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Improved FCDI algorithm for tokamak plasma equilibrium reconstruction

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The paper presents the improved FCDI plasma equilibrium reconstruction algorithm implemented at the Globus-M2 tokamak. The algorithm has been improved to be able to operate in real time. The FCDI-FF (Fixed Filaments) operation mode was added, in which the plasma is modeled by current filaments at fixed positions. New user interface for the algorithm displays reconstructed plasma separatrix and contours of the internal magnetic surfaces, the poloidal flux distribution, and graphs of the reconstructed plasma parameters, including profiles of plasma pressure, poloidal current and safety factor q, plasma energy, poloidal beta and internal inductance, which can be exported in *.mat, *.json and G-eqdsk formats.

Keywords: tokamak, equilibrium reconstruction, plasma shape.

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The Globus-M2 tokamak [1] at the Ioffe Institute is a compact spherical tokamak with major radius $R = 0.36$ m, minor radius $a = 0.24$ m, and aspect ratio $A = 1.5$. The EFIT code [2] and the method of movable filaments [3] developed at JSC „NIIEFA" have been used earlier for plasma equilibrium reconstruction at the Globus-M2 tokamak. The equilibrium EFIT code calculates the plasma equilibrium based on measured currents in poloidal field coils of the tokamak, the plasma current, and the values of poloidal beta β_p and internal inductance l_i specified by the user. The movable filaments method, which utilizes measured currents in coils, the plasma current, and voltages at magnetic loops of the tokamak, provides a more accurate calculated position of a magnetic separatrix than EFIT, but does not allow one to reconstruct correctly the configuration of magnetic surfaces inside a separatrix.

The FCDI (Flux-Current Distribution Identification) algorithm [4], which has been developed earlier for reconstruction of the shape and internal magnetic surfaces of plasma, makes it possible to reconstruct the plasma equilibrium at Globus-M2 and other tokamaks. This algorithm was implemented in the MATLAB/Simulink software environment.

Tokamak currents are modeled in FCDI by a continuous current density J_φ distribution (FCDI-IT mode) that satisfies the Grad–Shafranov equation:

$$r\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial\Psi}{\partial r}+\frac{\partial^2\Psi}{\partial z^2}$$
$$=\begin{cases}-\mu_0 r J_\varphi, & (r,z)\notin S_p,\\ -\mu_0 r^2 p'(\Psi)-F(\Psi)F'(\Psi), & (r,z)\in S_p,\end{cases}$$
$$\Psi\Big|_{r=0}=0,\quad \Psi\Big|_{r\to\infty}=0, \tag{1}$$

where S_p is the plasma region and $p(\Psi)$ and $F(\Psi)$ are the plasma pressure and the poloidal current as functions of poloidal magnetic flux Ψ. Functions $p'(\Psi)$ and $F(\Psi)F'(\Psi)$ are approximated in the algorithm by polynomials of a user-defined order in normalized poloidal flux.

The coefficients of approximating polynomials and the distribution of vacuum vessel current I_{VV} are determined by minimizing the quadratic functional of error between modeled and measured values of poloidal flux at magnetic loops Ψ_k and $\Psi_{k,exp}$, plasma current I_P and $I_{P,exp}$, and modeled distribution of vacuum vessel current I_{VV} and its estimate $I_{VV,est}$ derived from the Faraday law. Errors σ of measured values serve as weights in the functional:

$$\chi^2=\sum_k\left(\frac{\Psi_k-\Psi_{k,exp}}{\sigma_k}\right)^2+\left(\frac{I_P-I_{P,exp}}{\sigma_P}\right)^2$$
$$+\sum_j\left(\frac{I_{VV_j}-I_{VV_{j,est}}}{\sigma_{VV_j}}\right)^2. \tag{2}$$

The FCDI algorithm for plasma equilibrium reconstruction has been updated by now to make it applicable in real-time calculations. It may be compiled as a real-time application for QNX Neutrino [5], SimulinkRT [6], RTLinux [7], and „RITM" [8] real-time operating systems and, consequently, may provide feedback for a magnetic plasma equilibrium control system. The results of modeling performed at Speedgoat Performance [9] and „KPM RITM Standartnyi" [8] real-time target machines revealed that the FCDI algorithm reconstructs plasma equilibrium in real time at each time point of a discrete sample (within 200 μs in the FCDI-IT mode on a 33×33 rectangular grid).

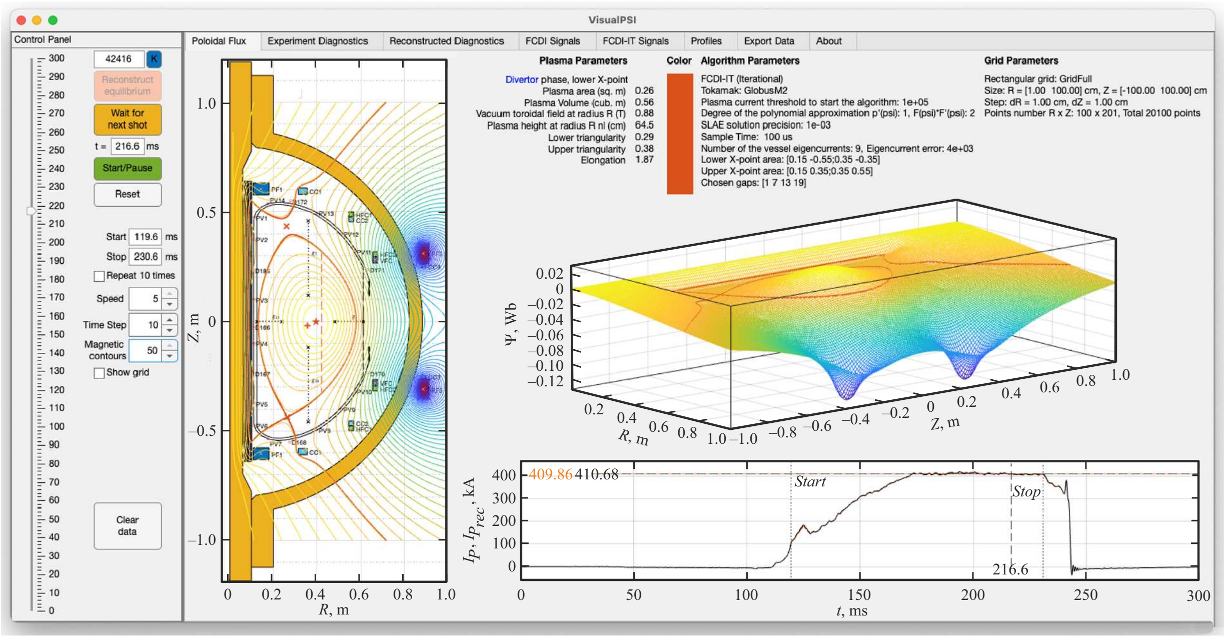

Figure 1. VisualPSI interface, „Poloidal Flux" tab. Discharge No. 42416, the time point is 216.6 ms. Reconstructed separatrix and magnetic surfaces of plasma, plot of the distribution of poloidal magnetic flux Ψ in the tokamak, and measured I_P and reconstructed $I_{P_{rec}}$ plasma currents.

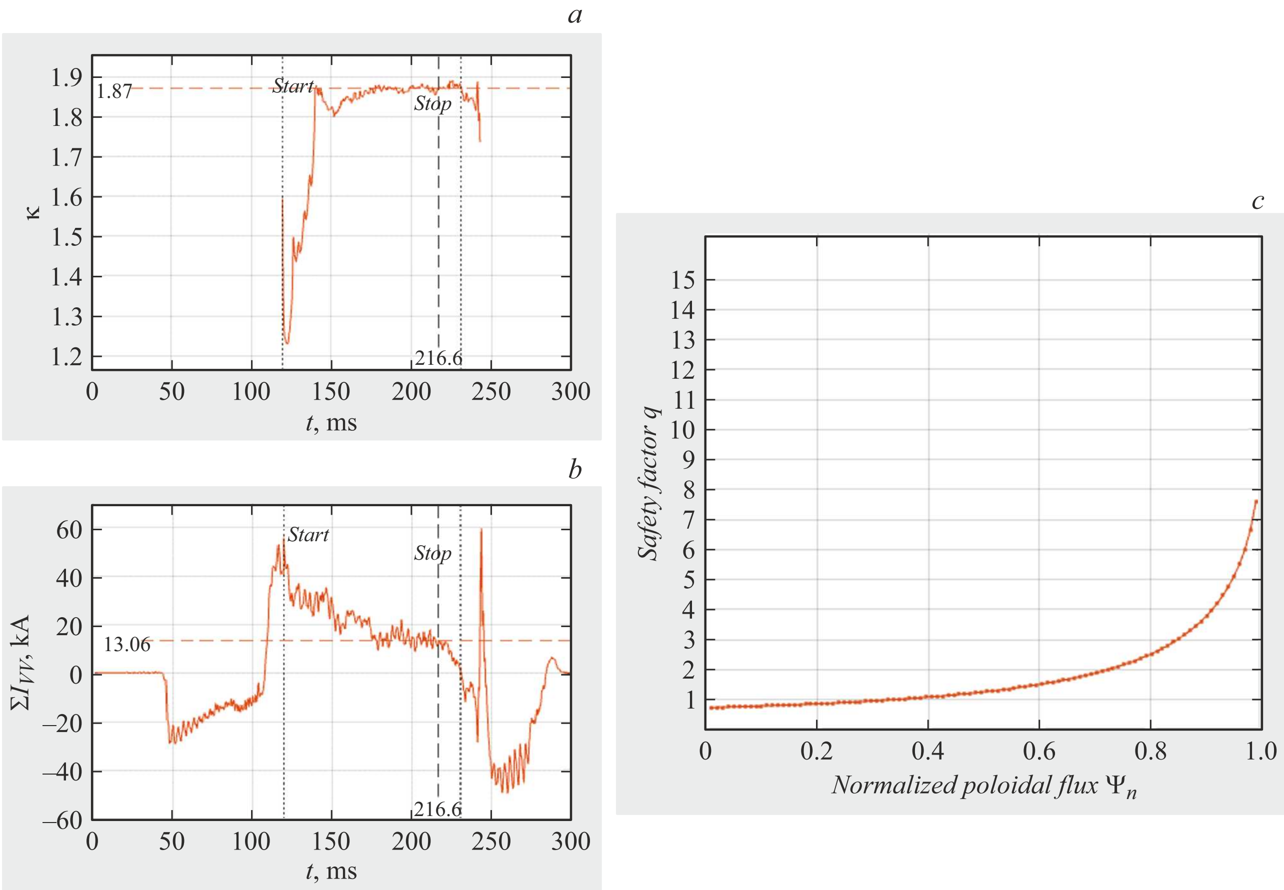

Figure 2. VisualPSI interface. Discharge No. 42416. *a* — Element of the „FCDI Signals" tab: elongation κ of reconstructed plasma; *b* — element of the „FCDI Signals" tab: reconstructed total vacuum vessel current $\sum I_{VV}$; *c* — element of the „Profiles" tab: profile of safety factor q at a time point of 216.6 ms.

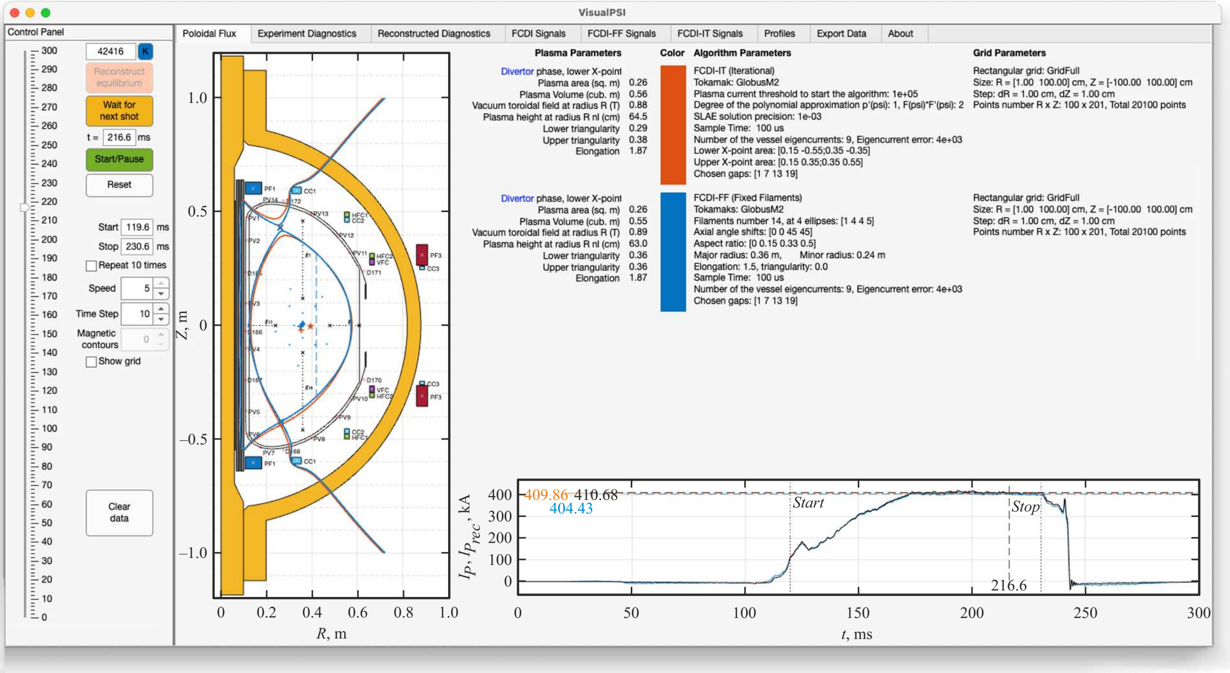

Figure 3. VisualPSI interface in the mode of comparison of separatrices. Discharge No. 42416, the time point is 216.6 ms. Separatrices reconstructed in the FCDI-IT and FCDI-FF modes and measured I_P and reconstructed $I_{P_{rec}}$ plasma currents.

To speed up the operation of this algorithm further, the FCDI-FF (Fixed Filaments) mode was added, wherein plasma is modeled by a set of fixed current rings (filaments) with coordinates defined by the user. The magnitudes of currents in filaments are determined by minimizing error functional (2). The algorithm in the FCDI-FF mode reconstructs plasma equilibrium within 30 μs on an irregular grid of 1000 points.

The updated version of the FCDI algorithm for plasma equilibrium reconstruction also features a user interface backed by the proprietary VisualPSI application (Figs. 1–3). The left panel allows one to configure the data presentation and display the reconstructed plasma equilibrium at different time points. Tabs with the following functions are located on the right:

• „Poloidal Flux“ — displays the separatrix position (plasma boundary), magnetic surfaces inside plasma, the distribution of poloidal flux Ψ, and measured I_P and reconstructed $I_{P_{rec}}$ plasma currents (Fig. 1);

• „Experiment Diagnostics“ — displays measured currents $I_{k,exp}$ in coils of the poloidal field, fluxes $\Psi_{k,exp}$ at magnetic loops, and estimated total vacuum vessel current $\sum I_{VV,est}$;

• „Reconstructed Diagnostics“ — comparison, which is performed to estimate the accuracy of equilibrium reconstruction, of measured fluxes at magnetic loops $\Psi_{k,exp}$ with fluxes at loops Ψ_k calculated based on the reconstructed poloidal flux distribution;

• „FCDI Signals“ — calculated plasma parameters: flux at separatrix Ψ_{sep}; coordinates R_P and Z_P of the geometric plasma center; vacuum toroidal field B_{TF} at radius R_P; elongation κ (Fig. 2, a); upper δ_{up}, lower δ_{lo}, and average δ plasma triangularity; volume V_{pl} and cross-section area S_{pl} of plasma inside a separatrix; reconstructed total vacuum vessel current $\sum I_{VV}$ (Fig. 2, b); height of the vertical plasma chord H_P at radius $R_{nl} = 0.42$ m through which goes the observation chord of the microwave interferometer of the Globus-M2 tokamak; error functional χ^2; and gaps g between a separatrix and the limiter;

• „FCDI-FF Signals“ — plasma parameters calculated additionally in the FCDI-FF mode: filament currents I_F and coordinates of the plasma centroid calculated based on them

$$R_{centroid} = \sum R_F I_F \Big/ \sum I_F, \quad Z_{centroid} = \sum Z_F I_F \Big/ \sum I_F;$$

• „FCDI-IT Signals“ — plasma parameters calculated additionally in the FCDI-IT mode: coordinates R_{axis} and Z_{axis} of the magnetic axis, magnetic flux Ψ_{axis} and plasma pressure p_{axis} on the axis, safety factors q_0 and q_{95}, plasma energy W, poloidal beta β_p, and internal inductance l_i;

• „Profiles“ — profiles of safety factor q (Fig. 2, c), plasma pressure p, poloidal current F, and their derivatives $p'(\Psi)$ and $F(\Psi)F'(\Psi)$;

• „Export Data“ — export of the reconstructed equilibrium in *.mat, *.json, and G-EQDSK formats.

The VisualPSI application may be operated in the mode of comparison of separatrices, wherein equilibrium is reconstructed by several algorithms with different parameters simultaneously. The reconstructed separatrices and signals are colored differently for ease of comparison (Fig. 3; a color version of the figure is provided in the online version of the paper).

A connection between the FCDI algorithm for plasma equilibrium reconstruction and the plasma discharge database is established by the proprietary „Tokamak Datasets Processing Toolbox“ software package, which provides an opportunity to process experimental plasma discharge data in MATLAB.

The discussed software was commissioned as part of the magnetic diagnostics system for plasma discharge at the Globus-M spherical tokamak in the fall of 2022 and provided an opportunity to reconstruct plasma equilibrium (including shape; position; current density; profiles of pressure, poloidal current, and safety factor q; positions of strike and X points; gaps between plasma and the tokamak limiter; and distributions of magnetic fields in the tokamak) based on the results of magnetic diagnostics (specifically, the readings of magnetic loops and Rogowski coils). In contrast to the algorithms used earlier at the Globus-M2 tokamak, the FCDI algorithm allows one to reconstruct the structure of magnetic surfaces inside plasma.

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Conflict of interest

The authors declare that they have no conflict of interest.

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