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REAL TIME EQUILIBRIUM RECONSTRUCTION FOR CONTROL OF THE DISCHARGE IN THE DIII–D TOKAMAK*

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Optimum performance of a tokamak discharge requires accurate feedback control of many of the discharge parameters. For this to be possible, the values of these parameters must be accurately measured. The values of many discharge parameters, such as shape and safety factor profile, are not directly measured but can be evaluated from the available diagnostic data: magnetic field and flux measurements, for example. The most complete evaluation comes from a least squares fit of the diagnostic data to the Grad-Shafranov model that describes the force balance of the tokamak equilibrium, while allowing for a distributed current source. This full reconstruction of the equilibrium has normally been performed off-line using a computation-intensive fitting code such as EFIT [1].

This paper provides an introduction to a practical method for performing an equilibrium reconstruction in real time for arbitrary time-varying discharge shapes and current profiles. A detailed description of the algorithm is given in Ref. 2. An approximate solution to the Grad-Shafranov equilibrium relation is found which best fits the diagnostic measurements so that an equilibrium solution consistent with force balance, expressed in terms of the spatial distributions of the toroidal current density and poloidal flux, is available in real time for accurate evaluation of the discharge parameters. The algorithm is very close to that of EFIT and is executed on a time scale fast enough for control of the DIII–D tokamak.

The equilibrium reconstruction algorithm has been implemented on the digital plasma control system [3] for the DIII–D tokamak and we describe here its first application for tokamak discharge shape control. Shape identification with this reconstruction technique is robust to changes in the shape, β_p, ℓ_i, and edge current density. Relative to what is required for practical shape control, the results from the real time algorithm do not differ significantly from those of the full off-line analysis. Motional Stark Effect (MSE) diagnostic data can be included in the real time equilibrium reconstruction in order to more accurately determine the toroidal current density profile and the safety factor profile.

Shape control is implemented with the ‘‘isoflux’’ technique [4], in which a set of locations is specified that define the desired plasma boundary and the poloidal field coil currents are adjusted to keep the poloidal flux equal at all of these locations. This is illustrated in Fig. 1 where, for the case of a single null divertor discharge shape, the diamonds indicate the ‘‘control points,’’ locations at which the value of the flux is controlled. Because the control is not based directly on errors in the shape, but rather on errors in the local poloidal flux value at the control points, the requirements on the equilibrium reconstruction algorithm are reduced since calculation of the plasma boundary is not necessary.

One of the control points is chosen as the reference and the flux at the other points is controlled to be equal to the value at the reference point. For instance, for a discharge which is intended to have the boundary limited by the vessel wall, the intended point of intersection

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with the vessel wall is used as the reference point. In a divertor discharge the X point locations are controlled directly. The actual X point locations are determined by finding the locations where $|B_\mathrm{p}| = 0$ and the coil currents are adjusted to move the X point to the intended location. The flux at the actual X point location is then used as the reference flux

The task of the equilibrium reconstruction algorithm is to compute the distributions in the R,Z plane of the poloidal flux (ψ) and the toroidal current density (J_t) which provide a least squares best fit to the diagnostic data and which simultaneously satisfy the model given by the Grad-Shafranov equation

$$\Delta^* \psi_\mathrm{p} = -\mu_0 R J_\mathrm{t}(R, \psi) \ . \tag{1}$$

The diagnostic data consist of measurements of flux and field outside the plasma, plasma current from a Rogowskii loop, internal field measurements made with the Motional Stark Effect diagnostic and current in the poloidal field shaping and Ohmic heating coils.

The full reconstruction algorithm [1] iterates the solutions for ψ and J_t until the changes in ψ between two successive iterations are small. This is illustrated in the flow chart in Fig. 2. In the figure, $(\vec{F} \cdot \vec{R})^{-1}$ is the weighted diagnostic response matrix used to implement the least squares fit, $\vec{\psi}_\mathrm{N}$ is the distribution of normalized flux on the computation grid which is used to form the basis functions for the least squares fit which are contained in the matrix $\vec{\Psi}$, and $\vec{I}_\mathrm{p}$ is the vector of values of the toroidal current on the computation grid.

In the real time version of the equilibrium reconstruction algorithm, the time consuming process of iterating to a well converged solution for a fixed set of diagnostic data is eliminated. Instead, for each new reconstruction a new set of diagnostic data is acquired, the most recent equilibrium solution is used as the starting point, and one iteration is performed. If the equilibrium is not evolving too quickly, the changes since the previous solution can be accounted for in one iteration so that the result has accuracy sufficient for discharge control. The first portion of the real time algorithm is the shape control (or ‘‘fast’’) computation loop in which the shape control power supply commands are generated. This shape control loop can be executed in approximately 1–2 ms because only the portion of a reconstruction iteration that generates $\vec{I}_\mathrm{p}$ must be executed. The input to the shape control loop is the data set $S = \{(\vec{F} \cdot \vec{R})^{-1}, \vec{\Psi}\}$. Each time this shape control loop is executed a new set of diagnostic data is obtained but the same value of the data set S is reused until a new data set is prepared. The second portion of the algorithm (the ‘‘slow’’ loop) completes the steps required in a reconstruction iteration by preparing a new S data set. This involves significant computation, approximately 25 times more than the shape control loop. As part of this process, the flux vector $\vec{\psi}$ is obtained. Quantities such as the safety factor profile, poloidal beta, internal inductance, etc., which are obtained using $\vec{\psi}$, can be computed at this point.

Other modifications were made to the reconstruction algorithm in order to increase the calculation speed. In order to determine the flux at the discharge boundary, the flux at the reference control point is used. This avoids a complex boundary tracing routine. To determine the magnetic axis flux the peak value of the flux at a grid point is used. The time to calculate S is strongly influenced by the number of fitting parameters. A direct measurement of the currents in each of the poloidal field coils is available, allowing these values to be treated as known rather than treating them as fitting parameters.

The real time equilibrium reconstruction algorithm combined with the isoflux technique has been used to control a variety of discharge shapes in the DIII–D tokamak. Some

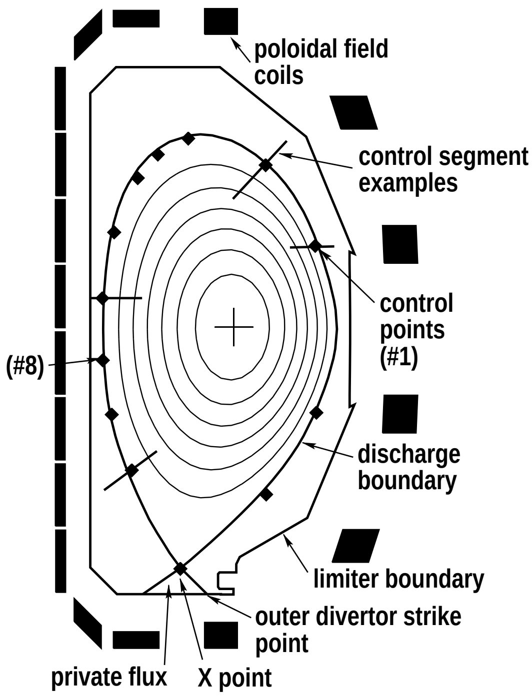

Fig. 1. *Example of a single null divertor discharge (#90291 at 2.5 s) produced using the isoflux control method in combination with real time equilibrium reconstruction. The diamonds show the locations of the control points.*

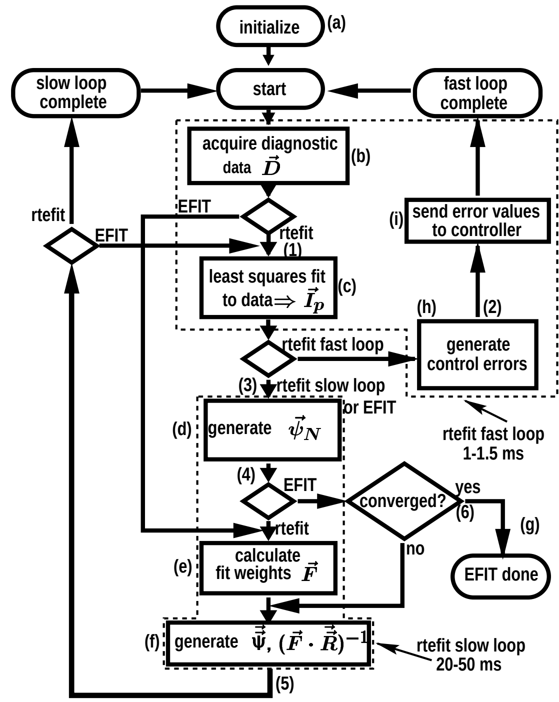

Fig. 2. *Flow chart illustraties procedure for equilibrium reconstruction calculation. Two paths through are shown, one for the full reconstruction (''EFIT'') and one for the real time implementation (''rtefit''). The calculation time values shown are for the implementation in the DIII–D plasma control system.*

examples are the single null divertor shape shown in Fig. 1 and the various shapes shown in Fig. 3. Strike point location control, a capability essential for operation of closed divertor geometries, has also been implemented relatively easily using the isoflux technique.

Experience with DIII–D discharges controlled with the isoflux algorithm shows that the real time equilibrium reconstruction yields results with good accuracy. This is illustrated by the comparisons shown in Fig. 4 between the real time result and the result from the full equilibrium reconstruction calculated off-line. The sample discharge has a preprogrammed sweep of the X point position [Fig. 4(a) and (b)] during which the two equilibrium reconstructions agree on the X point location within a few millimeters [Fig. 4(c)]. The two computations of the flux at the control points agree to within less than 1×10^{-3}V-s/radian. To put this value in perspective, it is displayed in Fig. 4(d) and (e) for two of the control points as a distance computed from $(\psi_{\mathrm{real\,time}} - \psi_{\mathrm{EFIT}})/(\partial\psi/\partial\ell)$ where $\psi_{\mathrm{real\,time}}$ and ψ_{EFIT} are the flux values computed in real time and off-line, respectively, and the flux derivative is taken along a line between the control point and the magnetic axis. This quantity is approximately the difference in the predictions by the two calculations of the boundary location in the region of the control point. Throughout the discharge, this difference is about 1 mm, small compared to the 0.62 m typical minor radius of the discharge.

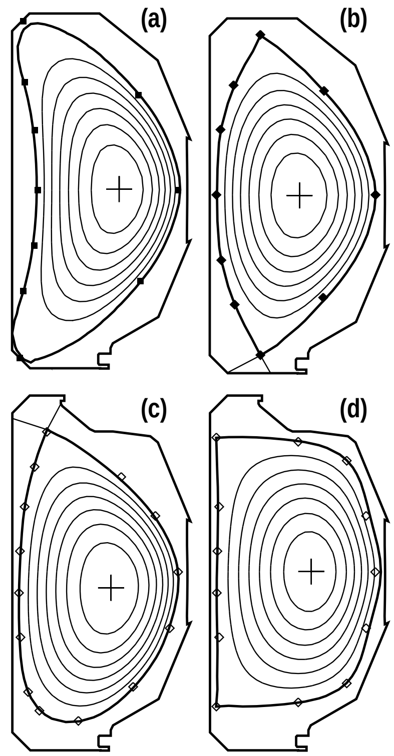

Fig. 3. Examples of discharge shapes produced in DIII–D using the isoflux control algorithm combined with the real time equilibrium reconstruction. (a) Crescent/beam shaped, (b) low triangularity double null divertor, (c) upper simple null divetor, and (d) highly ''square'' shaped duble null divertor.

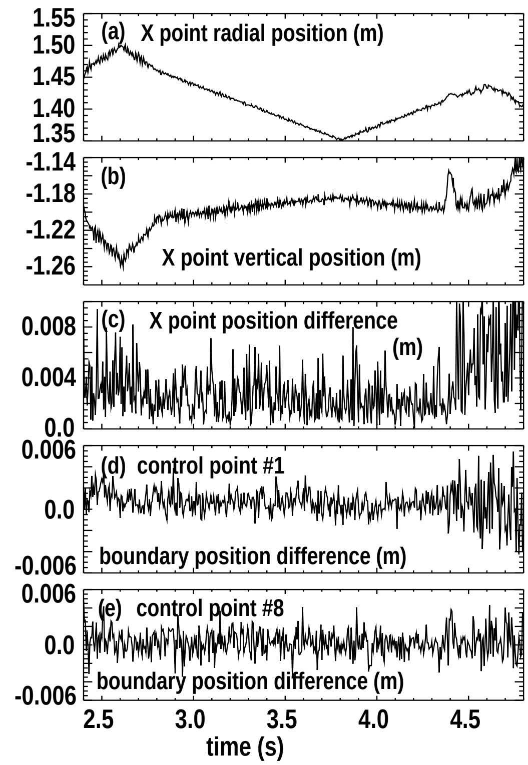

Fig. 4. Comparison of the results from the real time equilibrium reconstruction for the discharge shown in Fig. 1 to results from well-converged solutions from off-line calculations.

In this paper, we have demonstrated that with current digital computing technology it is practical to use an algorithm that executes in real time which is nearly identical to a standard equilibrium reconstruction technique. Equilibrium parameters can be evaluated directly from a solution to the Grad-Shafranov tokamak equilibrium relation. This even allows parameters such as the safety factor profile to be evaluated in real time. The small modifications to the EFIT reconstruction algorithm described here which make the real time execution practical affect the results only on a scale of precision that is not important for practical discharge shape control.

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