Alternative equilibrium reconstruction code for FTU plasma control

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1. Introduction

An alternative equilibrium reconstruction code for the plasma control purposes of FTU tokamak is presented. The existing codes adopted by FTU session leaders (SL) are not flexible, they lack of user friendly interface and cannot predict most of the plasma quantities of interest. The aim of a new equilibrium reconstruction code comes from the necessity to give to the FTU SL a tool: i) to easily design desired magnetic configurations with a user-friendly interface; ii) to help to identify in a reliable way the location of field null formation during the plasma current breakdown phase; iii) to detect faulty probes, misalignment of probe orientation in the poloidal plane or wrong calibration factors; iv) to have a reliable linearized model of the equilibrium to design robust plasma controller, advanced non-linear feedback and observers. The proposed alternative suite of tools XSCTools (eXtreme Shape Controller Tools), seems satisfactory answer to the above requests.

2. Equilibrium reconstruction tools and main assumptions

The XSCTools[1] is a set of procedures written in MatLab with Graphical User Interface (GUI) designed to be flexible and machine independent for tokamak modelling and shape control design and validation. The 2D axisymmetric finite element method (FEM) codes CREATE_NL (CNL) and CREATE_L (CL) [2] are embedded equilibrium reconstruction codes of XSCTools, providing linearized model describing the electromagnetic behaviour of plasma surrounded by conducting structures. The XSCTools were extended to FTU using i) a 2D FEM first order mesh (Fig.1); ii) a circuit schematization of poloidal field (active) coil connections (for the moment we neglect the eddy currents in the passive structures), see Fig.2; iii) a subset (see Fig.3) of reliable experimental magnetic signals (providing magnetic field and flux) to fit in the least square sense the plasma current density profile parameters for a given experimental configuration. The CNL code inputs (experimental magnetic measurements) are treated to remove electronic offset (coming from acquisition system) and toroidal field effects.

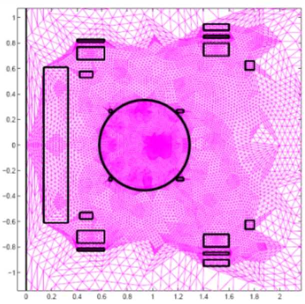

Fig.1 CNL first order FEM mesh with 30000 first order elements and 15000 nodes.

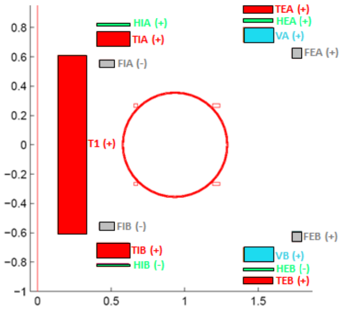

Fig.2 FTU PFCs circuit connections

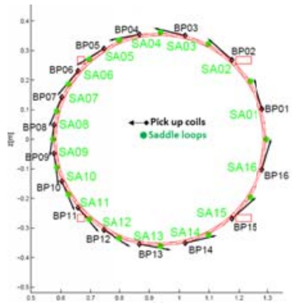

Fig.3 FTU magnetic probes location. Trusted magnetic signals subset

3.Benchmark cases

In order to verify if the main modelling assumptions made (PFCs geometry, coil turns, circuit connections etc.) for the XSCTools are correct, we started comparing the magneto-static flux map of each single PF circuit with the theoretical expectations. The CNL numerical reconstructions of the magnetostatic flux map (without plasma) of each coil have been compared with the expected theoretical behavior (using analytical methods), showing good agreement. Once assessed the CNL reconstructions, we analysed the breakdown phase of a plasma run during in order to localise poloidal null formation. Comparison of the CNL with the direct MAXFEA 2D equilibrium solver shows good agreement (see Figs.4-5). Owing to the CNL reasonable dry run time reconstruction (<2min for each snapshot) it can be used by SL during operation (intershot time ~20min) to localise null formation during the breakdown phase (Fig.6).

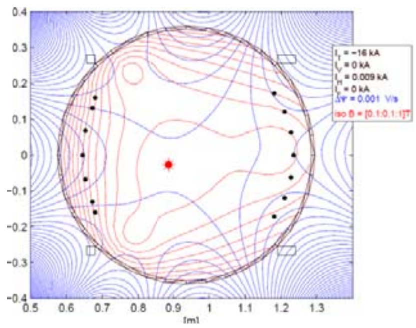

Fig.4 CNL snapshot of flux and poloidal field map. FTU case #30226@-0.100s using pre-programmed currents. A star indicates the poloidal field minimum. Dots indicate the poloidal limiter .

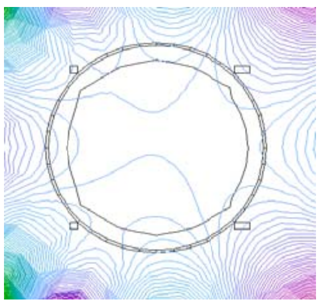

Fig.5 MAXFEA flux map. FTU case #30226@-0.100s using pre-programmed currents.

Further analyses were carried out on plasma runs, with low and high plasma current, comparing the CNL reconstructed flux map, the boundary (outermost magnetic closed surface) and reconstructed magnetic measurements against ODIN (the official FTU off-line equilibrium code) and rtODIN (the real-time version of ODIN used by MARTEFE[3] feedback system). For FTU pulse #36527@0.5s (360kA, 6T), low plasma current case, the maximum reconstruction error (CNL vs rtODIN) on plasma boundary was less than 1cm (Fig.7); the flux map (Fig.9) is not identical,, but we found same contact point as ODIN, while the absolute relative error on pick up coils signals was less than 5% (Fig.8). On FTU plasma #33354@1s (700kA, 7.2T), high current case, we found better agreement (Fig.10).

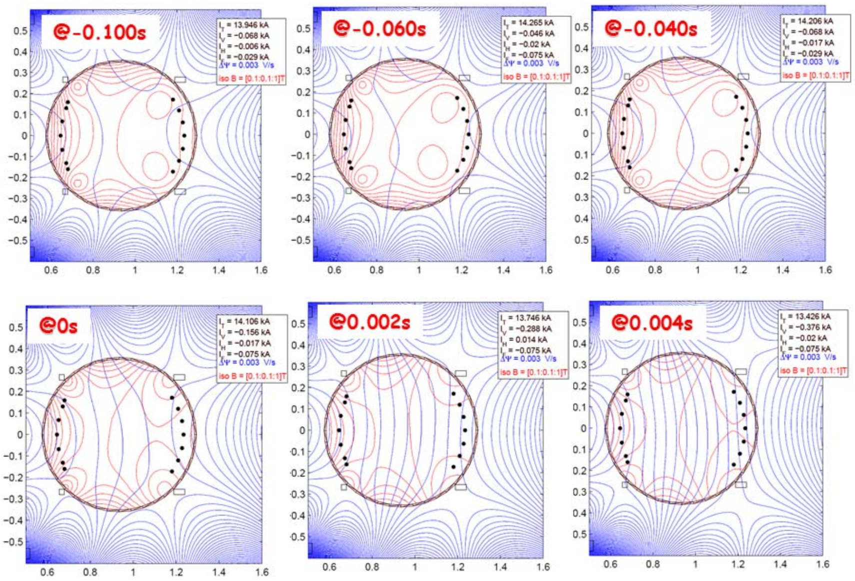

Fig.6 CNL flux and polidal field map evolution during FTU breakdown phase. FTU case #36527.

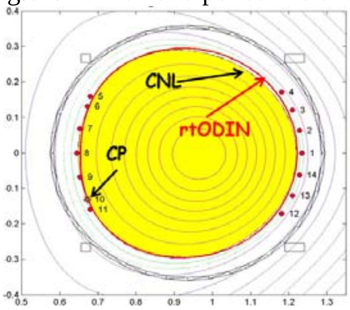

Fig.7 #36527@0.5s: CNL boundary vs rtODIN

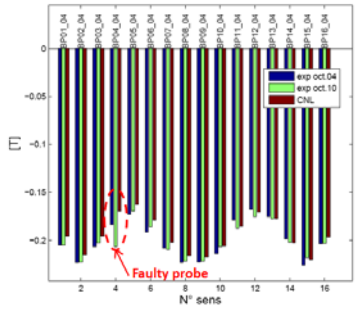

Fig.8 #36527@0.5s: absolute relative error on pick up coils on different octants

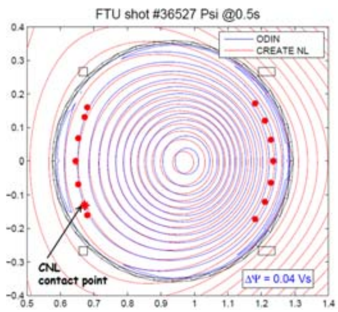

Fig.9 #36527@0.5s: CNL flux map vs ODIN

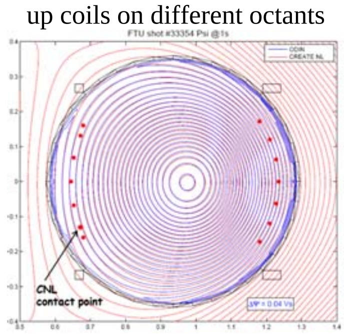

Fig.10 #33354@1s: CNL flux map vs ODIN

4.Open loop simulations

Once assessed the reliability of CNL equilibria, we linearized it in proximity of the equilibrium point. The obtained linearized model is given in the space state model form[4], to be easily integrated in the FTU plasma control algorithm based on MARTe application [2].

We carried out dynamic open loop simulations of experimental data using a current driven model[4] to prove the reliability of FTU linearized model by XSCTools, showing a fair agreement of the main plasma quantities of interest (Fig.11). The inputs of the model are the PFC active currents, plasma current while poloidal beta and internal inductance are considered as disturbances. The obtained results show that the linearized model given by CNL can be used as reliable alternative for the FTU plasma controller.

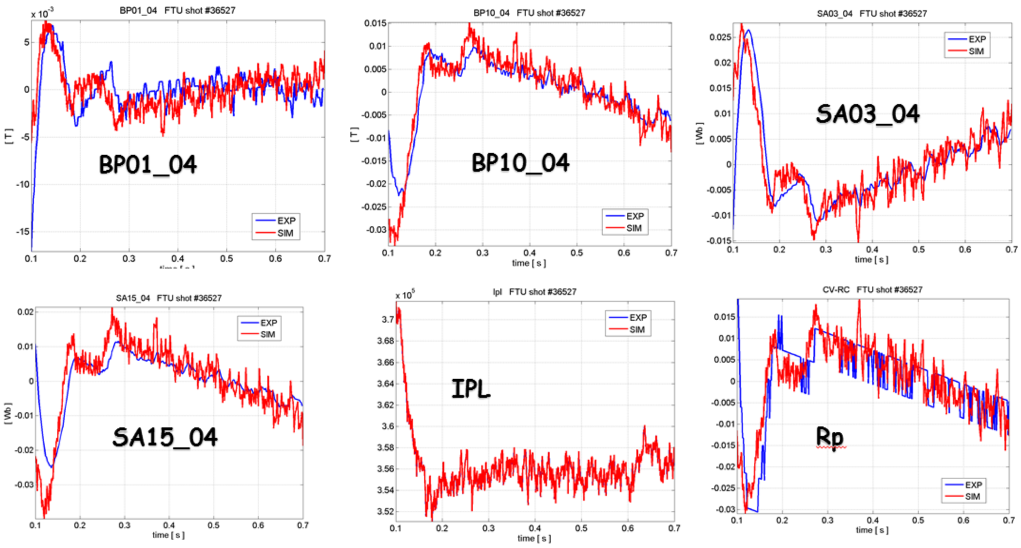

Fig.11 #36527: Open loop simulation of experimental data using CNL linearized model in the state space form (A,B,C,D). BP: pick up coils, SA: saddle loop, IPL: plasma current (perfectly match because used as input model), Rp: plasma radial position.

5.Conclusions

The XSCTools have been ported to FTU, can be used to reconstruct magnetic equilibria and provide reliable linearized models to simulate plasma quantities of interest. Comparison of CNL and MAXFEA flux and poloidal field map of dry run shows good agreement. Comparison of CNL and ODIN (or rtODIN) flux map and plasma boundary of plasma run shows a fair agreement. Reconstructed signals of pick-up coils shows a good agreement with the experimental ones. Preliminary open loop simulation of experimental magnetic measurements shows a good agreement giving the feeling that can be integrated into the FTU feedback system for a more robust control and to design advanced/alternative non-linear feedback and observers.

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References

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