30th IAEA Fusion Energy Conference (FEC)

Field / Topic: Systems Integration / Fusion Energy Technology (TEC)

A novel Multi-Timescale strategy for Fusion Systems Codes and its impact to parametric analyses of Fusion Power Plants

Tiago Pomella Lobo, Ivan Alessio Maione

Institute for Neutron Physics and Reactor Technology (INR), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Contact: t.pomella-lobo@kit.edu

March 17, 2025

Synopsis

Fusion Systems Codes (SCs) currently neglect the interdependence between systems operating in different timescales and this must be addressed. One major example is how the dwell-time should be consistent with reactor design – *e.g.* plasma, First Wall (FW), Balance-of-Plant (BOP) – and the impact this can have on the dynamics of both the power and fuel balances of a Fusion Power Plant (FPP). The goal of this work is to illustrate this need with unexpected parametric dependencies never reported in literature, such as between the ejection velocity of plasma filaments to the Scrape-Off Layer (SOL) and the net power production of the plant, or between the design temperature of the FW and aspects of tritium self-sufficiency.

Systems Codes are fundamental tools in Fusion Energy research that allow for parameter space exploration and evaluation of technology integration through parametric studies [1]. Many SCs focus on reactor design to identify relevant systemic dependencies, and a few target design of FPPs (*e.g.* [2–5]). However, current state-of-the-art SCs (of the latter type) model each plant system operating within its own inherent timescale and neglect the dynamic interdependence between them at the power plant level. That is, these implementations can be arguably classified as Reactor Design Codes (RDCs), some with post-processing modules for auxiliary plant systems, instead of true Plant Design Codes (PDCs).

In other words, Multi-Timescale (MT) Fusion SCs are needed. To fill out this gap, the following approach is proposed: to develop a strategy to convert current RDCs into PDCs. This would potentially increase the utility of codes already available. To that end, a candidate strategy has been tested on MIRA [6], a multi-fidelity RDC previously developed at the Karlsruhe Institute of Technology (KIT). Representative parametric analyses of the Helium-Cooled Pebble Bed (HCPB) variant of the European DEMOnstration Power Plant, 2017 Baseline (EU-DEMO), with an indirect BOP, were then produced to illustrate the importance of pivoting current Fusion SCs into PDCs.

The tested candidate strategy introduces a methodology to categorize FPP systems in one of three timescales relevant for MT analyses, as shown in Figure 1. The **(a)** *Operational* timescale comprises in collections of pulses and majorly impacts fuel self-sufficiency and availability of a FPP [7]. The **(b)** *Pulse* timescale is inherent to tokamak design and mainly impacts the net power production of the plant [8]. The **(c)** *Plasma* timescale represents the characteristic time in which its dynamics evolve [9], which is crucial to characterize the reactor. Novel models were produced and then organized into three SC modules depending on their impact to each timescale: a Fuel Cycle module (FC) for **(a)**, a Power Cycle module (PC) for **(b)** and a Reactor module (RC) for **(c)**. A final Time Control module (TC) was also devised to couple all three timescales and enable plant-wide systems-level analyses.

The RC was implemented by coupling the MIRA RDC with a new model for SOL plasma dynamics. This had the goal of estimating heat and particle distributions along the reactor chamber wall. To ensure consistency between Near- and Far-SOL distributions, both empirical scaling laws and a surrogate of the code TOKES [10] were employed. The latter was developed using a physics-informed machine-learning modeling technique, given the computational cost of TOKES as well as the current uncertainties in state-of-the-art models for Far-SOL dynamics. The surrogate was optimized through a novel methodology that revealed the exponent dependencies between plasma filament ejection parameters and FW load profiles [11].

The PC was implemented in a two-step modeling approach using a physics-specific first-principles technique. This meant individual thermodynamical modeling, due to the high level of maturity of design, to compute consistent 0D mass and power balances for each major BOP system. In the first step, a steady-state model was developed as a means of characterizing them and estimating the main stages of their dynamics; namely the flat-top and dwell phases of a reactor pulse. In the

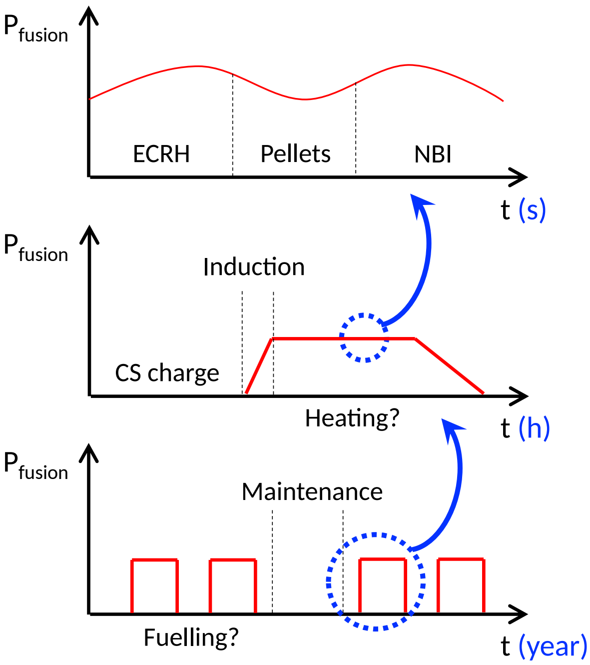

Figure 1: Schematic view of fusion power production in a tokamak-based FPP in different timescales (*top* to *bottom*: plasma, pulse, operation) and the potential impact of different plant systems.

second step, a transient model was developed to quickly compute the impact of thermal transients of the systems with most meaningful heat capacities. This was done by mixing steady-state thermal profiles for different time-steps, using a gauge based on the Green function of the heat diffusion equation and its Fourier number. Cumulative deviations during the transient phases of the pulse amount to less than 2% in comparison to commercial code, but are obtained much faster [12].

The FC was implemented with a similar two-step approach, but relied on a physics-generic first-principles technique instead. This meant a common residence-times (τ) modeling for all fuel processing systems, given the preliminary state of design for many of them, to compute 0D mass balances for the main eight fuel species of a FPP. In the first step, a steady-state model is used to characterize each major processing system with τ-parameters, based on literature review of representative technologies. In the second step, a Simulink model applies these parameters to estimate fuel accumulation rates in storage, to compute start-up inventories and doubling times [13].

Finally, the TC was implemented to import heat and particle loads from the RC and compute outgassing fluxes from the reactor chamber walls during phases other than the flat-top. This is done with a double-population hydrogen transport in metals code (TESSIM-X) [14], which allows the calculation of reactor pump-down times that directly impact the minimum time length of the dwell phase of the plant. Exporting these lengths to the PC and FC enables consistent coupling of the dynamics of all timescales. Figure 2 shows preliminary results of this type of coupling, where the trapping parameters of FW metals lead to significant outgassing fluxes, which ultimately increase the dwell-time to ~15 minutes. This implies in slower tritium accumulation rates than running the model with the standard dwell-time assumed for the EU-DEMO, and highlights the importance of MT SCs.

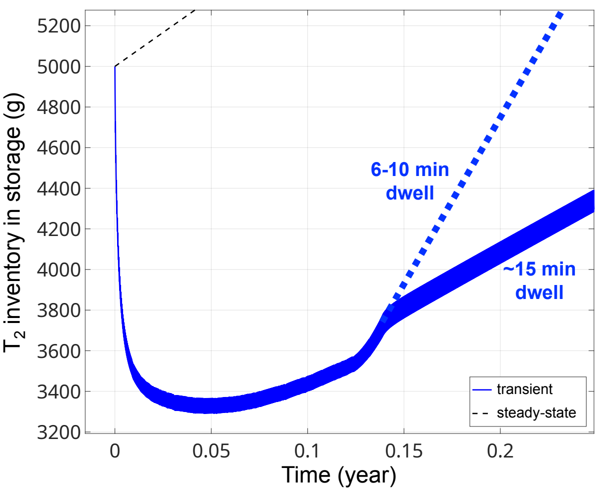

Figure 2: Tritium accumulation in storage as a function of operational time of a FPP. Comparison between asymptotic accumulation rates of: steady-state model (*black dashed line*), transient model decoupled from systems modeled in other timescales (*blue dotted line*), and transient model run using the MT candidate strategy (*blue continuous line*).

References

[1] Makoto Nakamura et al. “Efforts towards improvement of systems codes for the Broader Approach DEMO design”. en. In: *Fusion Engineering and Design* 87.5-6 (Aug. 2012), pp. 864–867. ISSN: 09203796. DOI: 10.1016/j.fusengdes.2012.02.034. URL: https://linkinghub.elsevier.com/retrieve/pii/S0920379612000944 (visited on 10/16/2020).

[2] Lane Carlson et al. “ARIES systems code development, visualization and application”. In: *2011 IEEE/NPSS 24th Symposium on Fusion Engineering*. Chicago, IL, USA: IEEE, June 2011, pp. 1–6. ISBN: 978-1-4577-0669-1. DOI: 10.1109/SOFE.2011.6052294. URL: http://ieeexplore.ieee.org/document/6052294/ (visited on 11/19/2024).

[3] C. Reux et al. “DEMO reactor design using the new modular system code SYCOMORE”. In: *Nuclear Fusion* 55.7 (July 2015), p. 073011. ISSN: 0029-5515, 1741-4326. DOI: 10.1088/0029-5515/55/7/073011.

[4] M. Kovari et al. ““PROCESS”: A systems code for fusion power plants – Part 2: Engineering”. en. In: *Fusion Engineering and Design* 104 (Mar. 2016), pp. 9–20. ISSN: 09203796. DOI: 10.1016/j.fusengdes.2016.01.007. URL: https://linkinghub.elsevier.com/retrieve/pii/S0920379616300072 (visited on 02/11/2021).

[5] M. Coleman et al. “BLUEPRINT: A novel approach to fusion reactor design”. en. In: *Fusion Engineering and Design* 139 (Feb. 2019), pp. 26–38. ISSN: 09203796. DOI: 10.1016/j.fusengdes.2018.12.036. URL: https://linkinghub.elsevier.com/retrieve/pii/S0920379618308019 (visited on 10/16/2020).

[6] Fabrizio Franza. “Development and Validation of a Computational Tool for Fusion Reactors’ System Analysis”. de. PhD thesis. Karlsruher Institut für Technologie, 2019.

[7] M. Coleman et al. “DEMO tritium fuel cycle: performance, parameter explorations, and design space constraints”. en. In: *Fusion Engineering and Design* 141 (Apr. 2019), pp. 79–90. ISSN: 09203796. DOI: 10.1016/j.fusengdes.2019.01.150. URL: https://linkinghub.elsevier.com/retrieve/pii/S092037961930167X (visited on 10/23/2020).

[8] Simone Minucci et al. “Electrical Loads and Power Systems for the DEMO Nuclear Fusion Project”. en. In: *Energies* 13.9 (May 2020), p. 2269. ISSN: 1996-1073. DOI: 10.3390/en13092269. URL: https://www.mdpi.com/1996-1073/13/9/2269 (visited on 03/09/2022).

[9] Ehud Greenspan, ed. *Encyclopedia of nuclear energy*. English. OCLC: 1258649274. Amsterdam: Elsevier, 2021. ISBN: 978-0-12-819732-5. URL: https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=2720599 (visited on 07/28/2022).

[10] I. S. Landman. *Tokamak Code TOKES Models and Implementation*. Tech. rep. FZKA 7496. Forschungszentrum Karlsruhe Technik und Umwelt, Sept. 2009.

[11] Tiago Pomella Lobo et al. “A reduced-order model to estimate first wall particle and heat fluxes for systems codes”. en. In: *Fusion Engineering and Design* 204 (July 2024), p. 114491. ISSN: 09203796. DOI: 10.1016/j.fusengdes.2024.114491. URL: https://linkinghub.elsevier.com/retrieve/pii/S0920379624003442 (visited on 05/21/2024).

[12] Tiago Pomella Lobo et al. *A Multi-Timescale approach for Fusion Power Plants Systems Codes focused on models for Fuel and Power Cycles*. Poster. Dublin City University, Ireland, Sept. 2024. URL: https://soft2024.eu/.

[13] Tiago Pomella Lobo et al. *A Time-Dependent Fuel Cycle developed for Multi-Timescale Systems-Codes to study technology integration in advanced Fusion Power Plants*. Poster. virtual edition, Sept. 2020. URL: https://soft2020.eu/.

[14] K. Schmid et al. “Transport of hydrogen in metals with occupancy dependent trap energies”. en. In: *Journal of Applied Physics* 116.13 (Oct. 2014), p. 134901. ISSN: 0021-8979, 1089-7550. DOI: 10.1063/1.4896580. URL: http://aip.scitation.org/doi/10.1063/1.4896580 (visited on 10/07/2020).