A MULTISCALE AND MULTIPHYSICS APPROACH TO THE DEVELOPMENT OF A HIGH-FIDELITY PHYSICS PLASMA SIMULATOR FOR BURNING PLASMA

F.M. POLI[1], P. ABREU[1], X. BONNIN[1], R. COELHO[2], D. COSTER[3], M. DUBROV[1], L. FIGINI[4], M. GUERINI-ROCCO[4], O. HOENEN[1], T. JONSSON[5], S-H KIM[1], F. KOECHL[1], S.D. PINCHES[1], A. POLEVOI[1], P. SAWANTDESAI[1], P. STRAND[6], L. VEEN[7], D. YADYKIN[6], J. ZIEGEL[8]

[1] *ITER Organization, Route de Vinon-sur-Verdon - CS 90 046 - 13067 St Paul Lez Durance Cedex – France*
[2] *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[3] *Max Planck Institute for Plasma Physics, Boltzmannstr 2, Garching bei Muenchen, Germany*
[4] Istituto per la Scienza e Tecnologia dei Plasmi, CNR, 20125 Milano, Italy
[5] *KTH, School of Electrical Engineering and Computer Science (EECS), Electrical Engineering, Electromagnetic Engineering and Fusion Science.*
[6] *Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden*
[7] *Netherlands eScience Center, 1098 XH Amsterdam, The Netherlands*
[8] *Institute for Fusion Studies, The University of Texas at Austin, Austin, Texas, USA*

The ITER Organization is collaborating with EUROfusion and with the international fusion community to develop a high-fidelity plasma simulator: a flexible, highly modular and scalable framework for dynamic modelling of plasma discharges from startup to termination, with physics, engineering and synthetic diagnostics components, in a native IMAS environment. While simulations in support of the ITER Research Plan [1] are actively being undertaken with JINTRAC-DINA and ASTRA [2-4], an approach based upon modern code architecture and software engineering requirements is being undertaken, for long-term sustainability, yet leveraging lessons learnt from over a decade of experience in integrated modelling. As opposed to interfacing pre-existing codes using couplers or wrappers, commonly referred to as Component Based Software Engineering approach, which has an advantage of requiring minimal modifications to external codes, the framework is being designed using a hybrid approach, where the multiscale framework is put in place first and the physics models are implemented afterwards. Such an approach requires refactoring codes and rewriting algorithms, which might not seem attractive at first, but is an investment for long term sustainability and scalability, towards use in a fusion power plant. The advantages of this novel framework are discussed, highlighting self-consistency and optimization of computational resources when complexity of the model increases and when the plasma model – which evolves with internal transport and MHD timescales - is coupled with external actuators and diagnostics observables, whose timescales are controlled by hardware response and sampling frequency.

The simulator is developed in a native IMAS environment and uses the Persistent Actor Framework (PAF) based on the MUSCLE3 library [5] for multi-scale and multi-physics coupling. While in a tokamak scales are separable, there is still a superposition in the computational domain when modeling problems that involve interaction between these scales [6]. Examples include excitation and stabilization of MHD instabilities by radiofrequency waves, and turbulence effects on MHD, as depicted in Fig.1. Characteristic plasma time scales regulate the extent of overlapping between individual domains. The European Transport Simulator (ETS) [7] is being used as the core driver for solving the partial differential equations (PDEs) for current diffusion, transport and sources. The ETS-PAF, the incarnation that uses the Persistent Actor Framework, has the modular architecture that is required for the project with minimum modifications to the existing components and therefore serves as the initial suite for the plasma model. A prototype of the framework is presented, as applied to the modelling of an ITER scenario for the Start of Research Operation (SRO) phase. Use cases include (a) simulation of a deuterium plasma at 5-7.5MA/2.65T with 40MW of Electron Cyclotron and 10MW of Ion Cyclotron heating and (b) the integration of a self-consistent workflow for triggering, detection and stabilization of tearing modes and neoclassical tearing modes, including observables from the Electron Cyclotron Emission radiometer and magnetic probes. In these examples, the ETS is used as the driver for external models, to take advantage of available IMAS-compatible components and workflows, like those for the Heating and Current Drive (H&CD) calculations [8]. At the same time, replacement of physics models with modified versions that retain the physics, but are refactored to satisfy the requirements of self-consistency in the framework and optimize the use of the MUSCLE3 library for task distribution, are being explored. Figure 1 shows a schematic of the physics components coupling in the plasma model. Every box in the diagram represents a persistent actor or a subworkflow, which has well defined input and output ports that exchange Interface Data Structures IDSes [9].

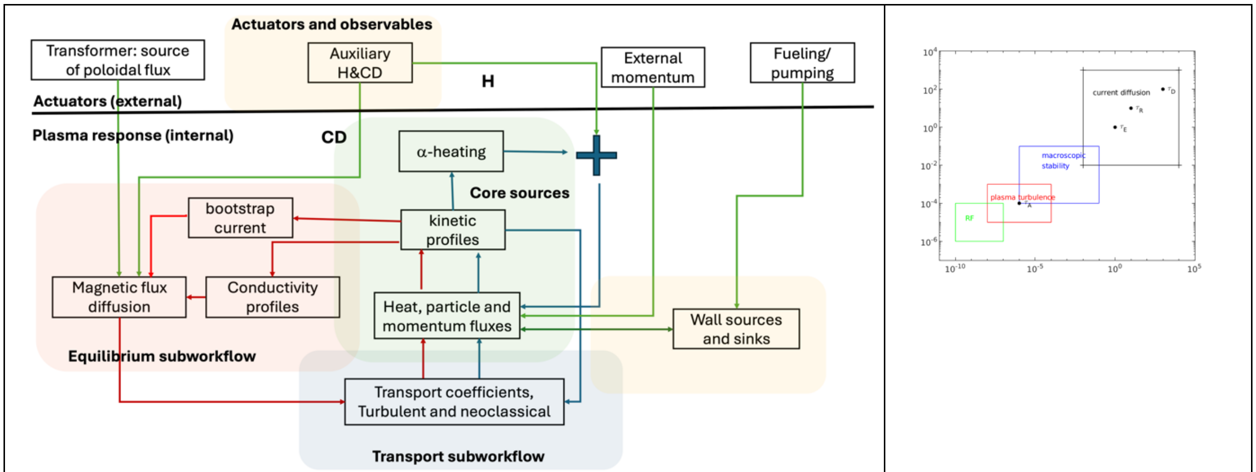

Figure1. (Left): schematics of the plasma model. Red arrows indicate current diffusion time scales, blue arrow indicate transport timescales, green arrows indicate timescales controlled form the outside. Shaded areas highlight subworkflows, as implemented in the ETS-PAF. (Right) sketch of the physics domain in the plasma model, with temporal scales on the horizontal axis and spatial scales on the vertical axis.

Any given set of actors can be grouped into a larger, hierarchical workflow, represented in the figure by the color-coded rectangles for transport, equilibrium and sources. The slow current diffusion timescales (red arrows) and the fast transport timescales (blue arrows) are coupled through an adaptive-step convergence loop, which also controls when core and edge sources need to be calculated. Models for diagnostics and actuators are interfaced to the plasma model through a time bridge, which manages the connection between external models and plasma response, e.g. for the H&CD (yellow box above the horizontal line). The depicted framework has demonstrated the ability of initiating a predictive simulation with the ETS from an existing scenario, at any given time step, including in the early ramp-up phase. This capability is desirable for developing individual segments for the various phases of the discharge, which can then be exchanged – for example - between the High-Fidelity Plasma Simulator and a Pulse Design Simulator. Not only this facilitates verification of models and experimental validation, but it also increases confidence on the application of modelling tools for the preparation of ITER Operation. It also supports the development of analysis workflows and assessment of diagnostics performance and sensitivity, by providing a high-fidelity plasma model, in a self-consistent multiscale and multi-physics framework. In view of the growth of the simulator to support burning plasma research, including use in a fusion facility, individual components and their inter-operability are being evaluated based upon a readiness scale, adapted from NASA Technical Readiness Levels and integrated with System Integration Readiness Levels [10]. This approach serves as a guideline to identify gaps in the model and to address research and development priority needs. The simulator shall serve as the reference tool for the high-fidelity modelling of ITER discharges in support of the Research Plan, including plasma response to external actuators via observables. The release of an Open-Source prototype to be tested on existing facilities is planned for the end of 2025, while extension to a self-consistent core-edge-SOL (Scrape-Off-Layer) integration will be a major effort in 2026, with the aim at having all critical physics components coupled and tested, either as reduced or advanced models, before the next FEC conference.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

[1] A. Loarte *et al*, “The new ITER Research Plan and open R&D issues”, submitted to Plasma Physics and Control. Fusion.
[2] F. Eriksson *et al* 2024 *Nucl. Fusion* **64** 126033
[3] Koechl F. *et al* "Integrated Modelling of ITER plasma scenarios in the SRO phase" 19th Int. Workshop on H-mode Physics and Transport Barriers (Mito, Japan, 24-27 Sept. 2024) P5-08
[4] A.R. Polevoi *et al* 2023 *Nucl. Fusion* **63** 076003
[5] L.E. Veen, A.G. Hoekstra, 2020, Computational Science ICCS vol **12142** Springer, https://doi.org/10.5281/zenodo.3258864
[6] F.M. Poli *Phys. Plasmas* 2018 **25**, 055602
[7] P. Huynh *et al* 2021 *Nucl. Fusion* **61** 096019
[8] M. Schneider *et al*, 2021, *Nucl. Fusion* **61** 126058
[9] F. Imbeaux *et al*, 2015 *Nucl. Fusion* **55** 123006
[10] B. Sauser *et al*, 2010, Information Knowledge Systems Management **9** 17-46