Validation of the new real-time equilibrium code EQUINOX on JET and Tore Supra

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**See the Appendix of F. Romanelli et al. Proc. 22nd IAEA Fusion Energy Conference,*

1. Introduction

The shape of the plasma current density profile, direct output of an equilibrium reconstruction, is known to play a leading role in triggering and sustaining high performance regimes. In the perspective of improving the control of these regimes, the objective is thus to develop real-time methods and algorithms that reconstruct the magnetic equilibrium in the perspective to use their outputs for feedback purposes.

The real time equilibrium reconstruction code EQUINOX, which solves the Grad Shafranov equation, has been recently rewritten and installed in both JET and Tore Supra (TS) real time control systems. This new version provides much more flexibility in terms of parameters tuning and constraints. Indeed in addition to the magnetic measurements it may consider as internal constraints MSE, polarimetry, and potentially others such as Soft X-rays measurements and/or plasma pressure profiles for magnetic axis determination. The calculation time, when internal constraints are included, is about 50ms on both machines, which is short enough to allow feed back control on the plasma current on medium and large devices.

2. Overview of the used RT resolution techniques

The problem of the equilibrium of a plasma in a Tokamak is a free boundary problem in which the plasma boundary is defined as the last closed magnetic flux surface. Inside the plasma, the equilibrium equation in an axisymmetric configuration is the Grad-Shafranov equation:

$$-\Delta^*\psi = rp'(\psi) + \frac{1}{\mu_0 r}(ff')(\psi) \quad \text{with} \quad \Delta^* = \frac{\partial}{\partial r}\left(\frac{1}{\mu_0 r}\frac{\partial}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu_0 r}\frac{\partial}{\partial z}\right) \tag{1}$$

Where μ_0 is the magnetic permeability of the vacuum, $\psi(r,z)$ the poloidal flux, r, z the Cartesian coordinates. The right hand side of this equation is a non-linear source which represents the toroidal component of the plasma current density. The goal of a real-time equilibrium code is to identify not only the plasma boundary but also the flux surface geometry outside and inside the plasma, the current density profile and derive the safety factor 'q' and other important parameters from the obtained equilibrium. In order to meet the real-time requirements, a new version of the EQUINOX [1] code has been designed and implemented in C++ using a finite element method, a non linear fixed point algorithm associated to a least square optimization procedure. Tokamak specific softwares like FELIX/XLOC [2] (or APOLO [3] at Tore Supra) provide to the EQUINOX code the boundary conditions (discrete poloidal flux values on the first wall of the vacuum vessel) in real-time. By means of least-square minimization of the difference between measurements and the simulated ones the code identifies the source term of the non linear Grad-Shafranov equation. The experimental measurements that enable the identification are the magnetics at the vacuum vessel, the interferometric and polarimetric measurements on several chords and the motional Stark effect measurements (only at JET). The finite element solver uses triangles interpolation, the calculation being limited to the vacuum chamber. A careful implementation inside the MARTe framework [4] at JET leads to execution time less than 50ms per iteration on a 2GHz PC, complemented with excellent robustness and very good precision (+/- 1cm compared to FELIX-XLOC code) of plasma boundary for an equilibrium code. Examples of reconstructed equilibria at Tore Supra and JET are provided in Fig.1:

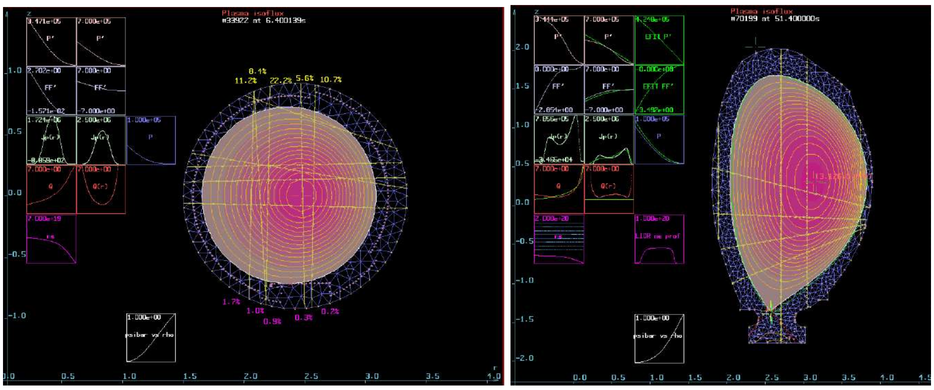


Fig.1: Examples of Equilibrium reconstruction: left Tore Supra case (#33922 at 6.4s) right JET case (#70199 at 51.4s).

3. Code validation at JET

Using a validated database of 150 pulses (shots with or without the new ITER Like Wall) well representative of JET operational space ($1.12<I_p<3.09$MA, $1.68<B_T<3.42$T, $0.06<\delta<0.51$), EQUINOX has been first fully and carefully benchmarked against the online plasma boundary shape reconstruction code XLOC, the off line equilibrium code EFIT [5] and MHD signatures. Statistical analysis confirmed the relevance of the EQUINOX reconstruction (Fig 2) for the reconstruction of global parameters.

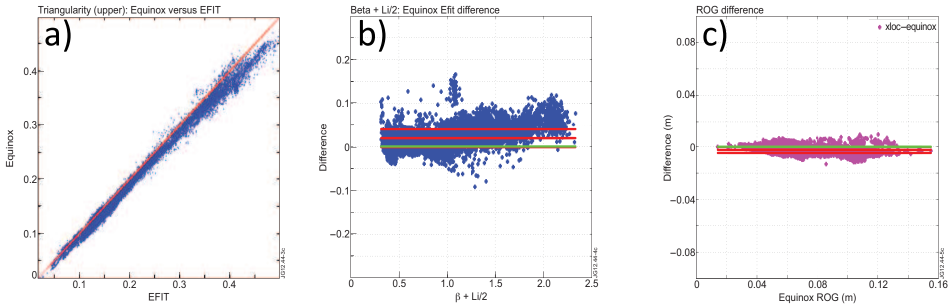
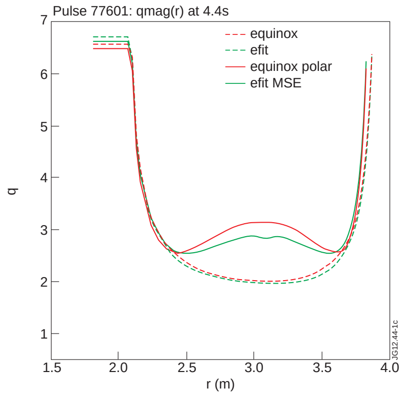


Fig.2 Statistical comparisons between EQUINOX and EFIT [5] for a) triangularity b) Shafranov Shift and XLOCc) Right Outer Gap (ROG)). Horizontal green line zero reference, horizontal red lines standard deviations

Validation has also been performed on specific shots to check the dynamical response of the code but also to validate the accuracy of the reconstruction when internal measurements are used (Fig.3).



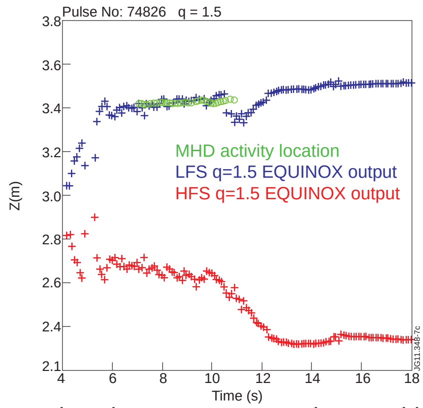


Fig 3 Comparison between EQUINOX and EFIT of q profile magnetic only (dotted lines), polarimetry and MSE (green plain lines) #77601, Ip=1.7MA BT=2.6T, 3MW LHCD (Lower Hybrid Current Drive), 6MW ICRH (Ion Cyclotron Resonance Heating), 20 MW NBI.

Fig 4 Comparison between MHD markers and location of q=1.5 (low and high field side) obtained in real time from EQUINOX (constrained with polarimetry), (#74826, 19MW NBI, I_p=1.6MA, B_T=2T)

Independent analysis of the database provides identification of MHD mode and their location. Fig. 4 shows the perfect agreement between EQUINOX and mode location (q=1.5) identified from Electron Cyclotron Emission (ECE) and magnetic measurements.

4. Code validation at Tore Supra

The validation of Equinox on Tore Supra has started and will follow the same methodology as JET. The new version of Equinox takes into account the polarimetry data. Indeed, this diagnostic is of crucial importance at Tore Supra where shots can last several minutes, these durations being presently much too large for continuous MSE measurements. Equinox input parameters have been tuned by calculating plasma equilibria for some typical shots of the last campaign, and compared with EFIT and with the current diffusion code CRONOS calculations. They have also been compared with results from APOLO code that controls the plasma position in real time, taking information from the poloïdal generators and the magnetic diagnostics. Figure 5.a shows an example of q profiles obtained by EQUINOX, EFIT and CRONOS for a sawtooth discharge with 5MW of Ion Cyclotron Radiofrequency Heating. EQUINOX and EFIT both using polarimetry are in a very good agreement, whereas slight differences can be seen with CRONOS, but the difference looks reasonable since these codes are based on different principles. Figure 5.b shows the evolution of the rational q surfaces position with time for the 3 calculations, still in good agreement. When possible the comparison with MHD information is performed. For instance in this figure, the sawtooth inversion radius derived from the ECE diagnostic is indicated. The tuning of EQUINOX now needs to be tested on a larger database of shots, and this code will be available for the next campaign, the new q profile control algorithm tools being developed in parallel.

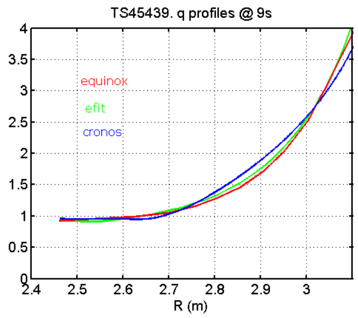


Fig 5.a Comparison of q profiles obtained by EQUINOX, EFIT, and the current diffusion code CRONOS

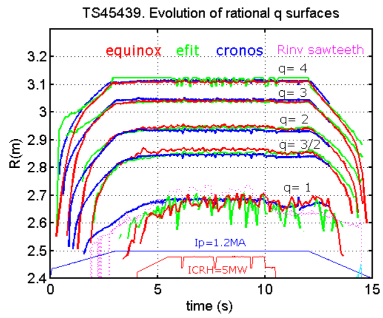


Fig 5.b Comparison of rational q surfaces evolution with time for EQUINOX, EFIT and CRONOS. The sawtooth inversion radius is indicated.

5. Conclusions and perspectives

The EQUINOX code is now available in real time in both JET and Tore Supra tokamaks and will be used for q profile feedback control experiments. The full validation of the real time reconstruction provides now a good base for real-time control but more generally systematic physics analysis. This code is also available inside the Integrated Tokamak Modelling platform which makes EQUINOX a potentially very powerful tool to predict equilibrium and current profile evolution in ITER or DEMO.

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