

CONFERENCE PRE-PRINT**DEVELOPMENT OF ITER HIGH-FIDELITY PLASMA SIMULATOR BASED ON JINTRAC AND DINA, AND STRATEGY FOR VALIDATION**

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Abstract

An ITER high-fidelity plasma simulator (HFPS) is currently being developed by combining a core-edge-SOL transport and source modelling suite, JINTRAC, and a free-boundary plasma equilibrium evolution code, DINA, following the ITER Integrated Modelling & Analysis Suite (IMAS) paradigm. It is required to refine and complete the development of the ITER plasma scenarios necessary for elaborating the ITER Research Plan (IRP) and preparing the experimental campaigns. It will also be used to support the analysis of ITER plasmas, including in the burning regime, by enabling the application of a wide range of physics models for interpretative integrated modelling analyses. Therefore, it includes capabilities to utilize additional external physics models within the overall workflow, e.g. via the dedicated heating and current drive (H&CD) workflow. The ability to perform integrated modelling including such additional physics components is now being extended by adopting the persistent actor framework, MUSCLE3, which enables a new co-simulation type of coupling between the different physics codes. The developed ITER HFPS will perform coupled physics simulations including core-edge-SOL (Scrape-Off-Layer) transport and sources, H&CD, fuelling, heat and particle exhaust, plasma interaction with wall and targets, integrated magnetic and kinetic controls, and plasma stability. This work presents the progress on the development of the ITER HFPS based on JINTRAC and DINA and discusses the currently foreseen strategy for its application and validation within the ITER Members’ facilities.

1. INTRODUCTION

A high-fidelity plasma simulator (HFPS) is required to refine and complete the development of the ITER plasma scenarios necessary for elaborating the ITER Research Plan (IRP), and to prepare and guide the experimental campaigns with variant plasma scenarios updated taking the status of the ITER machine configuration and plant systems into account. It will also serve as a high-fidelity physics software analysing ITER experiments and burning plasma physics. To fulfil all these requirements, an ITER HFPS is currently being developed by creating physics workflows combining the DINA [1] and JINTRAC [2] codes, which have previously been adapted to the ITER Integrated Modelling & Analysis Suite (IMAS) [3]. The DINA code computes free-boundary plasma equilibrium evolution, including currents flowing in the Poloidal Field (PF) coil systems, generated by the magnetic control systems, and induced currents in the surrounding conducting structures. It has been routinely used to simulate the ITER PF system operation for a full discharge period (i.e., from the start of Central Solenoid (CS) magnetization till the removal/decay of CS and PF coil currents at the end of a discharge) and estimated the magnetic poloidal flux linked with the plasma (e.g., to estimate the maximum duration of the plasma current flattop) and margins to the engineering limitations of operating the CS and PF coils and magnetic control systems [4-6]. It has been also applied to various tokamaks to investigate physics issues related to free-boundary equilibria (e.g. vertical stability and vertical displacement events) and validated against the experiments with dynamic plasma responses [7-9]. The JINTRAC code simulates time-dependent evolution of core-edge-SOL (Scrape-Off-Layer) coupled plasma transport, including advanced models of particle and heat sources, and provide high fidelity plasma modelling including transient events and kinetic controls [10-12]. It has recently further improved to model deuterium and tritium fuel ion species separately both at the core and edge regions [13]. Therefore, the ITER HFPS based on the DINA and JINTRAC codes is foreseen to perform coupled plasma simulations including free-

boundary equilibrium evolution, core-edge-SOL transport and sources, heating and current drive (H&CD), fuelling, heat and particle exhaust, plasma interaction with divertor targets and wall (on-going), magnetic and kinetic controls, and plasma stability. Additional external physics models can be applied within the developed workflow, e.g. via the dedicated IMAS H&CD workflow [14], and the ability to perform integrated modelling is now being extended by adopting the persistent actor framework, MUSCLE3 [15], which enables a new co-simulation type of coupling between the different physics codes. The application of a wide range of physics models through IMAS and MUSCLE3 shall provide an integrated modelling environment adequate for both predictive plasma scenario development and interpretative analyses of tokamak experiments. This work presents the progress on the development of the ITER HFPS based on JINTRAC and DINA and discuss the currently foreseen strategies for its application and validation within the ITER Members' facilities.

2. FIRST PROTOTYPE OF ITER HFPS FOR COUPLED FREE-BOUNDARY EQUILIBRIUM AND CORE TRANSPORT MODELLING

The first prototype of the ITER HFPS, which enables an integration of free-boundary plasma equilibrium evolution (DINA) and core transport and source modelling (JETTO component in JINTRAC), has been developed by applying two different schemes for coupling the codes and physics, namely loose and close coupling schemes. The loose coupling scheme [16] applies an iterative process of exchanging simulation data between DINA and JINTRAC runs for an end-to-end simulation or a segment of a scenario (see FIG 1). This iterative process is automatized within a single workflow with convergence tests satisfying specific criteria for each physics code. Therefore, the converged solution of a loose coupling simulation can be used, at least indirectly, to demonstrate the validity of close coupling scheme simulation results,

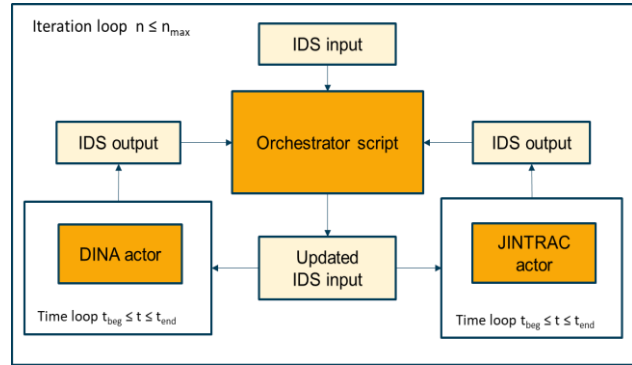


FIG 1. Loose coupling scheme applied to exchange simulation data between stand-alone DINA and JINTRAC runs executed for a given scenario segment.

where the iterative process is not implemented to accelerate the execution of simulations. At the first iteration, DINA computes free-boundary equilibrium evolution and current diffusion for a chosen discharge duration (usually $>$ a few seconds), taking the kinetic plasma profiles (e.g. densities, temperatures, pressures) and sources stored in an existing plasma scenario (given as input Interface Data Structures (IDSs)), and then JINTRAC computes fixed-boundary plasma equilibrium and evolution of kinetic plasma profiles (incl. current diffusion) for the same discharge duration, by taking the plasma boundaries computed by DINA. From the second iteration, DINA takes the kinetic plasma profiles and sources computed by JINTRAC at previous iteration step and re-computes the evolution of the free-boundary equilibrium and current diffusion and updates the plasma boundary evolution for next JINTRAC simulation. At the end of each iteration, simulation results collected from DINA and JINTRAC are stored as output IDSs and the orchestrator checks the convergence of simulation results from each code, i.e., *intra-code* convergence (see Section 3). Note that there are no physics quantities adequate for *inter-code* comparison between DINA and JINTRAC results, since the two codes compute different physic components by applying different models. Even the plasma equilibria inside the last close flux surface are not supposed to exactly match since different combination of physics components and computational domains are included. The DINA free-boundary equilibria are determined by the sum of the poloidal flux generated by the plasma current and currents flowing in all the surrounding conducting structures, whereas the fixed-boundary equilibria are determined by the plasma current only and without including the separatrix. Note that the current diffusion is computed differently in each code and therefore the evolution of the total current density and safety factor profiles can be different between DINA and JINTRAC. The scope of this work is to use the DINA free-boundary coupled current diffusion for more accurate modelling (eventually in close-coupling scheme), rather than verify the implementation of different current diffusion in the two codes. Note also that the loose coupling scheme simulation results would become less accurate if there are fast transient events insufficiently resolved for a given interval of the data exchange.

The close coupling scheme exchanges simulation results between the relevant physics components at a reasonably high frequency (~ 1 -10 ms), as previously demonstrated in DINA-CRONOS free boundary/core transport coupled simulations [17], to ensure the validity of simulations with explicit data exchange (see FIG 2). In this scheme, DINA computes the free-boundary plasma equilibrium and current diffusion and JINTRAC computes the heat and particle transport and sources. JINTRAC takes the DINA equilibria and does not compute the fixed-boundary equilibria and current diffusion. The current and bootstrap current density profiles computed by JINTRAC are provided as sources for the DINA current diffusion. In JINTRAC, two different ways of updating

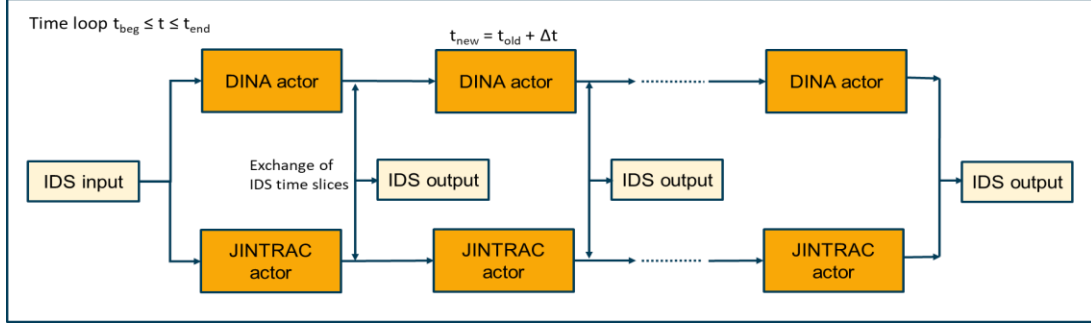


FIG 2. Close coupling scheme applied to exchange simulation data during the single execution of DINA and JINTRAC runs.

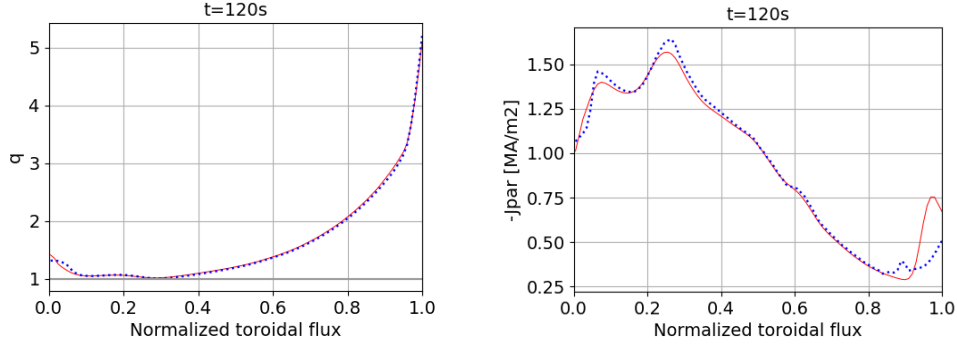


FIG 3. JINTRAC Safety factor (left) and total parallel current density (right) profiles in the DINA-JETTO close coupling scheme simulation of 15MA/5.3MA DT ITER Baseline scenario. Blue dotted lines: DINA safety factor profile is used to update JINTRAC safety factor profile, then JINTRAC parallel current density profile is computed. Red solid lines: DINA parallel current density is used to update JINTRAC parallel current density profile, then JINTRAC safety factor profile is computed.

the safety factor profile (as it does not compute the equilibrium) have been initially attempted, either by simply matching it to the DINA safety factor profile (total current density is re-computed inside JINTRAC) or by reconstructing it from the DINA current density profile that JINTRAC takes. It turned out that the latter is superior because the edge current density profile can be better resolved (red curves in FIG 3). Note that matching the current density profile (2nd derivative of the poloidal flux) mathematically guarantees a better match of the safety factor profile (1st derivative of the poloidal flux). Since the close coupling scheme simulations provide better accuracy, including improved capability of resolving the non-linearly coupled physics, it is proposed as the main approach to use for general application. The coupled free-boundary/core transport modelling capability of DINA-JETTO has been demonstrated by applying it to ITER scenarios such as the 15MA/5.3T DT Baseline and 7.5MA/2.65T Hydrogen scenarios [18]. These simulations include the current ramp-up, L-H confinement mode transition, magnetic and kinetic controls using the PF and CS coils, H&CD and fuelling systems, and are used to confirm the validity of the proposed coupling schemes and to identify areas of further improvements. Note that significant part of the initial validity checks, such as those performed to check the maximum simulation time step, data-exchange frequency, resolution of radial transport grid, has been done in the presence of several initial issues investigated in parallel and resolved later (e.g. perturbations driven by initial profile mismatch, synchronization of sawtooth triggering models, improving resolutions for the edge safety factor). However, those initial checks were useful to identify ranges of the simulation parameters adequate for loose and close coupling ITER simulations.

3. DEMONSTRATION OF COUPLED FREE-BOUNDARY EQUILIBRIUM AND CORE TRANSPORT MODELING TOWARDS END-TO-END SCENARIO DEVELOPMENT

An extended demonstration of the coupled free-boundary equilibrium and core transport modelling simulation has been done by applying the ITER HFPS to the 15MA/5.3T ITER Baseline scenario. The first part of the demonstration includes most critical phases of the plasma operation, such as the L-mode current ramp-up, L-H transition, access to burn and initial H-mode flat-top phase in a single simulation. A DINA-JETTO simulation applying the loose coupling scheme has been first developed to see if each code exchanges necessary plasma parameters and profiles and produces reasonable scenario results, while satisfying the *intra-code* convergence (see FIG 4). During the first iteration, DINA run has been executed to reproduce an existing DINA scenario with an ad-hoc heating and current drive (magenta dotted line in FIG 4), and then JETTO simulation has been performed with realistic Neutral Beam Injection (NBI) and Electron Cyclotron (EC) heating and current drive

settings and waveforms chosen for this scenario demonstration. In the second iteration, DINA takes the kinetic plasma profiles and sources computed by JETTO in the previous iteration, and therefore the evolution of coil currents was modified from the first iteration (see ICS1 in FIG4). The evolution of plasma parameters becomes very similar after the second iteration, as demonstrated by the maximum difference of the poloidal flux measured from the 1D poloidal flux profile of each DINA (D) and JETTO (J) simulations. The maximum difference between the second and third results becomes $\leq 0.1\%$ during the simulated duration with significant changes in the plasma parameters. Note that JETTO fixed boundary equilibria were not properly stored during [80s, 120s], however the evolution of other kinetic profiles showed that 2nd and 3rd JETTO runs were almost identical.

Then, the close coupling scheme has been applied to the same ITER Baseline scenario segment to compare the differences and check its validity for scenario development, up to the level of the interpretative JETTO modelling including several kinetic profiles and/or plasma parameters explicitly obtained from an experiment. The time traces of DINA-JETTO close coupling simulation results (red lines) are shown in FIG 5 and compared with three other stand-alone JETTO simulations. The stand-alone JETTO simulations were performed in different interpretative modes taking the DINA-JETTO close coupling simulation results as external inputs. The first JETTO case (blue dotted lines) reads the DINA-JETTO equilibria stored in the input equilibrium IDS and solves only heat and particle (h/p) transport. In the second case (green dashed lines), JETTO additionally solves the current diffusion (c/h/p). In the last case (magenta dash-dot lines), JETTO solves fixed boundary equilibria by taking the plasma boundaries stored in the input equilibrium IDS and predicts transport including current diffusion (eq/c/h/p). Note that the last case is in fact almost identical to the 3rd iteration results of the loose coupling case shown in FIG 4 and therefore the loose coupling case is not directly compared.

In this comparison, a few important features are observed. The total plasma current reconstructed (blue dotted lines) from the input equilibrium IDS (DINA-JETTO close coupling simulation results shown in red lines)

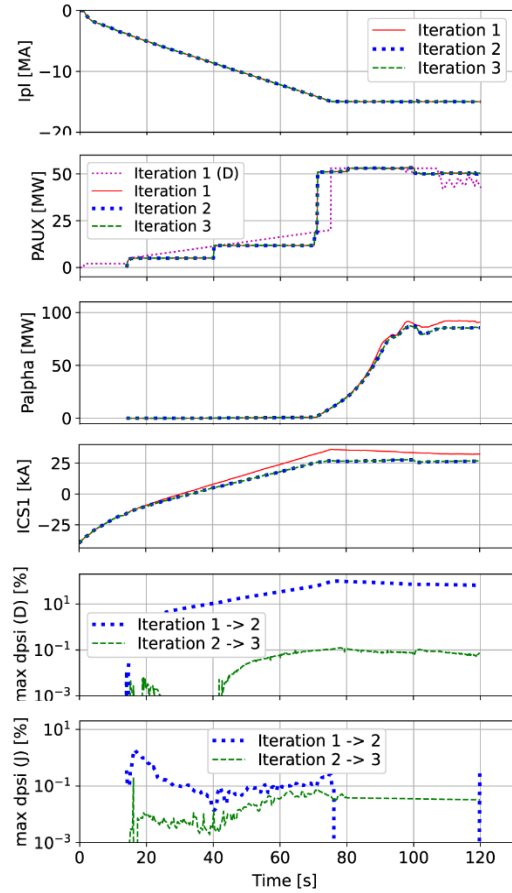


FIG 4. Time traces in the DINA-JETTO simulation of 15MA/5.3T ITER Baseline applying the loose coupling scheme [15s, 120s].

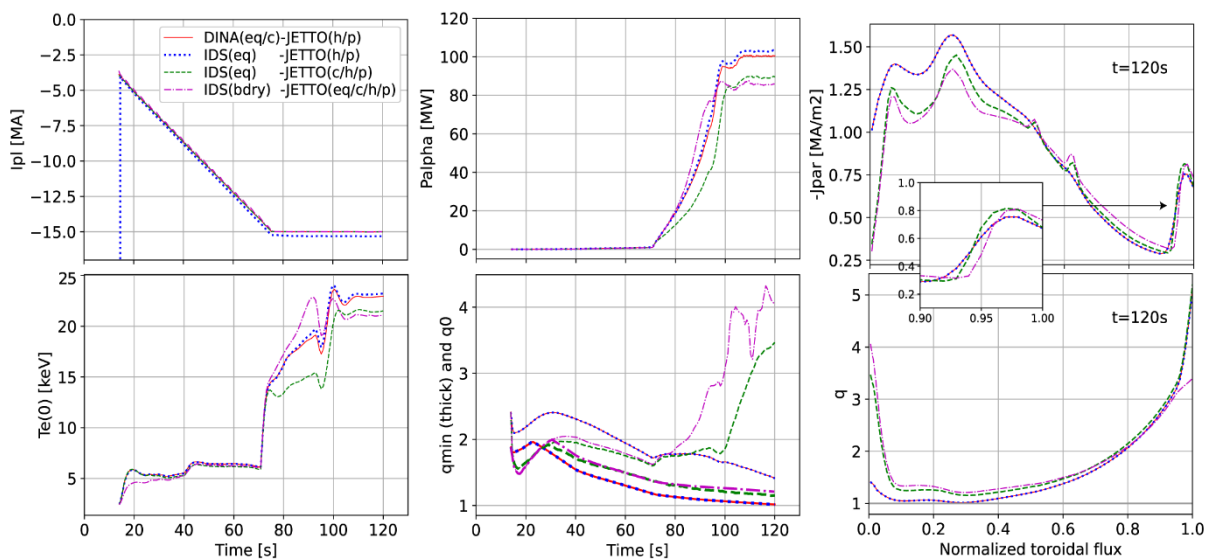


FIG 5. Time traces in the DINA-JETTO simulation of 15MA/5.3T ITER Baseline applying the close coupling scheme and three interpretative JETTO simulations are compared. (eq / c / h / p / bdry) represent respectively (equilibrium / current diffusion / heat transport / particle transport / plasma shape boundary).

showed slight deviations (a few percents) as the total current is not constrained (current diffusion was not solved by JETTO). It appears that the input IDS equilibria do not have sufficient resolution for JETTO integration routines for interpretation. However, note that this is not an issue for both loose and close coupling scheme simulations where the equilibria are computed consistently with current diffusion. The alpha particle self-heating power was predicted lower ($\sim 85\text{MW}$) when the current diffusion was computed by JETTO (green and magenta lines). The JETTO current diffusion predicted modified evolution of the central safety factors and therefore resulted in different evolution of the heat transport and confinement (the EDWM transport model is used in all the simulations presented in this work). The modified evolution of the safety factor profile is linked to many other physics components, such as the plasma conductivity models used for the current diffusion, different current diffusion for fixed-boundary equilibrium (i.e., the current diffusion in DINA is computed self-consistently with the free-boundary equilibria). The current density and electron heat deposition profiles from the DINA-JETTO close coupling simulation are shown in FIG 6. At $t=41\text{s}$, the responses of the total and ohmic parallel current density profiles to the ECCD demonstrate that the current diffusion computed by DINA using the ECCD sources from JETTO (GRAY code is used) is as expected. The total parallel current density has a higher peak at $\rho=0.25$ than another one at $\rho=0.5$, since the ECCD at $\rho=0.25$ is applied for a long duration, whereas the one at $\rho=0.5$ is applied for a short duration, starting from 40s. The total and ohmic current density profiles at $t=120\text{s}$ also show that the edge bootstrap current density is well resolved.

Another type of interpretive simulation has been performed to verify the DINA-JETTO close coupling simulation in terms of the PF coil scenario and magnetic control (see FIG 7). The DINA-JETTO

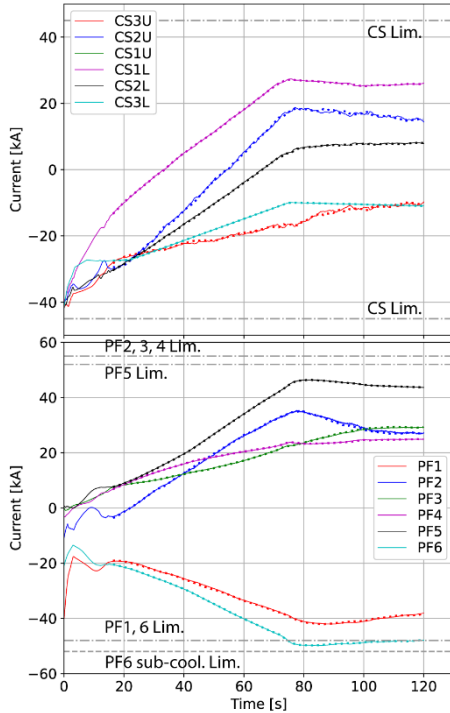


FIG 7. Time traces of poloidal field coils in the DINA-JETTO simulation of 15MA/5.3T ITER Baseline applying the close coupling scheme (solid lines) and interpretative DINA stand-alone simulation (dotted lines). Coil current limits are shown in grey dashed and dash-dotted lines.

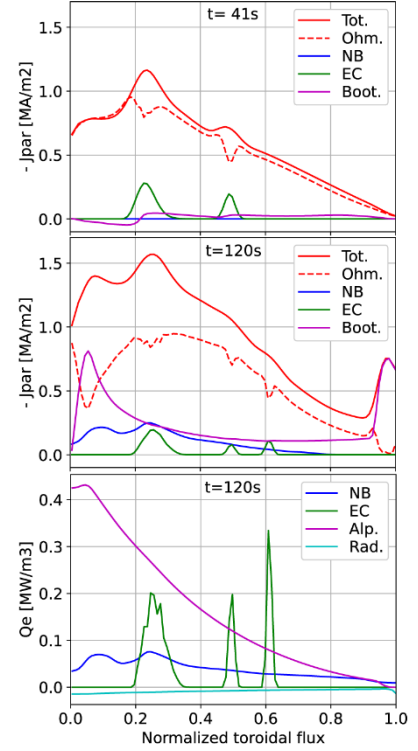


FIG 6. Parallel current density and electron power deposition profiles in the DINA-JETTO simulation of 15MA/5.3T ITER Baseline applying the close coupling scheme.

results have been used

as kinetic profile inputs to the interpretative DINA stand-alone simulation and the evolution of the free-boundary equilibrium and currents in the surrounding conducting structures is computed. The interpretative DINA stand-alone simulation shows that the time traces of the PF coil currents are almost identical with those in the DINA-JETTO simulation. One important observation to note from these simulations and FIG 7 is that the development of a plasma operation scenario requires both the free-boundary equilibrium evolution and kinetic profile evolution, to see if the developed scenario is applicable to the real experiment. The PF6 coil current in the designed scenario has evolved violating its current limit, although it was still within the relaxed limit for 0.4K sub-cooling conditions. This violation is linked to the reduced volt-second consumption than foreseen amount, and it is likely due to the improved L-mode confinement which was introduced to facilitate H-mode access at low density and inclusion of externally driven currents which was not included in the original DINA stand-alone scenario. This clearly shows that coupled free-boundary and transport simulations including all the scenario waveforms (e.g., plasma shape, H&CD power, fuelling) are essential to verifying the designed scenario in terms of its feasibility within the operational space of the tokamak systems.

The close coupling scheme has been also applied to model the end of the H-mode flat-top and H-L transition, exit from burn and current ramp-down, to demonstrate the feasibility of the ITER HFPS towards end-to-end plasma scenario development. The close coupling DINA-JETTO simulation results are compared with the stand-alone DINA scenario which has been used as input to control

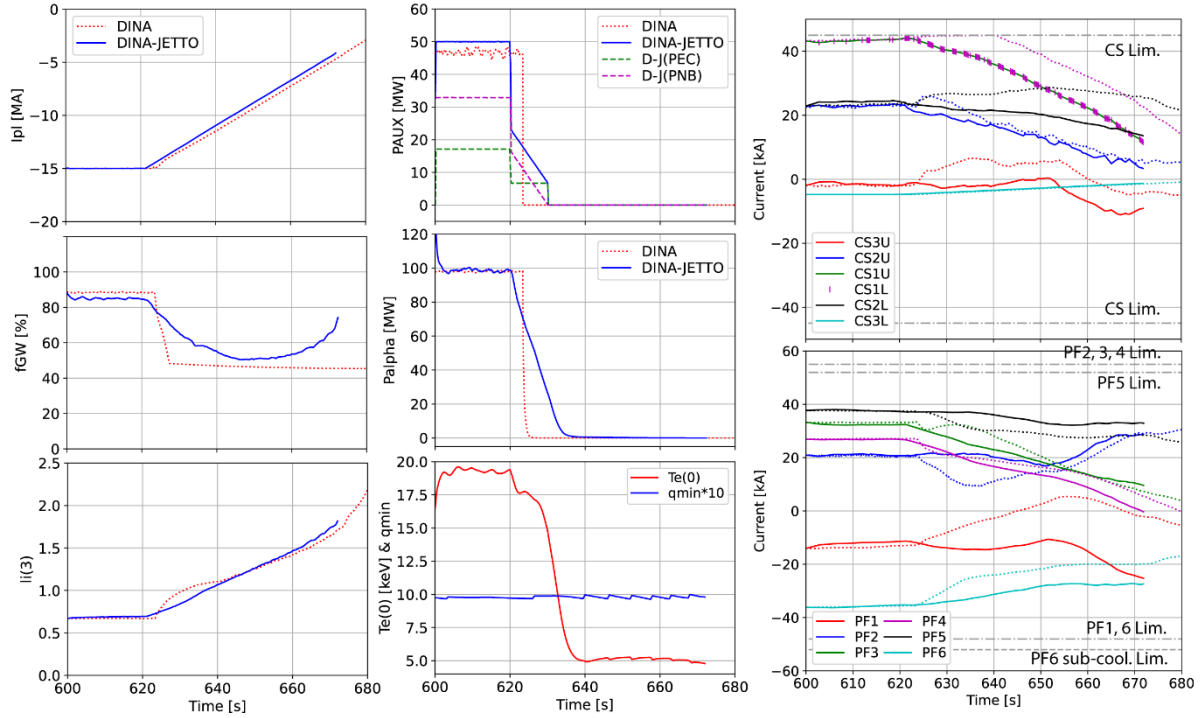


FIG 8. Time traces of plasma parameters in the DINA-JETTO simulation of 15MA/5.3T ITER Baseline applying the close coupling scheme (solid lines) [600s,672s]. The time traces of the stand-alone DINA scenario used as inputs are shown in dotted lines.

the plasma following the designed operational sequence. This simulation demonstrated that DINA-JETTO can model all the important transient ramp-down phases including synchronization of triggering an H-L back-transition as well as of sawtooth events between DINA and JETTO. In the DINA-JETTO close coupling simulation (see FIG 8), the auxiliary heating power was first reduced at $t=620$ s (in JETTO) and induced additional volt-second consumption in the CS1 coil. When CS1 coil current satisfied its criterion to start the ramp-down phase ($ICS > 44$ kA, $t \sim 621$ s), CS coil currents were reduced to ramp-down the plasma current and modify the plasma shape, as designed for the current ramp-down phase. Note that in the DINA stand-alone simulation the H-L transition occurred slightly later ($t \sim 623$ s). The alpha heating power decreased following the auxiliary heating waveforms and the plasma density also decreased as preprogrammed to go down from 85% in H-mode to 50% at the beginning of the L-mode. As the plasma current peaked along with the current ramp-down and shape evolution, the internal inductance, $I_i(3)$, increased similar to the original DINA stand-alone scenario. In FIG 8, the time-traces of the central safety factor and temperature are also compared to show that triggering of sawtooth events is synchronized between DINA and JETTO. When DINA triggered a sawtooth event during the L-mode ramp-down [640s, 672s], JETTO detected it (i.e., drop of q_{min} below 1.0) and then applied effective sawtooth to the temperature and density profiles using an ad-hoc continuous sawtooth model.

The DINA-JETTO simulations by applying the close coupling scheme and matching the current density profiles clearly demonstrate the feasibility of the ITER HFPS in terms of the development of plasma operation scenarios. The coupled evolution of the free-boundary equilibrium and core transport and sources is essential not only to designing the evolution of kinetic profiles and access to the target plasma conditions and plasma burn, but also to verifying that the developed scenario is within the operational constraints. This integrated modelling capability eventually needs to include the edge/SOL sources and transport to further verify that the divertor targets and wall are within the operational conditions (see next section).

4. EXTENDED PROTOTYPE OF ITER HFPS FOR COUPLED FREE-BOUNDARY EQUILIBRIUM AND CORE-EDGE-SOL TRANSPORT MODELLING

The first prototype of the ITER HFPS has been extended to enable coupled free-boundary equilibrium and core-edge-SOL transport modelling (using COCONUT component in JINTRAC) with a dynamic update of the 2D edge/SOL grids generated by DINA. This free-boundary/core-edge-SOL transport modelling capability (DINA-COCONUT) has been applied to a selection of ITER scenario segments around an L-H confinement transition and compared with the free-boundary/core transport simulations (DINA-JETTO). An example given in FIG 10 shows that DINA-COCONUT simulation (shown in red) can qualitatively reproduce DINA-JETTO simulations (shown in blue and green, and the line averaged density has been feedback controlled). The differences in the

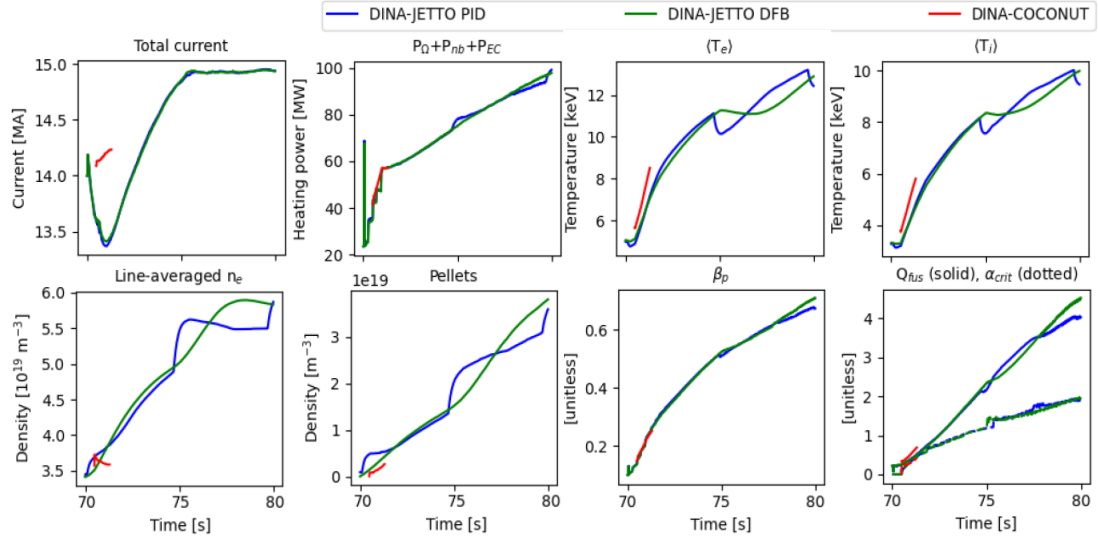


FIG 10. Time-traces of global plasma quantities in DINA-JETTO (either PID controller or default feedback controller (DFB) is used to control the line-averaged density using pellets) and DINA-COCONUT simulations (with PID) during the L-H transition phase of the 15MA/5.3T DT ITER scenario. The simulation interval of the DINA-COCONUT case is [70.5-71.3s] whereas it is [70.0-80.0s] in the DINA-JETTO cases.

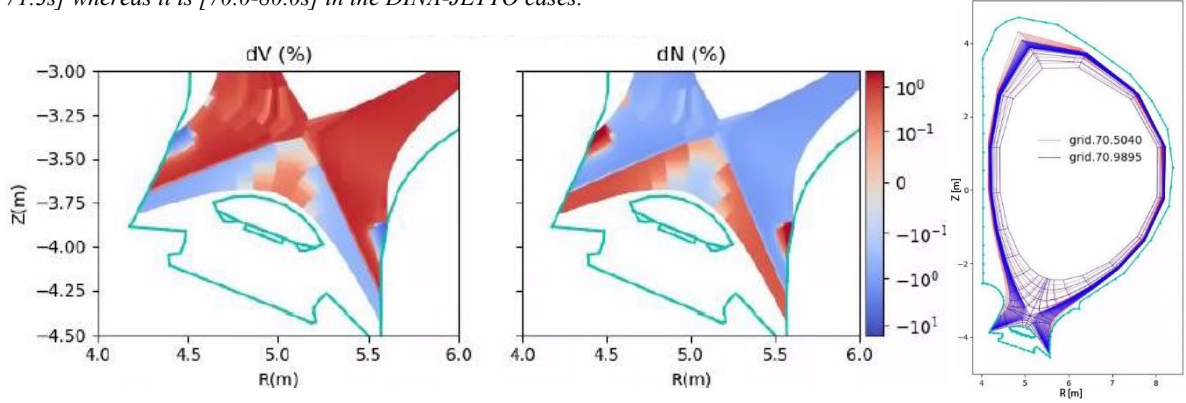


FIG 11. Changes of grid cell volume and main ion density during the update of 2D edge/SOL grid in a DINA-COCONUT simulation. Dynamic update of 2D edge/SOL grid is shown in comparison with the initial grid at 70.5s (red).

DINA-COCONUT simulations are attributed to significant modelling improvements achieved in modelling edge/SOL/divertor physics. In the DINA-COCONUT simulation the plasma parameters at the separatrix are self-consistently computed including edge/SOL transport and sources affected by gas puffing, pumping and plasma-target interactions, whereas user estimates are imposed as separatrix boundary conditions in the DINA-JETTO simulations. In the extended prototype HFPS, dynamic updates of the 2D edge/SOL grids are also applied with an assumption that the particle content within a single cell is conserved during the grid update. This simple assumption provides quasi-conservation of the energy and momentum if the average velocity and temperature are unchanged during the grid update interval defined by the edge transport solver ($\sim \mu\text{s}$). FIG 11 shows the changes of grid cell volume and main ion density during an update of 2D edge/SOL grid. As the update of the free-boundary equilibrium will be slower ($\sim \text{ms}$) than the typical timescale of the SOL transport, the plasma is expected to adapt quickly to the updated grid (cell volume changes) with fast parallel transport of particles and heat. The time-traces of the target plasma quantities, such as the density, temperature and maximum heat loads onto the inner and outer target plates are shown in FIG 12. Note that the DINA-COCONUT close coupling

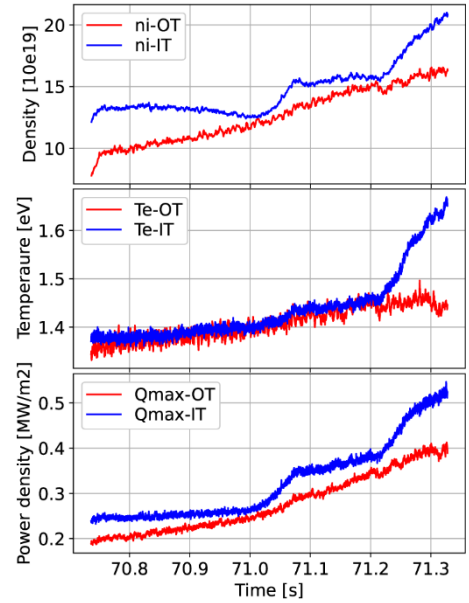


FIG 12. Time traces of plasma parameters on the divertor target in the DINA-COCONUT simulation [70.5-71.3s]. The maximum heat loads started to increase at this early phase of L-H transition.

simulation is time-consuming as the plasma and neutral interactions in SOL/targets are computed by applying EDGE2D/EIRENE. It is currently foreseen that the coupled free-boundary/core-edge-SOL transport DINA-COCONUT simulations are useful to verify the edge and target conditions of the coupled free-boundary/core transport DINA-JETTO scenarios.

5. FURTHER IMPROVEMENTS AND STRATEGIES FOR VALIDATION

Further extension of the high-fidelity physics modelling capabilities across the plasma core, edge/SOL and target/wall areas is foreseen with the application of parallelized/reduced physics-based transport and source models, inclusion of W source from the wall, improved event handling across various physics components (e.g., sawtooth), and fully consistent update of the 2D edge/SOL grids along with the dynamic free-boundary equilibrium evolution. An advanced scheme of conserving physics quantities during the update of the 2D edge/SOL grids [19] is being developed in parallel to updating the currently implemented scheme in near future. A simple model of W source from the wall is also being tested to improve the coupled core-edge-SOL transport modelling capability and better predict impurity transport and accumulation in ITER plasmas. Improvement in software functionalities is also foreseen to be carried out to make the developed prototypes to be more reliable and to provide user-friendly interface in preparing simulations and analysing experimental results.

The application and validation of the ITER HFPS within ITER Members' facilities is foreseen to follow a staged approach to prepare the modelling of ITER Members' devices. The standalone DINA and JINTRAC codes will be first deployed to demonstrate their magnetic and kinetic plasma modelling capabilities for the known complexities of modelling exercises. The evolution of free-boundary equilibria shall be reproduced by applying DINA, following the verification of implemented PF coil systems, passive conducting structures and magnetic controllers. In parallel, the evolution of kinetic plasma profiles will be modelled interpretatively and/or predictively by applying JINTRAC core-edge-SOL coupled transport modelling. Once both stand-alone simulations are validated to some extent, the coupled free-boundary/core and free-boundary/core-edge-SOL HFPS modelling will be attempted to validate their integrated modelling capabilities in the presence of both kinetic and magnetic plasma controls, as well as to guide development of new plasma experiments in ITER Members' facilities, similarly as foreseen to perform for preparing and analysing future ITER experimental campaigns. It would be worth to note that the foreseen activities require frequent interactions and exchange of personnel between the ITER Organization and ITER Members. Several collaborative activities for HFPS validation are recently initiated to deploy the software to ITER Members and to train ITER Members' contributors.

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