a pre-programmed poloidal field which is able to regulate the plasma column position during normal operation while the F coil generates a poloidal field to compensate for the horizontal plasma displacements during the experiment. The H poloidal winding performs, instead, a slight control of the vertical plasma displacement. The currents (I_T, I_V, I_F and I_H) flowing in the above-mentioned windings represent the actuating signals of the feedback system. The measurement of the The Plasma Position/Current Feedback System in FTU consists of 16 saddle loops, 16 poloidal field pickup coils that surround sector four of the vacuum vessel, one full-voltage loop all around the vacuum vessel and one Rogowsky coil that measures the current in the toroidal field magnet (see Fig.1). The feedback control system hardware architecture consists of a Pentium II@433MHz VME board, fast AD/DA converters and timing modules to catch the hardware

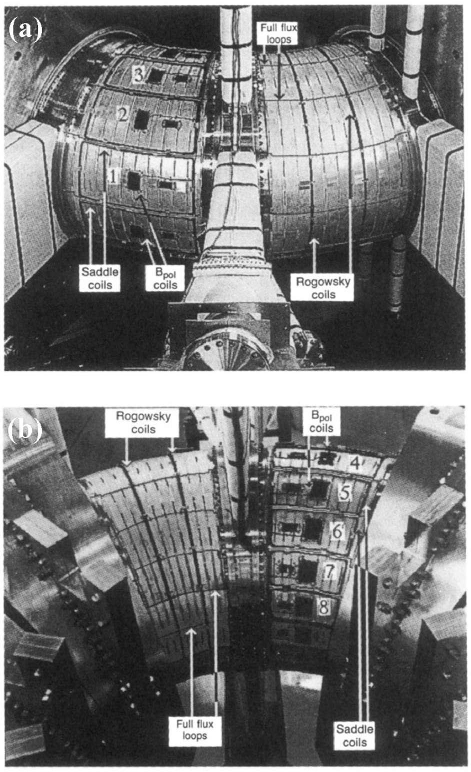

Figure 1. (a) Outer view of the torus. (b) Inner view of the torus. Sectors 10 and 11 of the FTU vacuum vessel and the interposed port No.11 before introduction into the corresponding magnet modules, photographed during the machine assembly. Sector 10 is covered by 16 saddle coils; at the center of each saddle loop a poloidal field coil is located. The numbers refer to the ordering of the saddle and poloidal field coils. Sector 11 houses two Rogowsky coils. The full flux loops can be seen to run along parallels of the torus in the empty space between adjacent saddles. Comparing the inboard and the outboard regions of the torus, it is quite clear that the poloidal extension of the saddle coils and the distribution of the poloidal field coils is not uniform in arc length; instead they both are equally spaced in the poloidal angle of the full toroidal coordinates [10].

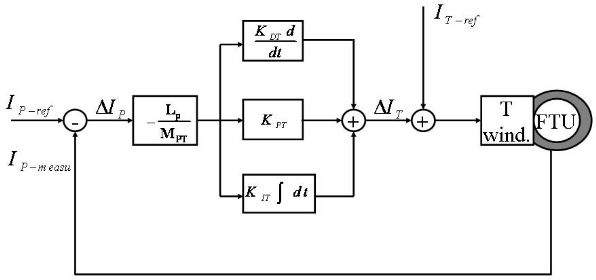

Figure 2. The plasma current control at FTU.

gates. The code currently running on the real-time machine is written in C/C++ language, and it has been carefully optimized so that the related complex algorithm takes less than 170 μs to perform the real-time plasma position, current and gas density regulation [8]

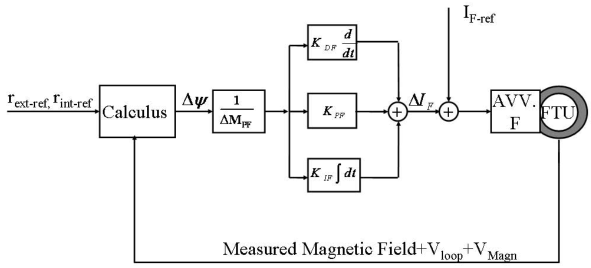

Figure 3. The plasma position control at FTU.

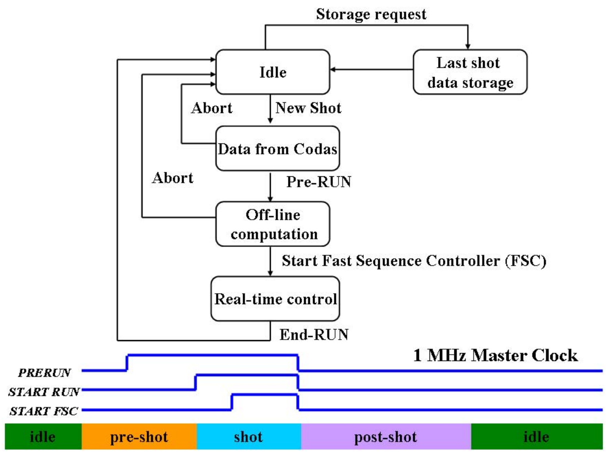

Figure 4. The feedback state diagram and pulse sequence of FTU.

(see Fig.4 for the feedback state diagram and pulse sequence of FTU).

2.2 Grad-Shafranov Equation and Multi-Polar Moments Solution

The main equation that describes the plasma force balance is the Grad-Shafranov equation, which is one of the most famous equations arising from Magneto Hydro Dynamics (MHD). The solution of the equation is used to reconstruct the magnetic equilibrium. (the operator Δ^* is: $\frac{\partial^2}{\partial R^2} + \frac{\partial^2}{\partial Z^2} - \frac{1}{R}\frac{\partial}{\partial R}$).

$$\Delta^* \psi = -\mu_0 R^2 p'(\psi) - {\mu_0}^2 f(\psi) f'(\psi) \quad (1)$$

Equation (1) is a second order partial differential equation, where the function $p(\psi)$ is the plasma pressure and $f(\psi)$ is the poloidal current density in an axial-symmetric torus. These functions are arbitrary and must be determined from considerations other than the theoretical force balance. Equation (1) can be analytically solved in two cases: inside ($\Delta^*\psi = 0$) and outside ($\Delta^*\psi = 2\pi\mu_0 R J_\phi$) the plasma, where J_ϕ is the current density source [3]. According to [2] the solution of the GSE in toroidal coordinates correspond to:

$$\psi(\theta, \tilde{\omega}) = \frac{1}{\sqrt{(ch\theta - cos\tilde{\omega})}} \times \sum_{m=0}^{\infty} \{[M_m^i(\theta) f_m + M_m^e(\theta) g_m] ch(\theta)\} cos(m\tilde{\omega}) \quad (2)$$

(see [2] for the explicit expression of the internal and external multi-polar moments M_m^i , M_m^e which are evaluated as an integral of the current density $J_\phi(\theta_0, \tilde{\omega}_0)$ that flows inside the torus with toroidal coordinates $\theta, \tilde{\omega}$). The antisymmetric part (sine) can be described by similar equations. Moreover:

1. *Outside the plasma, M_m^i, M_m^e are constant and depend on the conditions at the boundary of the domain.*
2. *Inside the plasma, $M_m^i(\theta)$, $M_m^e(\theta)$ depend on the current distribution inside the radial coordinate.*

The total plasma current is proportional to the sum of all the internal multi-polar moments [9], according to;

$$I_p = -\sqrt{2}(2\pi\mu_0 R_0)^{\frac{-1}{2}} \sum_{m=0}^{\infty} M_m^i \quad (3)$$

It is possible to estimate the plasma boundary under the approximation that the multi-polar expansion is constant at all the points of such a surface [9]. In addition, this approximation is strictly accurate only in the case of a circular plasma boundary coinciding with a constant θ coordinate. The ODIN code computes the distribution of the magnetic flux over the plasma and the surrounding vacuum region (see [2], [4] for details about the ODIN structure).

3 The Real-time Environment

RTAI stands for Real-Time Application Interface. It is a real-time extension for the Linux kernel which allows to run the code in a real-time environment both in user space and in kernel space. RTAI provides deterministic and preemptive performance in addition to permitting the use of standard Linux drivers, applications and functions. RTAI's performance is very competitive with some of the best commercial real-time Operating Systems such as VxWorks, QNX etc.

We run the ODIN implementation using the magnetic probes data stored in the FTU database, using the feedback simulator on a Virtual Machine [4], [5] with characteristics of a Pentium II@1.5 GHz using the Linux Kernel 2.4.18 patched with RTAI 24.1.10.

4 Structure of Real-time ODIN

The algorithm starts from reading a set of constants and known data ($sinh\theta$, $cosh\theta$, $sin\tilde{\omega}$, $cos\tilde{\omega}$, Fock functions and some compositions of them over all the mesh) which are evaluated off-line. In the real-time implementation we use an arbitrary and tabled guess for ψ (for example a conic surface centered in R_0 and monotonically decreasing or increasing along θ and constant along $\tilde{\omega}$). In addition, at the contact point ψ, the guess is forced to zero. Next, the moments are calculated and a least squares approximation which fits the magnetic measurements is performed. The moments are then adjusted based on this approximation and a new guess of ψ is computed until the difference between

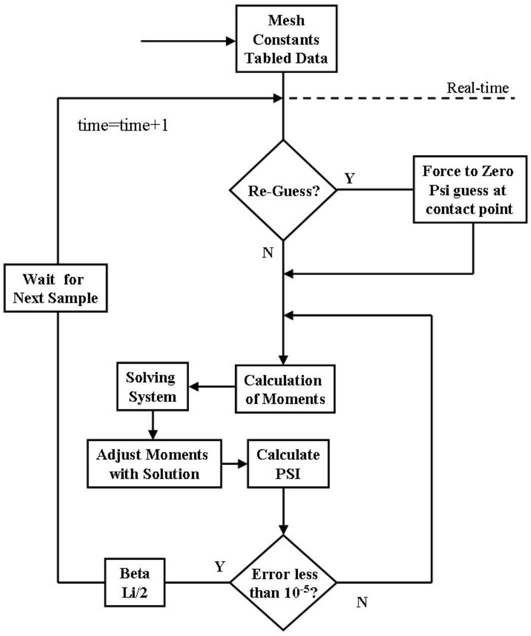

Figure 5. Real-time ODIN structure.

two subsequent iterations is less than a specified tolerance: $(|\psi - \psi'| < \varepsilon)$ over the whole mesh. Finally important quantities associated with the equilibrium are computed, such as the poloidal beta β_p and the internal inductance $l_i/2$. The above algorithm is repeated at each data sample (Fig.5).

5 Results on RTAI Virtual Machine

As result of this research, we show the time evolution of the real-time magnetic flux reconstruction of FTU, evaluated by using the new real-time C/C++ implementation in a virtual machine. The experimental data were analyzed for shot $\sharp 30145$ with the following conditions:

Table (2) Analyzed Experimental Data

Data	Value
Plasma Current	501 kA
Toroidal Magnetic Field	6.0 T
Average Plasma Density	$0.79 \times 10^{20} m^{-3}$
Elongation Rate	1.042
Tolerance	$\varepsilon = 10^{-5}$

The magnetic flux estimated in real-time by our algorithm are shown in figures 7 to 10. Figure 6 is the initial guess of ψ (a cone, as described before) and the final estimate of ψ available in real-time, referring to the experimental time $t = 0.6s$. Figures from 7 to 10 show the equilibrium reconstructions performed in real-time throughout the experimental time. In particular, to appreciate the evolution of the reconstruction with flowing time, each figure represents the last snapshot of the previous one and the first snapshot of the next one. The selected time instants are $t = 0.6\ s$, $t = 1.0\ s$, $t = 1.5\ s$, $t = 1.8\ s$ and $t = 2.1\ s$. The

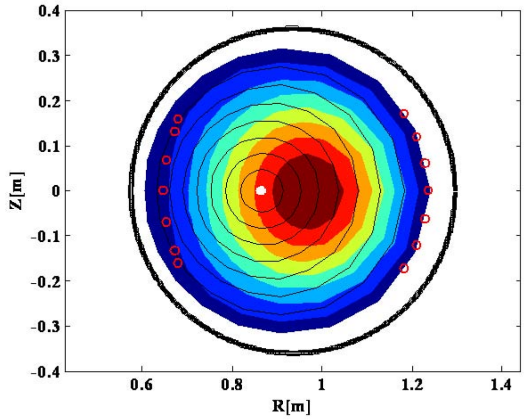

Figure 6. Initial guess of the magnetic flux ψ and final estimate of ψ in real-time at time $t = 0.6\ s$.

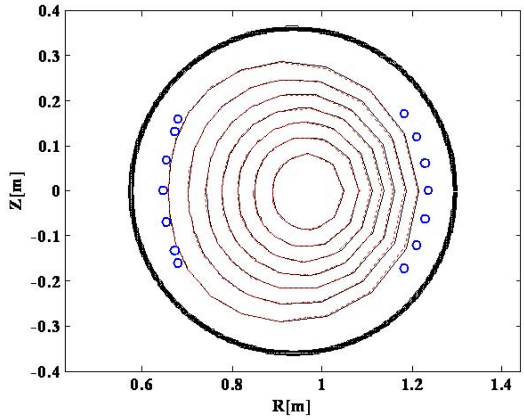

Figure 7. Real-time estimate of the magnetic flux at times $t = 0.6\ s$ (black) and $t = 1.0\ s$ (red)

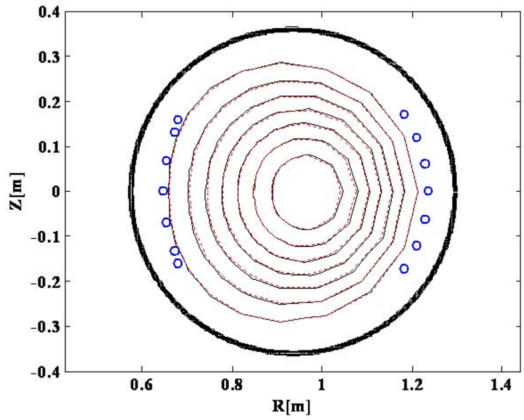

Figure 8. Real-time estimate of the magnetic flux at times $t = 1.0\ s$ (black) and $t = 1.5\ s$ (red)

gradual drift of the reconstructed flux along time can then be appreciated by looking at the sequence of the four figures. For each of the snapshots in Figures 6 to 10, the estimation algorithm converges in 4 iterations.

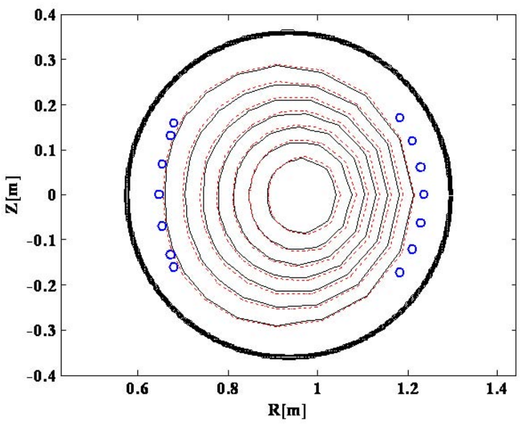

Figure 9. Real-time estimate of the magnetic flux at times $t = 1.5\ s$ (black) and $t = 1.8\ s$ (red)

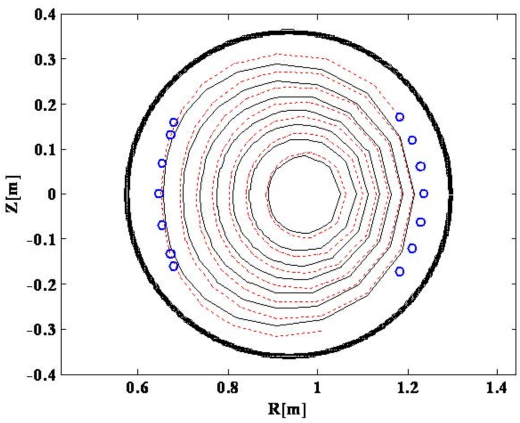

Figure 10. Real-time estimate of the magnetic flux at times $t = 1.8\ s$ (black) and $t = 2.1\ s$ (red)

6 Conclusion

In this paper we reported on the real-time reconstruction of the magnetic flux at FTU on an RTAI virtual machine using the ODIN algorithm. This method allows us to carry out fast real-time equilibrium reconstruction using magnetic probe data on a virtual computer with a Pentium II@ 1.5 GHz using a Linux Kernel 2.4.18 patched with RTAI 24.1.10. The following goals were achieved within this context:

1. *real-time testing of the code using the magnetic probes data stored in the FTU database;*
2. *reconstruction of the magnetic flux using multi-polar moments with few iterations (4 or 5).*

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