Topic: EX-C

Pulse Design Simulator for JT-60SA

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In the operation of modern tokamaks and future large machines, scientists and control room operators will develop their plasma scenario before proposing or implementing their experiment. They should rely on a reliable and realistic tool for the design of plasma discharges. Such Pulse Design Simulator (PDS) should be capable of simulating a discharge from plasma breakdown to the very end of the discharge going through the start of ramp-up plasma, X-point formation, current flat top right to the ramp-down and include heating and transient phases (such as transition to H-mode or high plasma β,…). The PDS should also include machine operational constraints and limits (current limits, forces, voltage limits, etc …) that a specific scenario should comply with. At the same time, the tool should be sufficiently light in computing time and accessible to any person without requiring lengthy training.

With these requirements, we have designed and implemented a PDS for JT-60SA based on the coupling of time dependent kinetic calculations from the METIS [1] code with the free boundary equilibrium code NICE [2]. For this purpose, NICE-METIS has introduced a specific novel numerical method to ensure the coupling between the Grad-Shafranov equation and current diffusion [3]. The simulator integrates controllers implemented in Matlab Simulink for the plasma shape, vertical stabilization and plasma current [4] for all phases of the discharge including transient, such as ramp-up, ramp-down, X-point formation, L to H and H to L transition, perturbation mitigation.

The simulator does not aim at describing transport with sophisticated high fidelity codes. It uses a light formulation for « reproducing » plasma kinetics parameters such as the evolution of density, temperature and energy content (in METIS). Nor is it a high fidelity model for plasma discharges (e.g. it does not contain disruption models or sophisticated edge or fast particle models …). In its first version, the simulator has been first tested on the Ip=5.5MA, B_T=2.25T (scenario 2 of the JT-60SA research plan [5]). More recently it was also successfully tested on the whole 4.6MA/2.28T (q_{95}~3) H-mode scenario which is planned to be run in the next JT-60SA campaigns in 2026 and 2027 [6]. This simulator was developed in a pragmatic way with modellers and operation specialists and is now addressing other JT-60SA scenario like the hybrid scenario (2.7 MA/1.70 T, q_{95} ~ 4).

The simulator runs in several steps (figure 1). The sequence of plasma shapes of the targeted scenario is defined and used as an input to METIS which computes the time evolution of kinetic parameters based on operator requirements in terms of plasma current, toroidal field strength, line integrated density and heating sources. Initially, METIS was including current diffusion and these results were coupled to the free-boundary code NICE or CREATE-NL [4]. During the tests of this process, it was observed that the coupling between the current diffusion and the free-boundary code

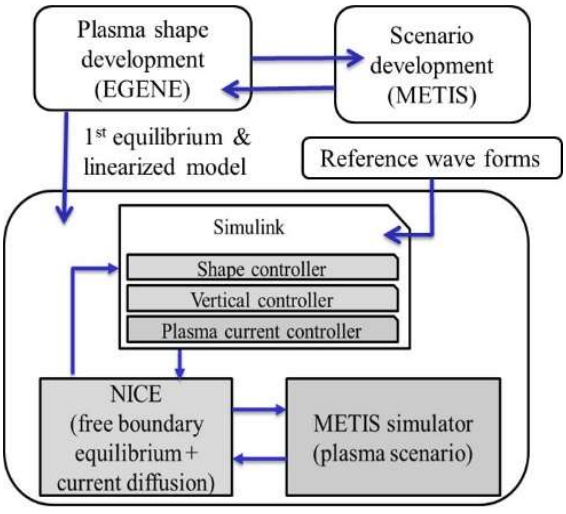

Figure 1: Structure and workflow of the JT-60SA simulator

was not optimum and led to numerical issues when the pressure and diamagnetic profiles were exchanged between the two codes. Hence, this coupling was improved using a cleaner mathematical formulation developed in reference [3]. Based on finite element method, it provides a 2D solution of the poloidal flux and the diamagnetic function evolution, taking into account plasma description, axisymmetric passive structures and poloidal coils. The new formulation in NICE is therefore equivalent to solve the current diffusion equation and the Grad-Shafranov equation simultaneously in a consistent way, thus avoiding the share of boundary conditions between the two codes

The NICE outputs and the reference waveforms for the controlled variables are sent at each time step to the magnetic controllers, which are returning the set of voltages to the poloidal field coils power supplies. The magnetic control algorithms [7] are implemented with different settings depending on the discharge phases: centroid position control in the early ramp-up phase (0.5s – 2.5s), isoflux control of the X-point formation (2.5s-6.5s & 111-117s) and the main phase (6.5s – 111s) for the 4.6MA pulses used as example (see figure 2). Gap controller is also a possible choice for controlling well-formed diverted plasma shape. The controllers used in the simulator have been designed in an ad hoc way, but the possibility exists to use those developed for the actual JT-60SA operation and tested in the first phase of operation of the machine (OP1) [8, 9] or future updates.

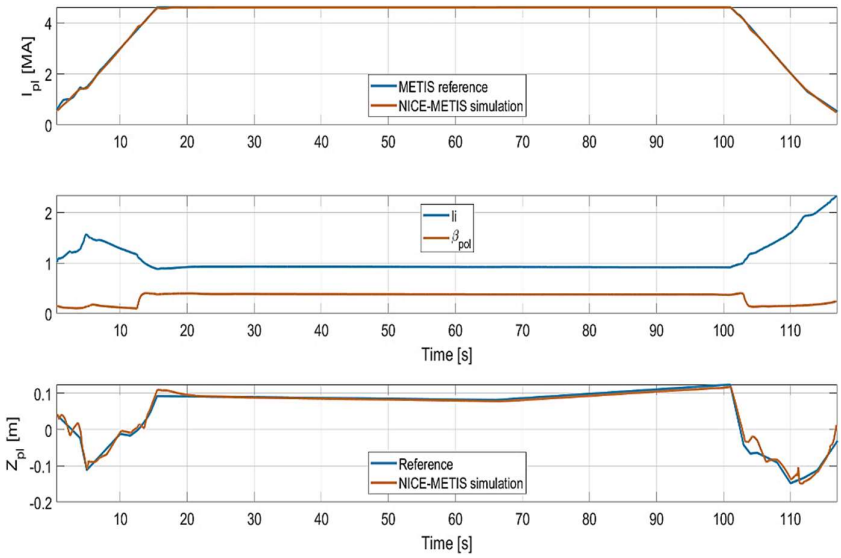

Figure 2: Simulation of the 4.6MA/2.25T scenario with the pulse design simulator with Ip (top), β, internal inductance (middle) and vertical position (bottom).

The simulator can be run in two different modes. The "light" and faster mode consisting in exchanging only global parameters (Ip, β and internal inductance) between the kinetic simulator (METIS) and the boundary equilibrium (NICE). The second coupling mode exchanges profiles, namely the diamagnetic function F, pressure function P and the plasma current Ip. Results using the "light" coupling have been successful initially with the 5.5MA scenario. With the PDS in its new configuration, the simulation was eventually run for the whole duration of the high current (4.6MA) OP1 scenario in flux control using the controllers described above.

The pulse design simulator (PDS) and its controllers are now ready for use by dedicated expert users to proof-test the suite of codes and improve their robustness for the benefit to common users. The simulator runs on the EUROfusion Gateway and a user manual has been produced. The CPU time has not yet been optimized but this is the task of future work together with the expert users.

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