First MAST-U Equilibrium Reconstructions using the EFIT++ code

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The MAST-U spherical tokamak has extensive capabilities to produce and explore strongly shaped plasmas and alternative divertor configurations, especially the Super-X. Robust and accurate reconstructions of plasma equilibria are the foundation of many physics analyses, and important intershot for informing operation of the tokamak.

The EFIT++ code[1] has been used to produce robust intershot equilibrium analysis for the first campaign of MAST-U data using magnetics constraints. An analysis of this data is presented here showing good fits to the magnetics measurements. Comparisons to diagnostics not used to constrain the equilibrium are also shown. The strike points are compared to the peak Isat measurement at the divertor target from Langmuir Probe measurements with agreement within 5cm. The separatrix location from the reconstructions is compared to the temperature profile from the Thomson Scattering system. It is found that the EFIT++ separatrix is 1cm away from where the separatrix would be expected to be from these profiles.

The first implementation for MAST-U of a polarisation angle constraint from the Motional Stark Effect diagnostic in EFIT++ is shown. This shows a good fit to the polarisation angle and the effect on the reconstructed q-profile when compared to the magnetics-only reconstructions is shown.

EFIT++ configuration for magnetics only reconstructions

MAST-U is equipped with a wide range of magnetics sensors which are used to constrain the p’ and ff’ functions in the reconstructions. The sensors used as constraints are shown in Fig. 1 : B-field measurements, flux loops, measurements of PF coil and coil case currents from

Rogowski measurements and a measurement of the plasma current from a partial Rogowski coil set.

Currents that are induced in toroidally continuous structures are modelled using an electromagnetic induction model[2]. These modelled currents are also used as constraints. The induced current model in EFIT++ has previously been benchmarked against a 3D model of the vessel using the VALEN code[3].

The p' and ff' functions of the Grad-Shafranov equation are setup with 2 degrees of freedom using polynomials. p' and ff' are set to be zero at the edge and (p')' and (ff')' are constrained to be zero at the edge using relational constraints with a weight of 0.1. These settings were chosen for robustness of convergence during intershot runs.

The error bars on the magnetic measurements are taken to be the maximum of either the calibration error or a minimum absolute error.

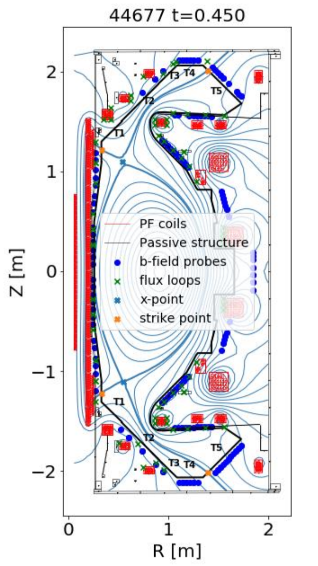

Figure 1 The location of magnetics used in EFIT++ and poloidal flux for shot 44677 at t=0.5 s

Magnetics constraint validation

The χ^2 can be used to study the fits to the magnetics data. $\chi^2 = \sum \frac{(X_i - X_R)^2}{\sigma^2}$ where X_i is the measured or modelled data, X_R is the reconstructed value and σ^2 is the uncertainty on X_i.

The χ^2 of the fits to the magnetics measurements and modelled induced currents has been evaluated for shots from the first campaign. Following removal of sensors that failed due to hardware faults the χ^2 is found to be < 2 for the majority of constraints.

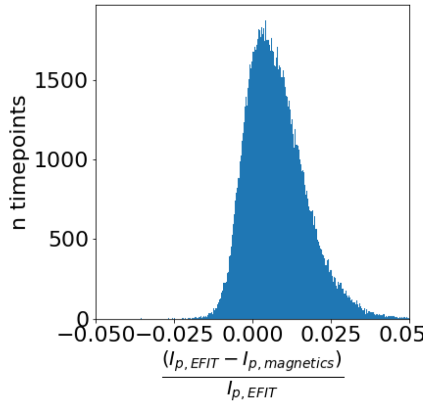

Figure 2 The fractional difference between EFIT++ reconstructed and magnetics measurements of the plasma current for flat-top times for all scenarios (Ip=450kA, 600kA, 750kA).

The reconstructed plasma current has been compared to the measured plasma current. The plasma current is used as a constraint in the reconstructions with large error bars of 20%. Fig. 2 shows that the reconstructed and measured plasma current for flat-top times are within 5% of each other.

Comparison of the upper outer divertor strike point to the Langmuir Probe data

The outer upper strike point from EFIT++ has been compared to the max(I_{sat}) at the target as measured by the Langmuir Probe system. Fig. 3 shows the comparison for shot 44905 where the outer strike points were swept in small oscillations on the T2 tile. The strike point reconstructed by the equilibrium is shown to be within 2.5cm of the max(I_{sat}) measurements at the target.

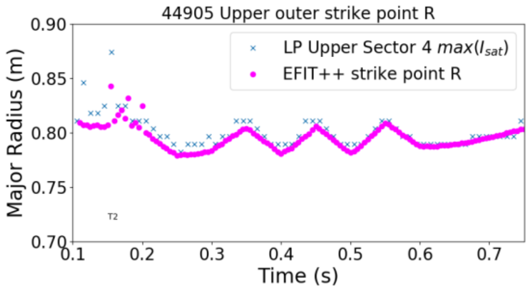

Figure 3. Comparison of the LP peak Isat flux to EFIT++ strike points for shot 44905

This example is chosen as a comparator because no strike point splitting is observed in this shot and the Langmuir Probe diagnostic has good sensor coverage in this region. It is expected that the difference will be greater for shots where the divertor leg is in Super-X on T4-T5 due to geometrical effects such as toroidal shaping of the outer divertor tiles and physics effects such as ExB drifts.

Comparison of the Last Closed Flux Surface (LCFS) to electron temperature profiles

The T_e profiles from the Thomson Scattering (TS) diagnostic have been compared to the outboard LCFS of the magnetics-only equilibrium reconstructions at the line of sight of the TS diagnostic. This comparison has been performed for H-mode inter-ELM times for a selection of shots.

Two methods are used to determine the LCFS location from the TS T_e profiles. The first is to evaluate R at Te=20eV,40eV taken from mtanh fits to the T_e profiles. From the 2-point model[4] the LCFS is expected to be in the range T_e=20-40eV for MAST-U. The second method uses a Bayesian analysis of the TS profiles to give possible pedestal temperature and density profiles. The LCFS location is then determined specifying a uniform distribution between Te=20-40eV. This gives an estimate and uncertainty that accounts for the LCFS T_e being any value in that range.

As can be seen in Fig. 4 the EFIT++ LCFS is shown to be within 2cm of the expected LCFS from the TS profiles. A systematic offset of ~1cm is seen for shots used for this analysis.

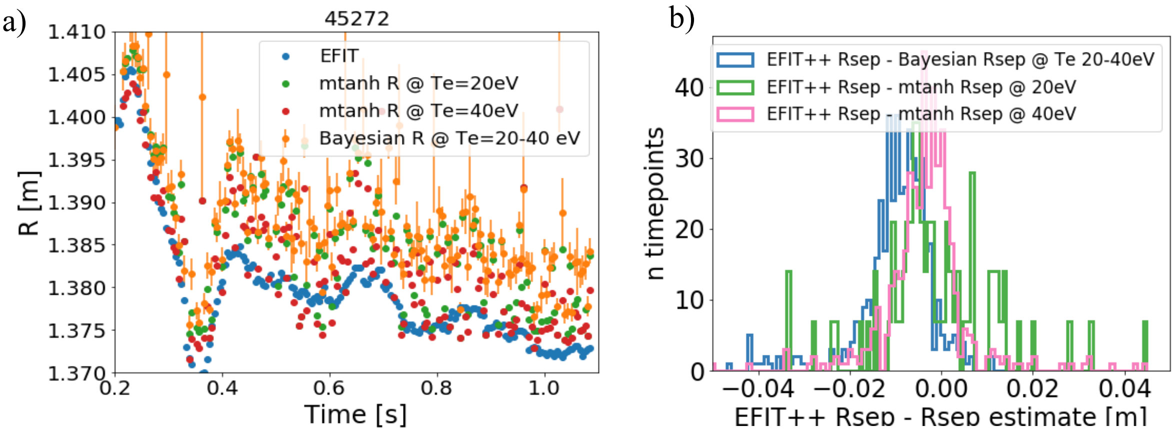

Figure 4 The LCFS location at z=0.015m (the TS line of sight) from EFIT++ compared to R at Te = 20,40eV from mtanh fits to the TS profiles, and the LCFS from the Bayesian analysis for a) an example shot 45272 vs time for inter-ELM times and b) the difference in LCFS across a range of shots and H-mode times.

First results of the MSE and magnetics constrained equilibrium

The implementation of a polarisation angle constraint in EFIT++ using data from the Motional Stark Effect (MSE) diagnostic has been demonstrated for MAST-U. MSE provides a measurement of the pitch angle in the plasma.

The MSE and magnetics constrained equilibrium uses spline fits for ff' and p' with 7 knots for ff' and 8 knots for p'. Knot points are clustered towards the LCFS. These settings are chosen to allow sufficient freedom to fit the shape of the polarisation angle data. MSE channels beyond the tangency radius (R~0.8m) and outside of the plasma boundary are excluded.

As can be seen in Fig. 5a) for shot 45272 the reconstructed polarisation angle fits the measured polarisation angle within error bars for the majority of channels. Fig. 5b) shows the effect of the additional pitch angle constraint on the reconstructed q-profile in comparison to the magnetics only equilibrium reconstructions.

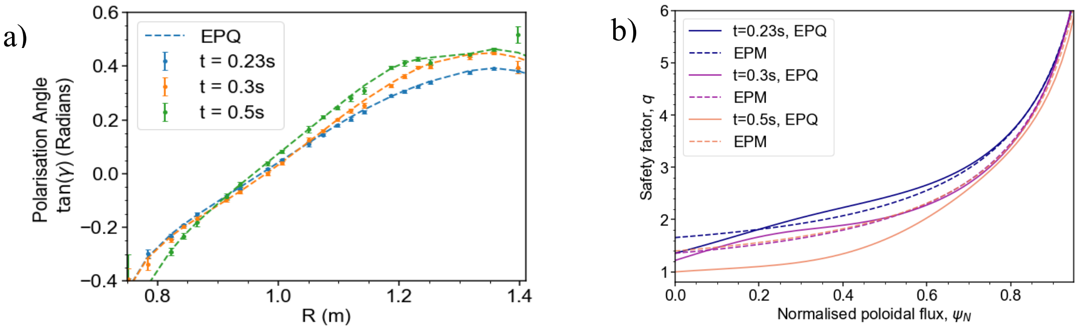

Figure 5 For shot 45272 a) tan(γ) measured by the MSE system compared to the EFIT++ reconstructed tan(γ) for a few times in shot 45272. The majority of channels show agreement within the MSE error bars. b) The q-profile from the magnetics + MSE constrained equilibrium (EPQ) compared to the magnetics-only equilibrium reconstructions.

Conclusions

Comparisons of magnetic only equilibrium reconstructions from EFIT++ using MAST-U 1^{st} campaign data show good agreement with diagnostic measurements. The inclusion of a polarisation angle constraint from the MSE diagnostic for MAST-U has been demonstrated. Next steps will include further validation of the equilibrium and inclusion of a robust pressure constraint to further improve the accuracy of the reconstructed profiles in the equilibrium.

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