Equilibrium reconstruction analysis of TCV tokamak plasmas in the EU- IM platform

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I – Introduction

Tokamak plasma equilibrium reconstruction is a fundamental step in the understanding of fusion plasma physics. Accurate reconstructions of the plasma shape and position are essential from the point of view of plasma control, ensuring that the target scenario requested is met and that no machine operational limits are reached with the consequent termination of the discharge. The range of different plasma equilibria, depending on shape, current density and pressure profiles, is also large and poses significant challenges on numerical tools to provide reliable equilibrium reconstructions that perform well in the vast majority of cases using the available experimental measurements. In the framework of the EUROfusion Code Development for Integrated Modelling Work Package, a scientific Kepler [1] workflow focused on the reconstruction of Tokamak plasma equilibrium was developed and already used for the modelling of selected JET and AUG plasma equilibrium. Magnetic data and Motional Stark Effect (on JET) and kinetic thermal pressure profile constraints (on AUG) were used [2]. The workflow interfaces to consolidated reconstruction codes such as EQUAL [3], CLISTE [4], EQUINOX [5] and SDSS [6], all using the same physics and machine data ontology and methods for accessing the data used in the European Integrated Modelling (EU-IM) framework [7].

In this work, first ever reconstructions trials with EQUAL and EQUINOX codes on TCV data are presented, using only magnetic diagnostic data. TCV is the most versatile EU device regarding plasma shapes and divertor configurations and is the ideal testbed for plasma equilibrium reconstruction validation focusing on the equilibrium geometry, potentially transiting during a discharge between different configurations. The discharges chosen were all

* See http://www.euro-fusionscipub.org/eu-im
& *See the author list of "Meyer et al, Overview of progress in European Medium Sized Tokamaks towards an integrated plasma-edge/wall solution, accepted for publication in Nuclear Fusion"*

L-mode plasmas, ohmically heated, with a normalised β_N~0.33-0.4, plasma currents in the range 140-265kA, toroidal field B_T~1.42T and shapes as summarised in Table 1.

#51262	#55549	#56243	#56253	#56301
Single-null down	ITER-like shape	Limiter, negative triangularity	Limiter, positive triangularity	Single-null down to single-null up

Table 1 – Plasma discharges used for the code benchmark exercise.

All plasma equilibria considered presented new challenges to EQUAL/EQUINOX in particular regarding the reconstruction of the plasma boundary e.g. on EQUINOX, the toroidal harmonics order (required for "extreme shapes") and the close proximity of the plasma to sensors leading to reconstruction biasing (internal blow up of the high order harmonics); on EQUAL, the boundary reconstruction at early stages of the iteration heading towards separatrix bounded plasma. The two limited plasmas, presumably amenable to reconstruction, have non-active X-points very close to the first wall, posing inevitable numerical problems. The plasma transiting from SND to SNU also presented challenges since EQUINOX had to be revised/upgraded to access SNU type of plasmas. Both codes were benchmarked against the results from LIUQE code [8], the de facto tool optimised for TCV plasma reconstructions.

II – Single null and ITER like shape plasmas

The first type of plasmas addressed were single-null plasma with ITER-like or similar shape. For a particular pulse (#51262), Infrared Camera data was available to validate the strike point estimates. Differences from the code estimates were below 5mm, as easily inferred from the flux map shown in Figure 1.

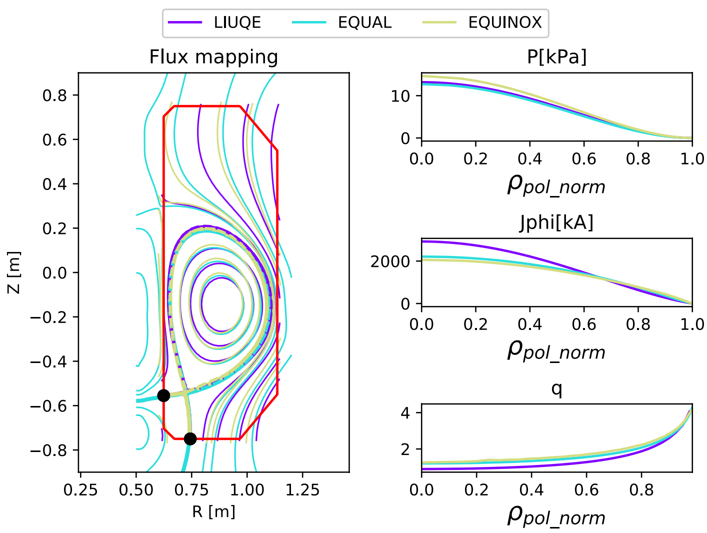

Figure 1 – Reconstruction of TCV #51262 at t=0.75s. Strike points deduced from IR camera are also shown

The agreement in the geometry (X-point, strike points, magnetic axis) is very good, with deviations below ~6mm (the *dashed line* in flux map indicates the estimated plasma boundary, the *thick lines* are post-processed estimations from interpolated null points). However, for this shot both EQUAL and EQUINOX had to raise the equivalent absolute error of flux loops (originally 1.2mWb) and lower that of the poloidal field probes (originally 10mT) in order to get good results. This artificial weighting to the sensors was then propagated to the remaining cases studied in EQUAL (in EQUINOX, using the nominal errors yields similar results despite a larger fitted error in the poloidal magnetic field). LIUQE estimates a higher core plasma current density (here and in some other cases studied) although the total plasma current is within 0.5% among the 3 codes. The resulting q-profile below unity on axis fortuitously concurs with the experimental observation of sawtooth. The next case considered was an ITER like shaped plasma, at a maximum plasma current of ~265kA. The match among codes is once more quite good as seen in Figure 2.

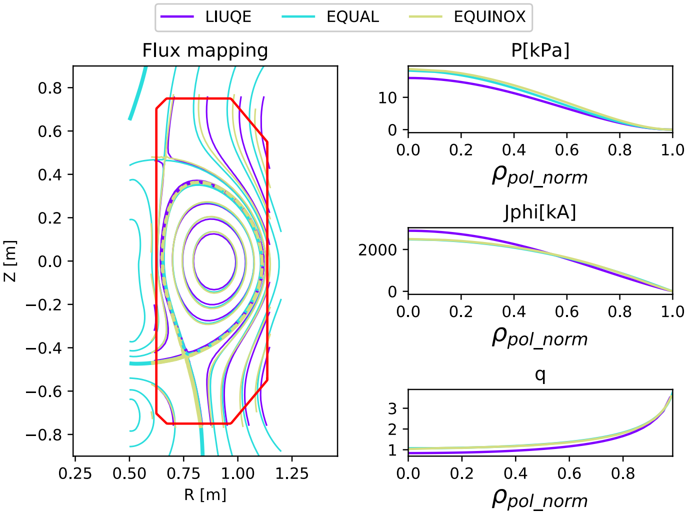

Figure 2 – Reconstruction of TCV #55549 with ITER-like shape at t=1.0s.

Excellent agreement (<4mm) in the geometry is obtained including the non-active upper X-point, the q-profile on axis is marginally above 1 for EQUAL and EQUINOX. Averaged errors in poloidal field and flux in the sensors was 2.23/2.63/5.85mT and 3.51/8.03/3.05mWb respectively for LIUQE, EQUAL and EQUINOX.

III – High triangularity limited plasmas

Analysis of positive (#56253, t=0.75s) and negative (#56243, t=1.1s) triangularity plasmas aimed at assessing the code capabilities when X-points close to the first wall are present. This is shown in Figure 3, with the negative triangularity case showing more notable differences in the boundary shape among the 3 codes, with EQUINOX showing in both cases the largest area, elongation and triangularity and EQUAL the smallest ones.

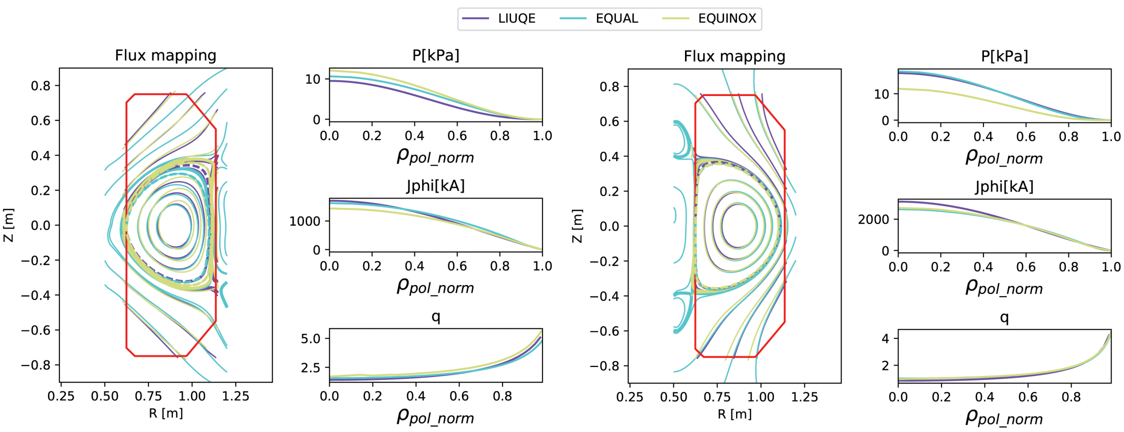

Figure 3 – Reconstruction of TCV negative (left) and positive (right) triangularity plasmas.

IV – Single to double null transiting plasmas

The transition from single lower null to double null and then to single upper null that characterises pulse 56301 tested the code's handling of time dependent plasma boundaries. All codes captured the transition in active X-points, as shown in Figure 4, although at a different time (LIUQE at t~1.1s, EQUAL and EQUINOX at t~1.15-1.17s). The challenge in the transition is apparent by the increase in fitting errors at the transition (EQUAL errors remain at ~2mT/11mWb, EQUINOX at 1.4mT/4.7mWb whereas LIUQE's raises from ~2.5mWb to ~10mWb at the transition while magnetic field remains around 2.5mT).

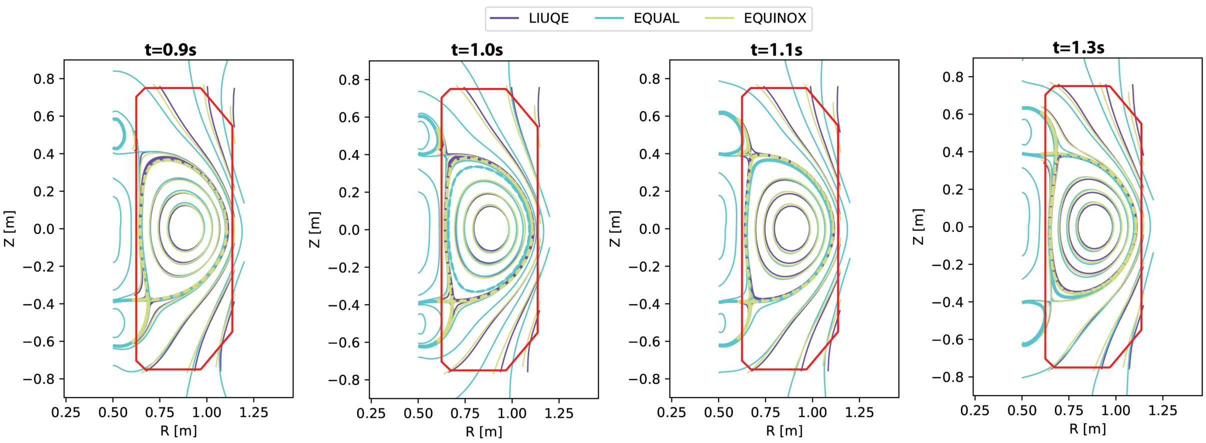

Figure 4 – Reconstruction of TCV pulse 56301 showing the transition SND->DN->SNU as obtained by all 3 codes. A noticeable boundary calculation fail in EQUAL is observed at t=1.0s (dashed line).

V – Conclusions

Equilibrium reconstructions of a representative set of TCV plasma discharges, with different shapes, have been achieved using a dedicated EU-IM scientific workflow. EQUAL and EQUINOX, run for the first time with TCV data, show excellent agreement on magnetic axis, X-point and strike point positions with the LIUQE code, the benchmark code routinely run on TCV. The discrepancy on the core toroidal current density is not unexpected considering that only magnetic diagnostic data was used and different code optimizations do play a role (also, LIUQE used flux loops measurement in "differential mode" as constraints except in #51262).

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