Real-Time Reconstruction of Plasma Equilibrium in FTU

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Real-Time Reconstruction of Plasma Equilibrium in FTU

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***Abstract*—An important goal of magnetic-field study in tokamak machines is to determine and reconstruct the magnetic isoflux surface characterizing the plasma boundary condition and the full mapping of the magnetic surfaces inside that isoflux surface. This task can be accomplished by using the multipolar moment method which results from the homogenous solution of the Grad–Shafranov equation. The real-time reconstruction of a magnetic-field map is important to evaluate some quantities that can be used to control the plasma. This paper addresses the real-time implementation of that task.**

***Index Terms*—Grad–Shafranov equation (GSE), isoflux surface, plasma equilibrium, real-time ODIN.**

I. Introduction

PREVIOUS research works have shown the relationship between multipolar moments and magnetic flux [1]. In this paper, we are interested in providing a procedure that implements in real time the existing equilibrium code ODIN, currently working (offline) at the Frascati Tokamak Upgrade (FTU). In this paper, we will first give a brief explanation of the ODIN algorithm, and then, we will illustrate the proposed real-time implementation. This implementation amounts to precomputing a number of constant parameters before the experimental pulse (shot) and then evaluating key quantities in real time, based on the magnetic measurements that are available from the plant and acquired by the real-time acquisition boards during the experiment. In this paper, we will discuss a few aspects about the magnetic-flux reconstruction based on experimental data, as presented in [1] and [2]. The developed real-time algorithm will be shown to be effective by running it in real time on a virtual machine whose operation exactly coincides with the operating conditions of the real-time control system during the FTU experiments (see [3] for a specification of the underlying architecture).

Most of the plasma equilibrium codes are based on a current profile and flux distribution estimate consistent with the Grad–Shafranov tokamak equilibrium relation [4]. The equilibrium fit code EFIT was developed in 1985 to perform plasma equilibrium analysis for the Doublet III tokamak [5]. The plasma reconstruction in rt-EFIT, the real-time version of EFIT, provides a real-time shape estimation using a set of approximate formulas derived in part from the theory and in part from the fitted data. Plasma shape and position estimation in DIII-D uses "gap control" based on the capability of the real-time EFIT algorithm to calculate the magnetic flux at specified locations within the tokamak vessel. The real-time EFIT code provides shape identification with accuracies previously produced only by non real-time analysis [6]. Differently from EFIT, the ODIN algorithm that we focus on in this paper [1] is based on a multipolar expansion (that can be thought of as a Fourier expansion) to describe the magnetic configuration with semianalytical functions to approximate the plasma flux distribution. Therefore, while the method hinges upon an approximate solution of the Grad–Shafranov equation (GSE) (as with EFIT), its solution is purely analytical without using the extra degree of freedom of fitting the experimental data.

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II. FTU

FTU is a compact medium-sized high-magnetic-field tokamak machine and is provided with three additional heating systems (lower hybrid, electron cyclotron resonance heating, and ion Bernstein wave), two pellet injection systems (one shooting along the major radius and 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 real-time control for plasma position/current feedback and gas density regulation. The control system architecture is composed of a measurement subsystem, a controller unit, and several different actuating devices.

A. PPCFS

The measurement of the position/plasma current feedback system (PPCFS) 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 Rogowski coil that measures the current in the toroidal field magnet. The feedback control system hardware architecture consists of a Pentium II 433 MHz VME board, fast AD/DA converters, and a timing module to catch the hardware 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 position, plasma current, and gas density

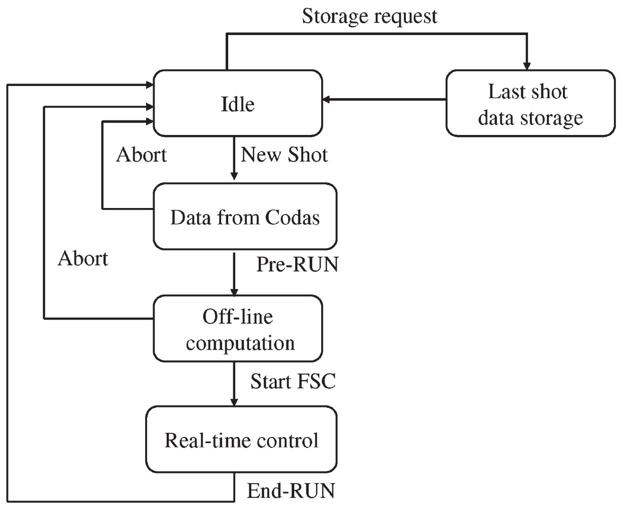

Fig. 1. Position and plasma current feedback system (PPCFS).

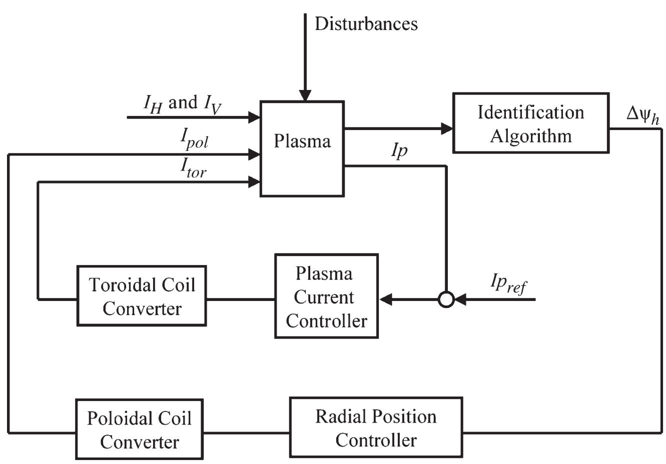

Fig. 2. Plasma current and position controller of FTU.

regulation [7] (see Fig. 1 for the state diagram of PPCFS and Fig. 2 for the plasma radial position and plasma current controller of FTU).

B. GSE

The main equation to describe the plasma force balance is the *GSE*, which is one of the most famous equations arising from magnetohydrodynamics. The solution of the equation is used to reconstruct the magnetic equilibrium

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

(the operator Δ^* is $\partial^2/\partial R^2 + \partial^2/\partial Z^2 - (1/R)(\partial/\partial R)$). Equation (1) is a second-order partial differential equation, where the function $p(\psi)$ is the plasma pressure and the function $f(\psi)$ is the current flux function which is related to poloidal current density in an axial symmetric torus [4]. These functions are arbitrary and must be determined from considerations other than theoretical force balance. The *GSE* can be analytically solved in two cases: *outside of the plasma* ($\Delta^*\psi = 0$) and *inside the plasma* ($\Delta^*\psi = 2\pi\mu_0 R J_\phi$), where J_ϕ is the "toroidal" current density [8].

III. Multipolar Moments and Solution of the GSE

The FTU magnetic measurement system has been realized to optimize the equilibrium reconstruction; consequently, some voltage loops and saddle coils measure the poloidal flux function, and some poloidal pickup coils measure its normal derivative over a contour enclosing the plasma cross section. These two different sets of data represent the Cauchy conditions to solve the magnetostatic problem and to find the plasma boundary, starting from "external" measurements. The plasma boundary is defined as the outermost closed flux surface contained inside the plasma first wall. The magnetic flux ψ can be expanded in a series of toroidal multipoles by using the toroidal coordinate system $(\theta, \tilde{\omega}, \phi)$ with the definitions of $0 < \theta < \infty$ and $0 < \tilde{\omega} \leq 2\pi$, and those are linked to the cylindrical coordinates (R, Z, ϕ) by the relations $R = R_0 sh\theta[(ch\theta - \cos\tilde{\omega})^{-1}]$ and $Z = R_0 \sin\tilde{\omega}[(ch\theta - \cos\tilde{\omega})^{-1}]$. The coordinate θ defines the circular cross section that is non-concentric with the major $R(\theta)$ and the minor $a(\theta)$ radii. The coordinate $\tilde{\omega}$ defines the spheres passing through the pole $(R - R_0)$ and has the simple meaning of a poloidal angle. According to [1], the solution of the *GSE* in toroidal coordinates corresponds to

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

By fitting the magnetic measurements with this analytical solution and by assuming that all the measurements are external to the plasma boundary, it is possible to evaluate the values of the multipolar moments in the vacuum. Furthermore, the explicit expression for the internal multipolar moments is evaluated as an integral of the current density $J_\phi(\theta_0, \tilde{\omega}_0)$ that flows inside the torus with coordinate θ

$$M_m^i(\theta) = \frac{\mu_0 R_0^3 (2 - \delta_{m0})}{(m^2 - 1/4)} \times \int_0^{2\pi} \int_\theta^\infty J_\phi(\theta_0, \tilde{\omega}_0) \frac{g_m(ch\theta_0)\cos(m\tilde{\omega}_0)}{(ch\theta_0 - \cos\tilde{\omega}_0)^{5/2}} \, d\tilde{\omega}_0 d\theta_0 \tag{3}$$

$$M_m^e(\theta) = \frac{\mu_0 R_0^3 (2 - \delta_{m0})}{(m^2 - 1/4)} \times \int_0^{2\pi} \int_0^\theta J_\phi(\theta_0, \tilde{\omega}_0) \frac{f_m(ch\theta_0)\cos(m\tilde{\omega}_0)}{(ch\theta_0 - \cos\tilde{\omega}_0)^{5/2}} \, d\tilde{\omega}_0 d\theta_0 \tag{4}$$

where δ_{m0} is Kronecker's symbol and f_m and g_m are Fock's functions [1] given in terms of half-integer-order first-degree Legendre functions of the first and second kinds.

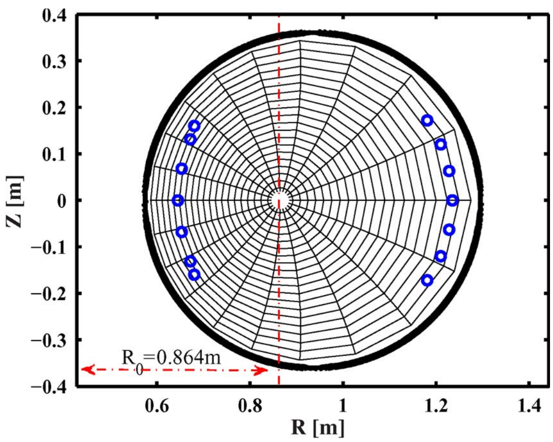

Fig. 3. (Spider web) Mesh, (central circle toroidal coordinate) R_0, and (small circle at the edge) the possible plasma contact points.

M_m^i and M_m^e in (3) and (4), respectively, indicate the *cosine* part of the solution. A similar expression can be written for the *sine* part. Furthermore, the following are valid.

1) *Outside the plasma,* M_m^i and M_m^e *are constant and depend on the conditions at the boundary of the domain.*
2) *Inside the plasma,* M_m^i and M_m^e *are internal and external multipolar moments of order* $m = 0, 1, 2, \ldots$ *of the toroidal current density.*

IV. ODIN Structure

The ODIN code computes the distribution of magnetic flux over the plasma and the surrounding vacuum region. All the magnetic probes in FTU are located outside the circular cross section of the vacuum vessel, on a toroidal contour with a major radius of 0.935 m and a minor radius of 0.356 m. The method by which the toroidal multipolar expansion of the magnetic configuration is derived is a Fourier analysis that determines separately, order by order, the multipolar moments. In the ODIN algorithm, a fixed toroidal coordinate center $R_0 = \sqrt{R_{\text{probe}}^2 - a_{\text{probe}}^2} = 0.864$ m (here, R_{probe} and a_{probe} are constant for all probes) has been used.

A. Mesh Function

In order to compute the flux inside the plasma, a mesh $(\theta_j, \tilde{\omega}_k)$ based on the toroidal coordinates with $j = 1, 2, \ldots, N_\theta$ and $k = 1, 2, \ldots, N_\omega$ is considered, which satisfies $\tilde{\omega}_{k+1} - \tilde{\omega}_k = \Delta\tilde{\omega}_j$ for all k and j and $[ch\theta_{j+1}]^{-1} - [ch\theta_j]^{-1} = \Delta\varepsilon$ for all j. Using this definition, we can construct the required mesh for demonstrating the multipolar moment expression in our process. Fig. 3 shows an arising mesh, together with all the possible contact points, namely, all the possible points where the plasma will touch the first wall.

B. Expansion of $p(\psi)$ and $f(\psi)$

From a physical point of view, all the experimental equilibria so far analyzed in tokamak experiments seem to be very well fitted by the polynomial expansions; $p(\psi) = p_\alpha\psi^\alpha + p_\beta\psi^\beta$ and $f(\psi) = f_\alpha\psi^\alpha + f_\beta\psi^\beta$, where (α, β) are both positive real numbers smaller than four. To obtain the value of the external and internal moments of orders 0, 1, 2, and 3 in (3) based on the probe measurements at $\theta = \theta_{\text{pr}}$ (θ_{pr} is the θ for a single probe), the four constants $(p_\alpha, p_\beta, f_\alpha, f_\beta)$ are computed together with the ψ distribution.

C. Reconstruction Process

The iterative process follows these steps.

1) Based on geometrical information, the geometrical distributions $P_m^i(j,k)$, $P_m^e(j,k)$, $F_m^i(j,k)$, and $F_m^e(j,k)$, where $m = 0, 1, 2, 3$, are precomputed as

$$P_m^i = \frac{2\pi\mu_0 R_0^4(2-\delta_{m0})}{(m^2-1/4)} \frac{(ch^2\theta_0)\cos(m\tilde{\omega}_0)}{(ch\theta_0 - \cos\tilde{\omega}_0)^{7/2}} g_m(ch\theta_0)$$

$$P_m^e = \frac{2\pi\mu_0 R_0^4(2-\delta_{m0})}{(m^2-1/4)} \frac{(ch^2\theta_0)\cos(m\tilde{\omega}_0)}{(ch\theta_0 - \cos\tilde{\omega}_0)^{7/2}} f_m(ch\theta_0)$$

$$F_m^i = \frac{\mu_0^2 R_0^2(2-\delta_{m0})}{4\pi(m^2-1/4)} \frac{(ch^2\theta_0)\cos(m\tilde{\omega}_0)}{(sh^2\theta_0)(ch\theta_0 - \cos\tilde{\omega}_0)^{3/2}} g_m(ch\theta_0)$$

$$F_m^e = \frac{\mu_0^2 R_0^2(2-\delta_{m0})}{4\pi(m^2-1/4)} \frac{(ch^2\theta_0)\cos(m\tilde{\omega}_0)}{(sh^2\theta_0)(ch\theta_0 - \cos\tilde{\omega}_0)^{3/2}} f_m(ch\theta_0).$$

2) The tentative values of $\tilde{M}_m^i(\theta_{\text{pr}})$ of the internal multipolar moments at probe positions are evaluated based on (1), (3), and (4) as

$$\tilde{M}_m^i(\theta_{\text{pr}}) = \sum_{l,k} P_m^i(j,k)\left[\alpha\tilde{p}_\alpha\psi^{(\alpha-1)}(j,k) + \beta\tilde{p}_\beta\psi^{(\beta-1)}(j,k)\right] + \sum_{l,k} F_m^i(j,k)\left[\alpha\tilde{f}_\alpha\psi^{(\alpha-1)}(j,k) + \beta\tilde{f}_\beta\psi^{(\beta-1)}(j,k)\right]. \quad (5)$$

3) A set of correction factors $(\tilde{p}'_\alpha, \tilde{p}'_\beta, \tilde{f}'_\alpha, \tilde{f}'_\beta)$ is computed by solving the following linear system of four equations in four unknowns:

$$\begin{aligned} M_m^i(\theta_{\text{pr}}) = (\tilde{p}'_\alpha)&\left[\alpha\tilde{p}_\alpha \sum_{j,k} P_m^i(j,k)\psi^{(\alpha-1)}(j,k)\right] \\ &+ (\tilde{p}'_\beta)\left[\beta\tilde{p}_\beta \sum_{j,k} P_m^i(j,k)\psi^{(\beta-1)}(j,k)\right] \\ &+ \left(\tilde{f}'_\alpha\right)\left[\alpha\tilde{f}_\alpha \sum_{j,k} F_m^i(j,k)\psi^{(\alpha-1)}(j,k)\right] \\ &+ \left(\tilde{f}'_\beta\right)\left[\beta\tilde{f}_\beta \sum_{j,k} F_m^i(j,k)\psi^{(\beta-1)}(j,k)\right], \\ &m = 0, 1, 2, 3 \end{aligned} \quad (6)$$

(see [1] for more details on the radial behavior of the internal multipolar moments with $\theta_l > \theta_j$ and on the external multipolar moments with $\theta_l < \theta_j$).

4) The flux ψ is calculated using (2), along with the product of the previously evaluated coefficients $(\tilde{p}_\alpha, \tilde{p}_\beta, \tilde{f}_\alpha, \tilde{f}_\beta)$ times the newly determined coefficients $(\tilde{p}'_\alpha, \tilde{p}'_\beta, \tilde{f}'_\alpha, \tilde{f}'_\beta)$. These are fed back into step 2) of the procedure (5) until the difference between two subsequent iterations is less than a specified tolerance ε; $(|\psi - \psi'| < \varepsilon)$ over the whole mesh.

After succeeding in achieving the convergence of ψ using the determined $(p_\alpha, p_\beta, f_\alpha, f_\beta)$ coefficients and the ψ distribution, it is easy to calculate some important quantities associated with the equilibrium such as the poloidal beta β_p, the internal inductance $l_i/2$, and the plasma diamagnetism as

$$\beta_p = \frac{1}{2\pi R_{\text{ref}}} \frac{8\pi}{\mu_0 I_p^2} \int p dV \tag{7}$$

$$l_i/2 = \frac{1}{4\pi R_{\text{ref}}} \frac{8\pi}{\mu_0 I_p^2} \int \frac{B_{\text{pol}}^2}{2\mu_0} dV \tag{8}$$

$$\mu_i = \frac{1}{2\pi R_{\text{ref}}} \frac{8\pi}{\mu_0 I_p^2} \int_{Vp} \frac{B_{\phi 0}^2 - B_\phi^2}{2\mu_0} dV \tag{9}$$

where B_{pol} is the poloidal magnetic field, p is the kinetic pressure, I_p is the total plasma current, V_p is the plasma volume, R_{ref} is the reference major radius, $B_{\phi 0}^2$ is the vacuum toroidal field, and B_ϕ^2 is the toroidal field in the presence of the plasma.

V. Real-Time Environment

The real-time environment is based on RTAI, which stands for Real-Time Application Interface. It is a real-time extension for the Linux kernel which allows running the code in a real-time environment both in user and kernel spaces. We run the ODIN implementation using the magnetic probe data that come from the FTU database using the feedback simulator on a virtual machine [3] with characteristics of a Pentium II at 1.5 GHz using the Linux Kernel 2.4.18 patched with RTAI 24.1.10 and then on a real VME CPU board equipped with an Intel Core 2 64-b T7400 2.16-GHz CPU with 1-GB RAM using Linux Kernel 2.6.23 $x86$ (64 b) patched with RTAI 3.6.2.

A. Real-Time ODIN Implementation

Starting from the Fortran offline implementation of ODIN, first, we ported to C/C++ the inner temporal loop in which the analysis of the magnetic measurements is carried out. During the integration of the moments [(3) and (4)], half of the number of $\tilde{\omega}_k$ have been used. A set of constants and known data $(\sinh\theta, \cosh\theta, \sin\tilde{\omega}, \cos\tilde{\omega}$, and some compositions of them over all the mesh) is evaluated offline to be used as tabled data in the real-time section. We minimize the use of conditional branches in the nested loops and eliminate the zeroth- and the third-order moments in the *sine* part of the calculation. We unroll some cycles to better fit the processor pipeline use. We optimize the array dimension as a power of two to prevent the compiler from using strange offsets in the output assembler.

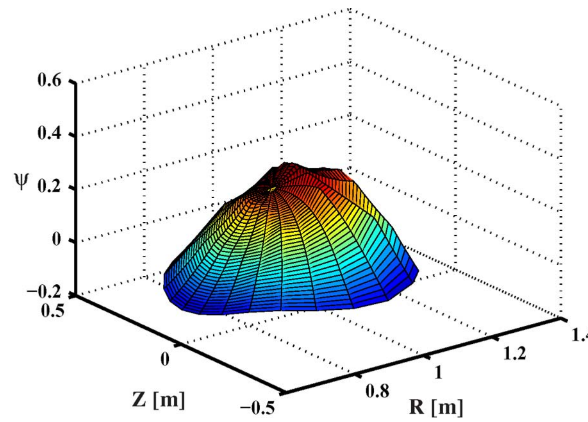

Fig. 4. Offline first guess of the magnetic flux ψ at time $t = 0.60$ s.

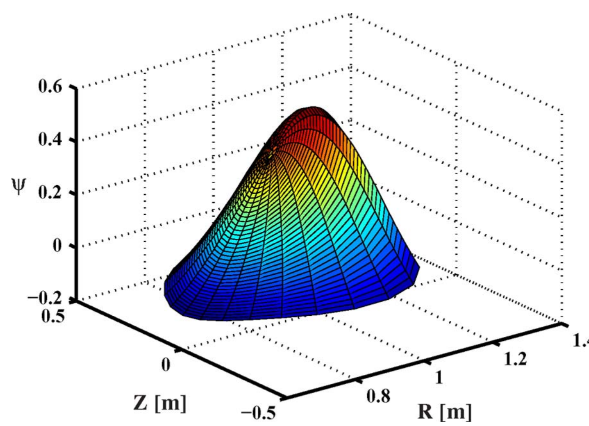

Fig. 5. Offline estimate of the magnetic flux ψ at time $t = 0.60$ s coincident with the offline second guess of the magnetic flux ψ at time $t = 0.62$ s.

In the Fortran implementation, ψ is first guessed during the loop as the magnetic field generated by a wire carrying the plasma current. Instead, in our implementation, we start from 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 $\tilde{\omega}$).

VI. Results

In this part, we show some preliminary results of the real-time reconstruction of the magnetic flux in FTU evaluated by using both the offline Fortran code and the new real-time C/C++ implementation. The estimated quantities in the offline Fortran code and the real-time code are shown in Figs. 4–13. To speed up the real-time computations, the first guess in RT operation is selected in a simpler way as compared with the offline case (see Figs. 4 and 9). This simpler selection did not cause any evident increase of convergence time for the iterative algorithm, while it sometimes even led to an improvement.

The experimental data were analyzed for shot no. 30 223 with the following conditions: plasma current $I_p = 501$ kA, toroidal magnetic field $B_T = 6.0$ T, and averaged plasma density 0.79×10^{20} m^{-3}. The elongation in this shot is 1.042, the average number of iterations to reach a tolerance of $\varepsilon = 10^{-5}$ is five, and each iteration takes less than 0.4 ms. For this particular shot, the minimum convergence time (four iterations) is 1.6 ms,

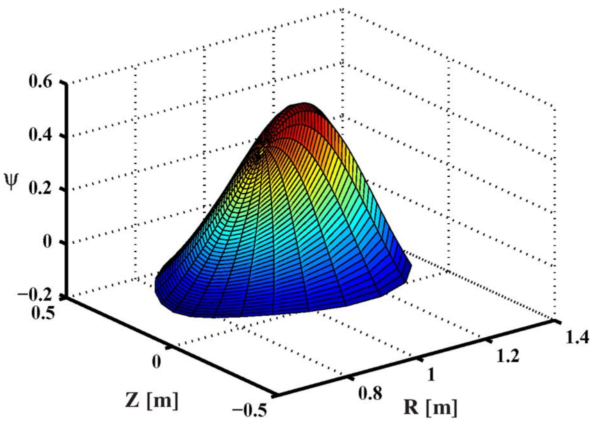

Fig. 6. Offline estimate of the magnetic flux ψ at time $t = 0.62$ s.

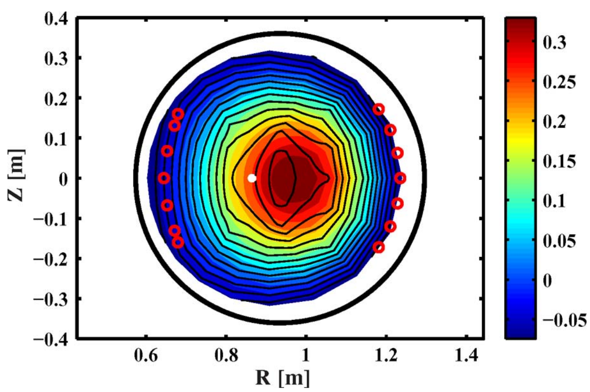

Fig. 7. Offline estimate of the (*colored*) magnetic flux ψ and (*solid lines*) guess ψ at time $t = 0.60$ s.

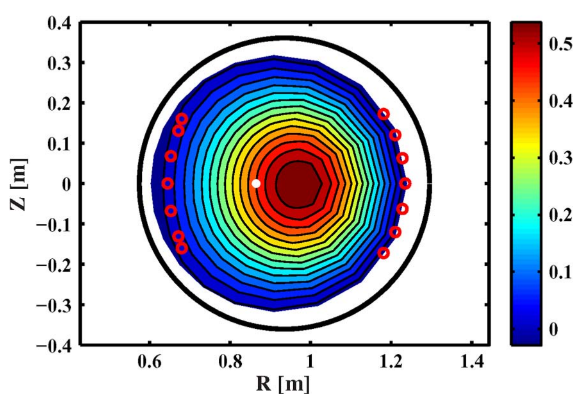

Fig. 8. Offline estimate of the (*colored*) magnetic flux ψ and (*solid lines*) guess ψ at time $t = 0.62$ s.

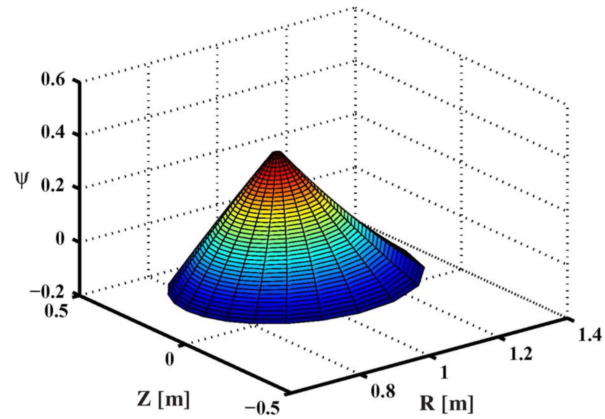

Fig. 9. Real-time first guess of the magnetic flux ψ at time $t = 0.60$ s.

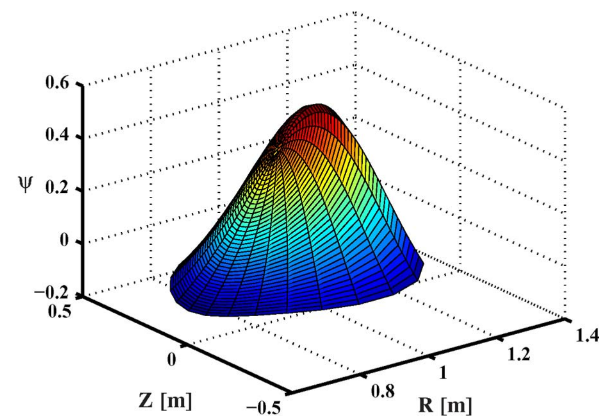

Fig. 10. Real-time estimate of the magnetic flux ψ at time $t = 0.60$ s coincident with the real-time second guess of the magnetic flux ψ at time $t = 0.62$ s.

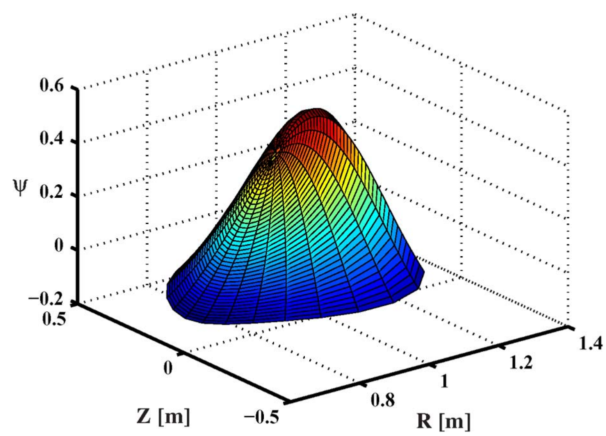

Fig. 11. Real-time estimate of the magnetic flux ψ at time $t = 0.62$ s.

and the maximum convergence time (eight iterations) is 2.8 ms. The C/C++ code is run on the CPU 0 of the Intel Core 2 64-b T7400 2.16-GHz CPU with 1-GB RAM as a static real-time thread using a mesh dimension of 41×20 $(\theta \times \tilde{\omega})$.

VII. Conclusion

In this paper, we have succeeded in performing ODIN and reconstructing the magnetic flux in real time. The multipolar method allowed us to perform a quick real-time equilibrium reconstruction code using magnetic probe measurements on the aforementioned VME board. The following goals were reached in this paper for the real-time ODIN algorithm:

1) Test of the code with the moments coming from the feedback simulator on a virtual machine.
2) Real-time test of the code on a VME board using a single CPU.
3) Reconstruction of the flux with few iterations (four or five).
4) The computing time for the algorithm convergence, without any parallel optimization, is less than 0.4 ms for

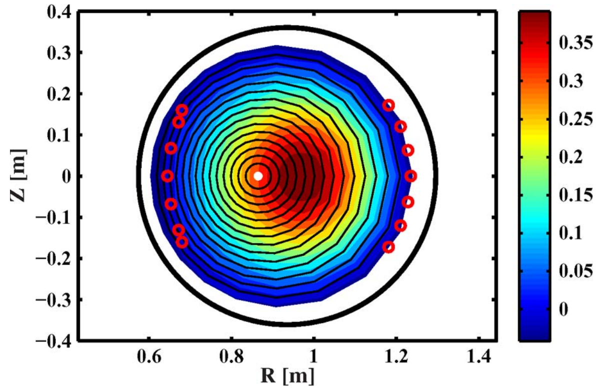

Fig. 12. Real-time estimate of the (*colored*) magnetic flux ψ and (*solid lines*) guess ψ at time $t = 0.60$ s.

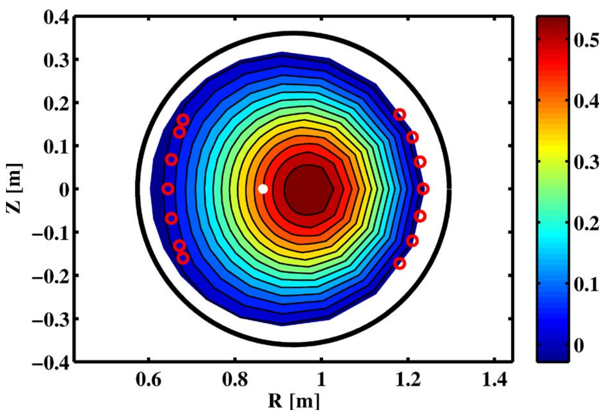

Fig. 13. Real-time estimate of the (*colored*) magnetic flux ψ and (*solid lines*) guess ψ at time $t = 0.62$ s.

each iteration. Most of the calculations are independent, and parallelizing them could reduce computing time by almost one half.

VIII. Future Work

Future work involves further reducing the ODIN algorithm computation time by applying *parallel processing* over two or more CPUs using two or more real-time threads. The idea is to split over those threads the independent *sine* and *cosine* parts of the calculation or to separate them out in different sections of the mesh, letting the main thread merge the results when needed. Once the equilibrium is reached, the system could send the output data to the main feedback controller performing shape and position regulation (using a real-time network such as RTNET or using DACs and ADCs). In addition, future research work will involve implementing the equilibrium fit code (EFIT), which is the standard equilibrium code to obtain the solution of the GSE at JET. The real-time implementation of EFIT is currently being used at DIII-D [9]. Its extension to FTU is not trivial, and we regard it as future work. Finally, a possible future real-time version of EFIT should be applied to other tokamaks and compared to the available offline EFIT reconstructions to verify the effectiveness of the real-time code.

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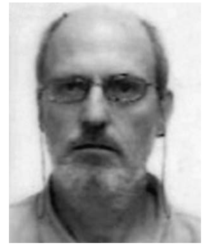

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