Equilibrium reconstruction of discharges from EUROfusion tokamaks using the WPCD scientific workflows

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Introduction

Equilibrium reconstruction codes are the corner stone of many workflows for analysis of tokamak discharges. Code benchmarking can be facilitated when the codes share the same data ontology, which also allows for easier porting to new devices. Such an approach has been adopted by the Work Package for Code Development (WPCD) using the ITER Integrated Modelling and Analysis Suite (IMAS) [1], building upon the work of the European Integrated Modelling framework. Following up on some initial work [2], we report here on a benchmarking exercise using the EQRECONSTRUCT workflow [3], developed within WPCD and sporting the EQUAL [4] and NICE [5] equilibrium reconstruction codes, using data from the TCV, AUG and JET EUROfusion tokamaks. Most reconstructions presented here will use magnetics data only but the workflow is already equipped to also handle data from interferometry, polarimetry or MSE diagnostics. The plasma pressure in the outer radius can also be constrained by input profiles. Results from the EQUAL and NICE codes will be compared to the local codes used for reconstruction on each machine.

Equilibrium reconstruction

Our first example of the use of the EQRECONSTRUCT workflow uses a discharge from the TCV tokamak. The sensors included in the reconstruction are the measurements of the current flowing in each of the 20 groups of poloidal field (PF) coils, including that of the toroidal field coils, 38 poloidal flux measurements corresponding to ideal loops with perfectly circular paths at fixed (R,Z) (pre-processed from the real measurements), 38 poloidal magnetic field measurements from the magnetic probes distributed poloidally around the vacuum vessel and one plasma current estimate using the discrete Rogowski coil made of the 38 magnetic probes. The typical error used for the reconstruction for each measurement is 200 A for the coil currents, 8.5 mWb for the flux loops, 10 mT for the magnetic probes and 24 kA for the plasma current. Other available sensors includes an estimate of the toroidal diamagnetic flux and estimates of the toroidal vessel currents in the 38 vessel segments associated with each flux loop. These sensors are used in the local LIUQE runs but were excluded from this study, in particular since the time slices were chosen well within the flat top of the discharges the vessel currents were expected to have little influence on the equilibrium.

Figure 1 details the different reconstructions by EQUAL and NICE using the EQRECONSTRUCT workflow and the standard LIUQE reconstruction of TCV discharge #67455 at $t = 0.7$ s. All codes provide very similar reconstructions with the reconstructed sensors within the

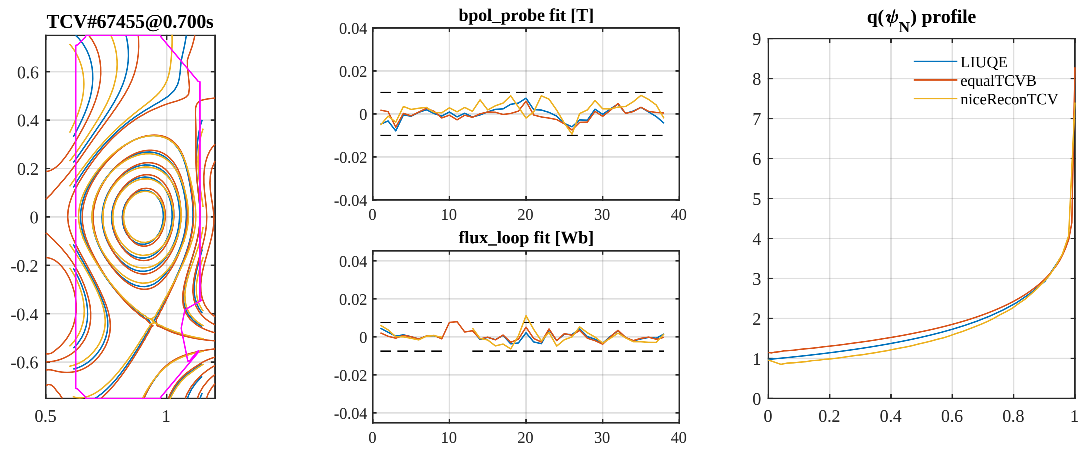

Figure 1: Comparison of flux contours, magnetic probe and flux loop reconstruction errors and obtained $|q|$ profiles for the codes LIUQE, EQUAL and NICE using data from TCV discharge 67455 at $t = 0.7$ s. Black dashed lines indicate the absolute error for the different signals.

error bars. The reconstructed separatrix and q-profiles show small differences probably due to the differences in the choice of basis functions and regularization schemes for the 3 codes.

In figure 2 we show a comparison of the reconstructed flux contours for 5 TCV discharges. Again the agreement between the codes is fully satisfactory. For discharge #68667 LIUQE produces an equilibrium with a smaller Shafranov shift and smaller stored energy than the 2 EQRECONSTRUCT codes owing to the fact that LIUQE did use the toroidal diamagnetic flux estimate in its reconstruction. Important to note is the fact that these discharges contain all 4 configurations for the direction of plasma current and toroidal field, validating the data mapping of the input data and its handling by the NICE and EQUAL codes.

The next example is based on data imported from an AUG discharge. The input data contains 13 PF coil currents, 18 flux loops and 62 magnetic probes (of which 20 are excluded from

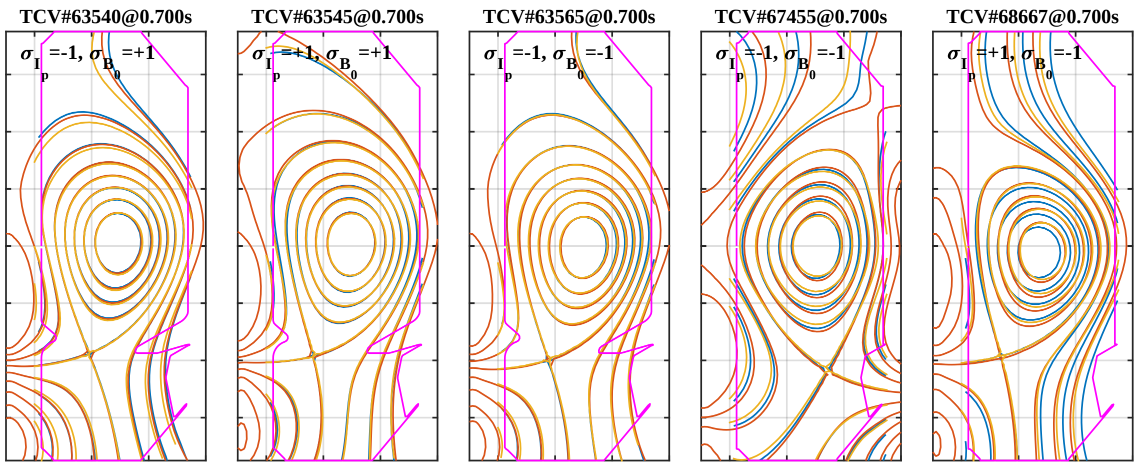

Figure 2: Comparison of the flux contours from LIUQE, EQUAL and NICE for a few TCV discharges. The correspondence between colors and codes is the same as for figure 1.

the reconstruction) and a plasma current measurement. The resulting reconstruction for AUG #33173 at $t = 3.0\,\mathrm{s}$ is shown in figure 3. The agreement between EQUAL, NICE and CLISTE is

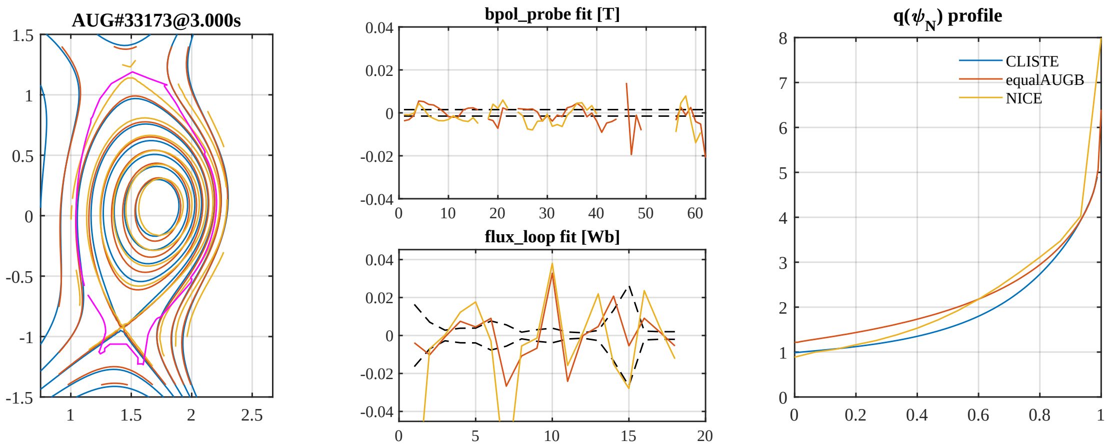

Figure 3: Comparison of flux contours, magnetic probe and flux loop reconstruction errors and obtained $|q|$ profiles for the codes CLISTE, EQUAL and NICE using data from AUG discharge 33173 at $t = 3.0\,\mathrm{s}$. Note that the reconstruction errors for CLISTE are missing since this data hasn't been mapped to IDS format.

still satisfactory although the reconstruction errors for some of the flux loops suggest that there is room for improvement.

Our final example is based on a JET discharge and includes a constraint on the plasma pressure profile on top of the standard magnetic diagnostics. The magnetics input data contains 16 PF coil currents, 38 flux loops (of which 5 are excluded) and 71 magnetic probes (of which 34 are excluded) and a plasma current measurement. The pressure constraint is given as a radial profile as function of $\rho = \sqrt(\psi_N)$, with the core values ($\rho \leq 0.25$) excluded from the reconstruction. In figure 4 we show the resulting equilibria from EQUAL and NICE and compare them with the data imported from an EFTP run. Both EQUAL and NICE show some discrepancy

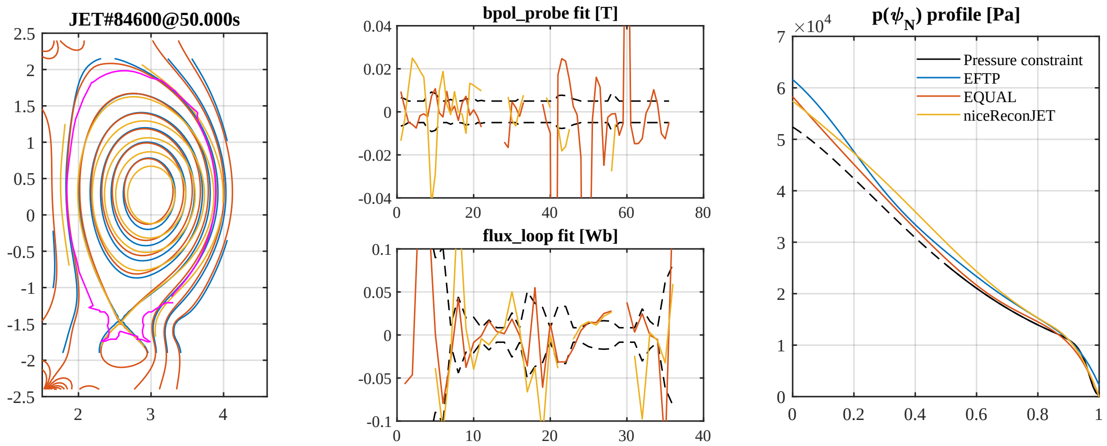

Figure 4: Comparison of flux contours, magnetic probe and flux loop reconstruction errors and obtained pressure profiles for the codes EFTP, EQUAL and NICE using data from JET discharge 84600 at $t = 51.0\,\mathrm{s}$. Similarly to CLISTE in figure 3, reconstruction errors are missing for EFTP.

relative to EFTP in the boundary reconstruction, this also shows in the reconstruction errors for the different sensors. The pressure profiles however show a nice similarity indicating that the constraint was correctly handled. This shows our current best effort, changing the sensor selection or weight can certainly improve the agreement of the flux map and the reconstruction of the different sensors.

Conclusion

The EQRECONSTRUCT workflow developed within WPCD and using the IMAS framework provides an ideal test-bed for benchmarking equilibrium reconstruction codes. The workflow already includes the codes EQUAL and NICE. These have been tested over a variety of TCV, AUG and JET discharges and have been found to perform close to or on par with in-house reconstruction codes such as LIUQE, CLISTE or EFTP. The workflow also includes the possibility to store a fixed-boundary version of the obtained equilibria (not shown here), which eases the integration with the Equilibrium and stability (EQSTABIL) workflow [6]. Upcoming extensions include the integration of new codes such as EFIT++, CLISTE or LIUQE and new machines such as WEST, MAST or MAST-U.

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