Flight simulator development for the COMPASS Upgrade Tokamak

Marchioni S.[1†], Kripner L.[1], Jaulmes F.[1], Havránek A.[1], Hečko J.[1], Hromádka J.[1], Imríšek M.[1]

[†]*email: marchioni@ipp.cas.cz*
[1]*Institute of Plasma Physics of the Czech Academy of Sciences.*

1 Introduction

A flight simulator for the COMPASS Upgrade tokamak[1, 2] is being developed at IPP-CAS. It integrates reduced plasma models with machine-specific components like actuators and diagnostics to support control system development and discharge design. Fast computations allow linear discharge simulations in 5–10 minutes.
A major challenge is developing the simulator without experimental data, requiring a flexible, modular codebase to adapt to design changes. The simulator also helps assess planned discharges and can accelerate early operations through real-time planning and testing.

2 Codes and workflow

The flight simulator under development is based on the MEQ code suite. It uses FBT[3] for coil current design, LIUQE[4] for equilibrium reconstruction, and FGS/FGE[5] for discharge evolution. All are free-boundary equilibrium codes linking plasma equilibrium to external coil currents. The workflow is shown in figure 1.

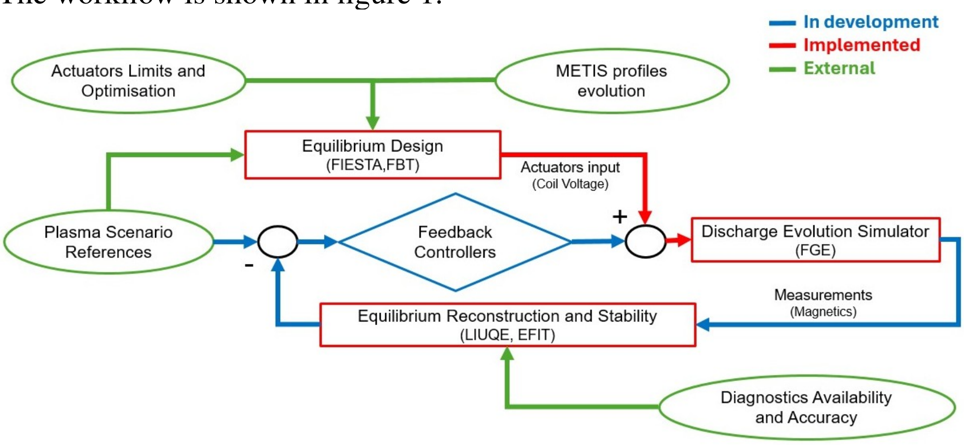
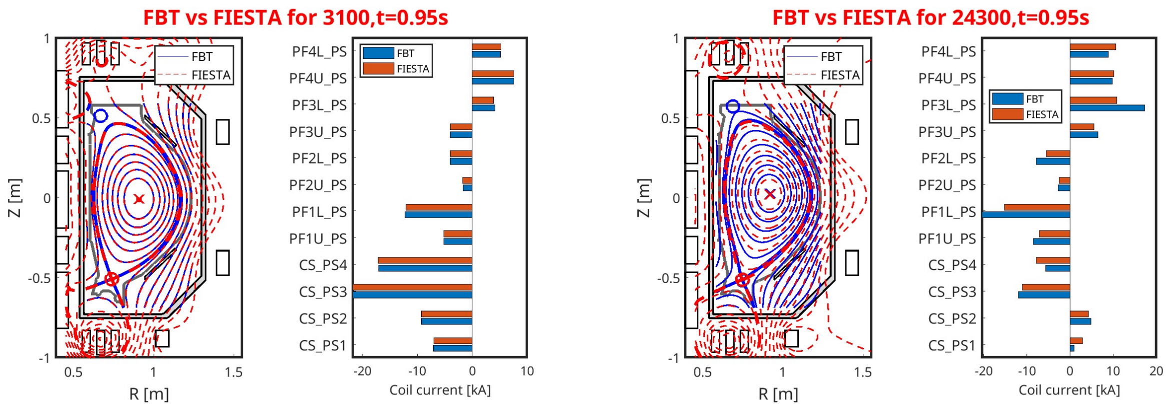


Figure 1: Flight Simulator Workflow. Blocks and connections highlighted in blue represent components yet to be implemented; those in red are already implemented; and elements in green indicate external inputs (codes or data currently maintained outside the flight simulator project).

3 FBT and FIESTA comparison

The FBT code has been benchmarked against FIESTA[6], which is used to design coil currents for COMPASS Upgrade. Both are free-boundary inverse solvers: by constraining points on the last closed flux surface (LCFS), pressure, TT' profiles, and global quantities (like I_p, β_p, W_k, q_A, l_I), they compute plasma equilibrium and required coil currents. The codes were compared for L-mode (3100) and H-mode (24300) discharges. LCFS points for FBT come from interpolated FIESTA results, with METIS[7] providing input profiles. In FBT, profiles can be scaled to match I_p and W_k. FIESTA coil currents serve as initial guesses for FBT, as multiple coil sets can sustain the same equilibrium. Results in figure 4 show excellent agreement for L-mode, while H-mode displays some differences, likely due to grid resolution, LCFS detection, and solver details.



(a) (b)

Figure 2: FBT vs. FIESTA comparison. For L-mode shot 3100 (2a). Left: flux maps; right: coil current comparison. Same for H-mode shot 24300 (2b).

4 LIUQE reconstruction

The LIUQE code is tested for plasma reconstruction using the planned magnetic diagnostics in COMPASS Upgrade. It uses simulated magnetic measurements from FBT, while the plasma profiles are based on polynomial basis functions, differing from the FBT ones (taken from METIS), due to the impossibility of reconstructing internal profiles using only external measurements. Another key point is the absence of vessel measurements, as no design has been finalized for COMPASS Upgrade. To circumvent this difficult, which result in many unknown to reconstruct, an eigenmodes decomposition of the passive structures is applied. Figure 3 shows reconstructions with and without artificial passive conductor measurements, using 15 and 50 eigenmodes. With 15 eigenmodes, the reconstruction closely matches FBT results; with 50, accuracy is lost due to too many unknowns.

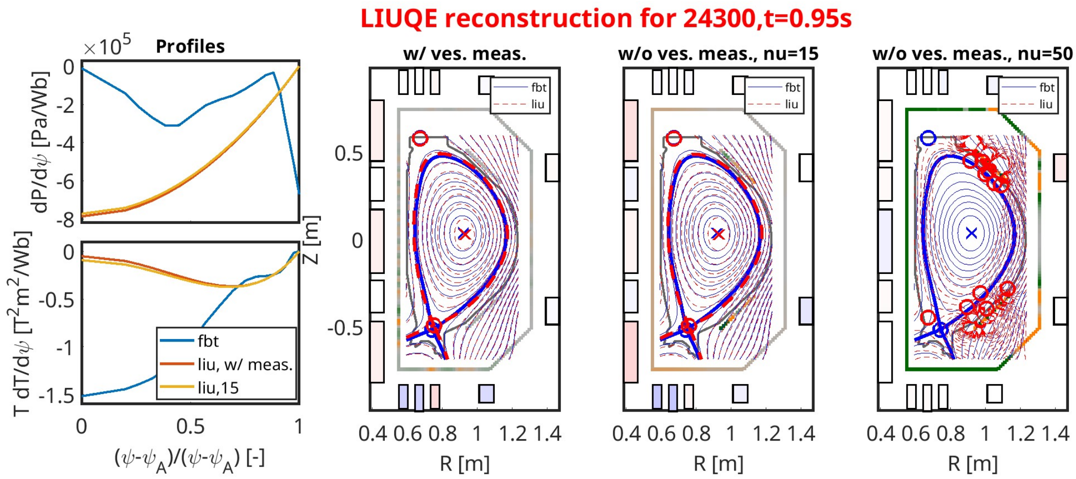


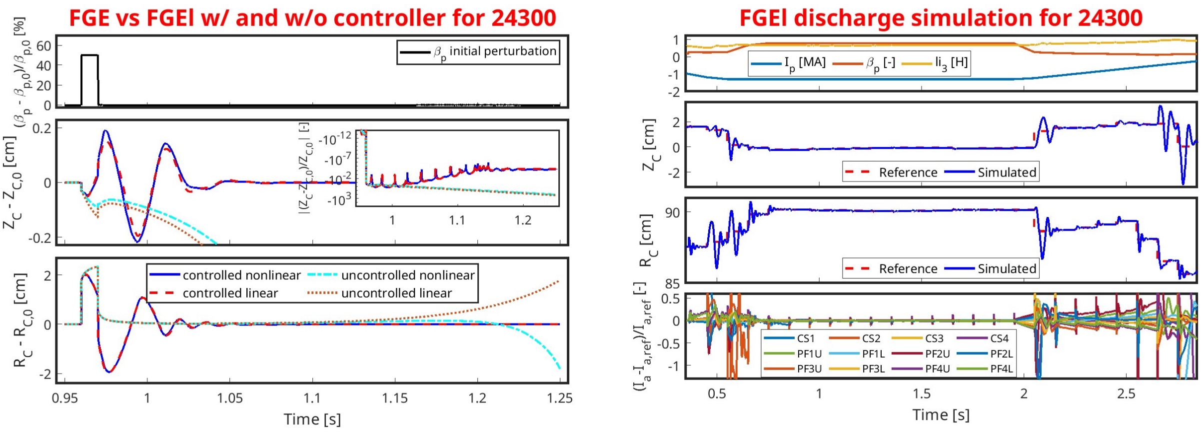
Figure 3: LIUQE Reconstruction for H-mode Shot 24300. From left to right: comparison of the p' and TT' (with $T = RB_\phi$) profiles obtained from FBT (METIS) and LIUQE (polynomial basis); LIUQE flux reconstruction using passive conductor measurements; reconstruction without measurements employing 15 eigenmodes; and reconstruction with 50 eigenmodes.

5 Discharge simulation with FGE

The FGE code simulates discharge evolution and coupling with a controller. Its input are feed-forward voltages from FBT, plasma profiles (currently polynomial), and an initial equilibrium recalculated with FGS (its static version). An externally developed controller can update coil voltages during the simulation. Controlled and uncontrolled plasma evolution after an initial β_p perturbation are compared in figure 4a. The controller can recover and maintain plasma position and coil currents to reference values, while the uncontrolled plasma disrupts Linear and non-linear simulations give similar results for the controlled case, with linear runs being $\sim$15 times faster. A full linear controlled discharge (figure 4b) demonstrates the codes' ability to simulate complete discharges, with a runtime of $\sim$300s.

6 Conclusions

We presented the development and capabilities of the COMPASS Upgrade flight simulator, integrating equilibrium design, reconstruction, and static and evolutive solvers. Benchmarking between FIESTA and FBT shows good agreement, especially in L-mode with differences in current tuning in H-mode. Plasma equilibrium reconstruction without vessel measurements is possible using a reduced vessel representation. Finally, discharge evolution simulations with controller coupling have been successfully implemented.



(a) (b)

Figure 4: FGE Simulations for H-mode Shot 24300. Left: Comparison of controlled vs. uncontrolled cases, and linear vs. non-linear dynamics. Top to bottom: initial β_p perturbation, vertical displacement (with logarithmic plot to highlight the disruption), and radial displacement. Right: Fully linear controlled discharge. Top to bottom: evolution of plasma current (I_p), poloidal beta (β_p), internal inductance (l_{i3}) from METIS, vertical and radial positions with references, and coil current deviations from references.

Acknowledgment

This work has been carried out within the framework of the project COMPASS-U: Tokamak for cutting-edge fusion research (No. CZ.02.1.01/0.0/0.0/16_019/0000768) and co-funded from European structural and investment funds.

This work has been carried out within the framework of the EUROfusion Consortium (TSVV15 project), funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

[1] R. Panek et al. In: *Fusion Engineering and Design* 123 (2017), pp. 11–16.

[2] P. Vondracek et al. In: *Fusion Engineering and Design* 169 (2021), p. 112490.

[3] F Hofmann. In: *Computer Physics Communications* 48.2 (Feb. 1988), pp. 207–221.

[4] J.-M. Moret et al. In: *Fusion Engineering and Design* 91 (Feb. 2015), pp. 1–15.

[5] F. Carpanese. PhD thesis. Lausanne: EPFL, 2021.

[6] G. Cunningham. In: *Fusion Engineering and Design* 88.12 (2013), pp. 3238–3247.

[7] J.F. Artaud et al. In: *Nuclear Fusion* 58.10 (Aug. 2018), p. 105001.