Validation Procedure of the Tokamak Equilibrium Reconstruction Code EQUAL with a Scientific Workflow System

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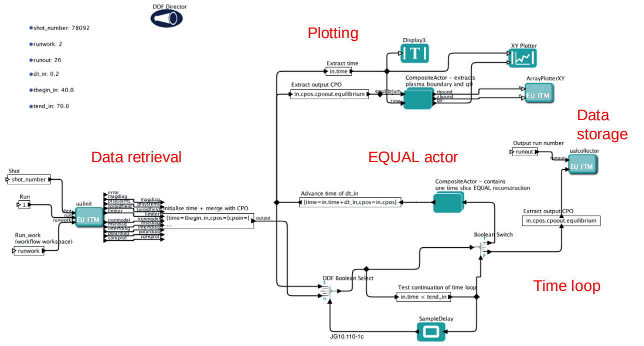
**See the Appendix of F. Romanelli et al., Proceedings 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland*

The equilibrium reconstruction code EQUAL (EQUilibrium AnaLysis) is based on the algorithm of EFIT [1] and solves the Grad-Shafranov equation using data from magnetic, MSE and Faraday diagnostics to determine the unknown current profile in the plasma. The code has been developed within the European Task Force on Integrated Tokamak Modelling (ITM-TF), which aims at providing a framework of validated codes for simulation, preparation and analysis of discharges for the ITER device as well as existing fusion machines. Verification and Validation (V&V) is a key component of the ITM-TF activity, and the simulation infrastructure developed by the ITM-TF has been designed with this in mind. ITM-TF codes are independent of a particular device and interact with each other via predefined data structures [2]. EQUAL is the first of these codes using the simulation infrastructure based on Kepler [http://www.kepler-project.org] for validation.



Kepler workflow for time-dependent analysis of a complete discharge with the code EQUAL. The blue boxes represent actors fulfilling complex tasks and can be a complete analysis code, while the rectangles represent parameters or simple actions. The actor "ualinit" retrieves shot data from the ITM database and feeds the data to the time loop in the lower right part of the figure, comprising EQUAL within the composite actor. The top right part shows the plotting facilities of Kepler, displaying the plasma boundary in real time and the central safety factor as a function of time.

THE EQUAL ALGORITHM

Grad-Shafranov equation (Isotropic pressure P, negligible plasma flow, toroidal symmetry)

$$-\frac{\partial^2\Psi}{\partial R^2}+\frac{1}{R}\frac{\partial\Psi}{\partial R}-\frac{\partial^2\Psi}{\partial Z^2}=\mu_0 R^2 P'(\Psi)+F(\Psi)F'(\Psi)+\mu_0 R J_{ext}(R,Z)$$

$$\chi^2=\sum_{m=1}^{N_{meas}}\left(\frac{F_m^{calc}\{\Psi,\underline{x}\}-F_m^{meas}}{\sigma_m}\right)^2+\lambda^2\Re(\underline{x})$$

- Profiles P' and FF' parameterised as a linear superposition of suitable test functions.
- External sources poloidal field coils, ferromagnetic materials, vessel currents, as superposition of sources with known geometry (Greens'function method).
- Unknown coefficients $\underline{x}$ (current profile and external sources) determined by minimising the least squares functional χ^2
- F_m^{meas} measured value
- F_m^{calc} corresponding synthesised measurement
- σ_m estimated uncertainty.
- Tikhonov regularising term $\Re$ controls unphysical oscillations of the current profile.

- Written in ANSI Fortran 95, public domain libraries (Lapack, FFTW), see [4]
- Verification of field solver and calculation of physical quantities against analytic solution: < 0.1 % deviation

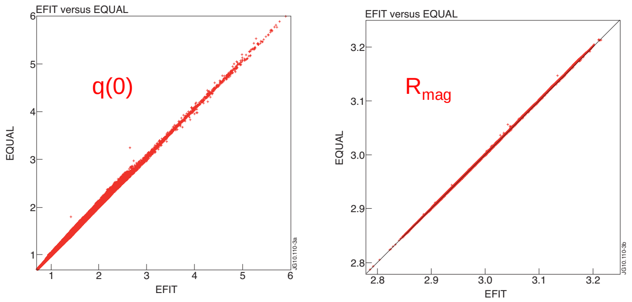
- CPU time: 65x65 grid , 4 test functions: 0.2 sec (workstation 1.4 GFlops)
  512x512 grid, 4 test functions : 20 sec.

BENCHMARKING AGAINST EFIT

The first systematic test of EQUAL is the benchmarking against the code EFIT [5] routinely run for JET discharges. Only data from the magnetic diagnostics is being used. The machine description files of the JET device are set up for discharges 68613-78157 (to be extended), describing magnetic diagnostics, poloidal and toroidal field coil system, ferromagnetic transformer and first wall, has been reviewed, mapped into the ITM generic tokamak description and put into the ITM database. JET studies [6] identified a series of JET discharges that contain MHD marker data suitable for comparison with EQUAL. Data required for equilibrium identification of 147 discharges has been transferred with the ITM tool exp2ITM [2] to the ITM database.

For benchmarking with EFIT, the same number and type of test functions for P' and FF' are used, polynomials up to second order and a suitable regularisation. First tests confirm the strong dependency of the central safety factor on the amount of regularisation. This is easily explained, since the core structure of the equilibrium is not well constrained by magnetic data only [3]. One reference shot is used to adjust the regularisation parameter, which is then applied to the whole set of 147 discharges. The results of both codes have been compared by producing scatter plots on selected common time points. Results for the central safety factor and the position of the magnetic axis are given in the scatter plots below.

Scatter plot on common time points



The result of the comparison of safety factor, position of magnetic axis and X-point, beta poloidal and plasma current are summarised in the table below. There is very good agreement of parameters well constrained by the magnetic diagnostics close to the plasma boundary. The deviation of core related parameters, especially q(0) and β_p, can be explained by differences of the two codes, as different grid size and position, and different algorithms for treating the field contribution of the ferromagnetic transformer.

Average deviation of physical quantities calculated by EQUAL and EFIT	
q(0)	0.05
q(95%)	0.05
Position of magnetic axis	2 mm
Position X-point	1 mm for radial, 3 mm for vertical coordinate
plasma current	1 kA
beta poloidal	0.012

CONCLUSIONS AND OUTLOOK

In the first phase of the validation procedure of the ITM code EQUAL a benchmark comparison was performed against results from the JET code EFIT, giving very good agreement. The geometric and discharge data have been retrieved with the formalised procedure according to ITM standards. Note that since the ITM data description is machine generic, the workflow discussed here can readily be used to process discharges from any other tokamak (e.g. Tore Supra which has its ITM description ready). The next stage of the validation procedure will use internal plasma data from Faraday and MSE diagnostics to compare with rational surfaces of the safety factor profile obtained from the analysis of MHD instabilities.

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