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

T. Pomella Lobo[1*], I. A. Maione[1]

[1] Institute for Neutron Physics and Reactor Technology (INR), Karlsruhe Institute of Technology (KIT), Karlsruhe

Abstract

System Codes (SCs) are essential for exploring parameter spaces and assessing technology integration in Fusion Power Plants (FPPs). Yet, conventional SCs treat plant systems operating in different timescale independently, and neglect dynamic interdependencies between them. This work introduces a Multi-Timescale (MT) SC approach that identifies three characteristic timescales: (**a**) plasma dynamics, (**b**) single-pulse operation, and (**c**) long-term plant operation. Dedicated models have been implemented for each: SOL transport via scaling laws and a surrogate of the TOKES code to represent (**a**); Balance-of-Plant thermodynamics in a Power Cycle Module to represent (**b**); and multi-species fuel processing with a residence-times Fuel Cycle Module to represent (**c**). Applied to the EU-DEMO model in MIRA (a multi-fidelity SC developed at KIT) and coupled with the double population diffusion/trapping code TESSIM-X, reactor wall outgassing is consistently computed and reveals stronger systemic dependencies than independent timescale analyses. Examples include how plasma filament dynamics in the Scrape-Off Layer (SOL), First Wall temperature limits, and fuel cycle performance impact each other and affect the net electricity output and tritium self-sufficiency. This MT strategy provides a more realistic basis for evaluating FPP design and technology integration.

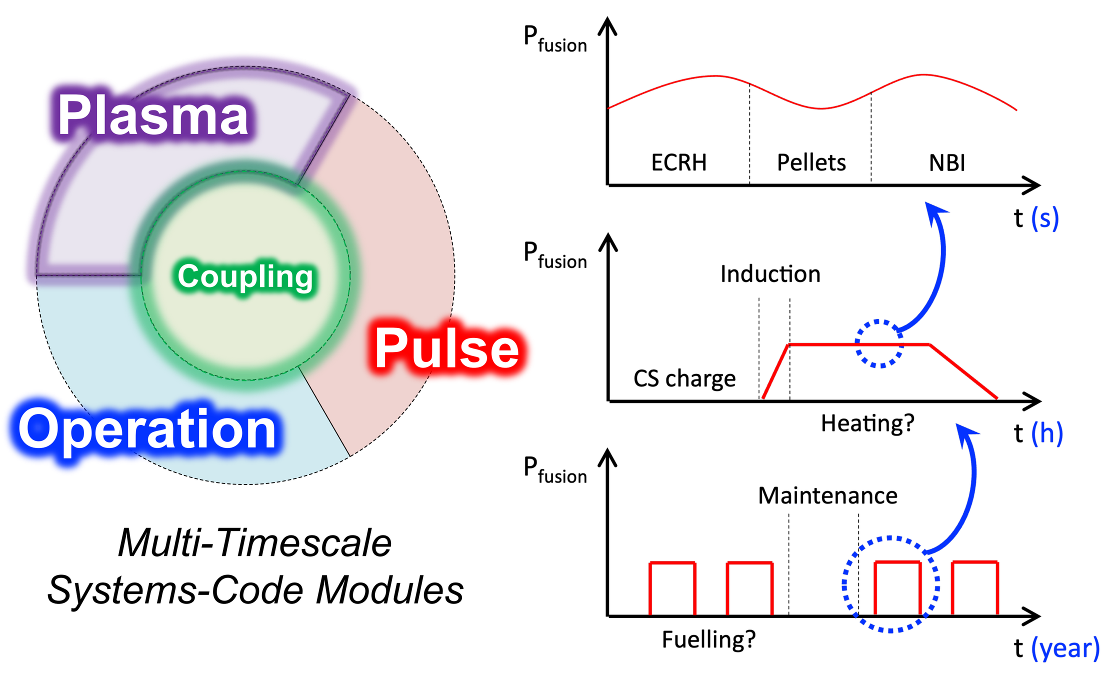
Keywords: Scrape-Off Layer (SOL), Balance-of-Plant (BOP), Fuel Cycle, Systems-Codes, EU-DEMO

***Contact:** t.pomella-lobo@kit.edu

Context & Objectives

- Problem: current **Fusion Systems Codes (SCs)** focus on reactor systems and neglect dynamic interdependencies with (auxiliary) plant systems.

Reactor Design Code (**RDC**) ≠ Plant Design Codes (**PDC**)

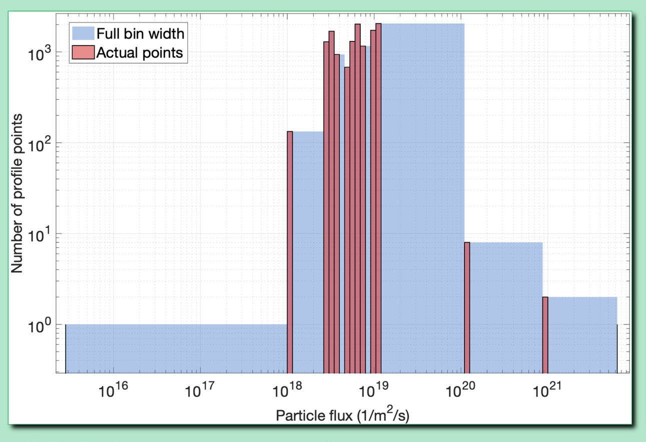


Multi-Timescale Systems-Code Modules

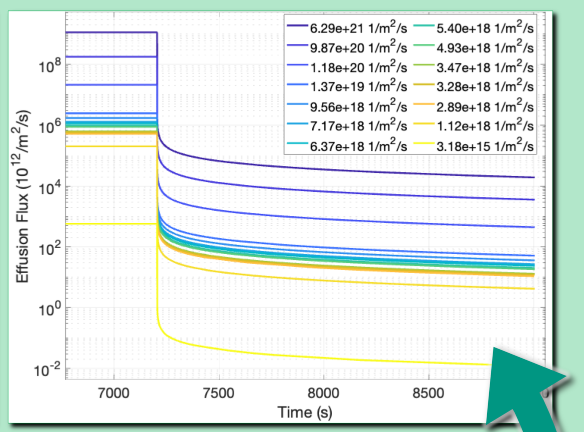
- Proposal: develop novel methodology for SCs, to convert RDCs into **Multi-Timescale** PDCs.
- Showcase: apply methodology to multi-fidelity RCD **MIRA** [1]; run parametric analyses for major plant systems due to different pump-down times.
- Novel SC models presented in this work to couple timescales: (1) SOL transport and (2) outgassing.

(2) Outgassing Model

- **Goal:** compute pump-down dynamics.
- **Approach:** assume log. relationship between loading (from SOL transport) and unloading (outgassing) and integrate effusion fluxes.
- **Expected Outputs**:
  - representative particle flux samples using binning logarithmically spread over range of profile values.
  - develop model to estimate effusion fluxes for other (non-sample) profile points.
  - (toroidal) integral of fluxes for total effusion flow.
  - solve pump-down ODE to estimate time to reach target pressure, plus derive residence-time (τ) parameter for future coupling with Fuel Cycle model.

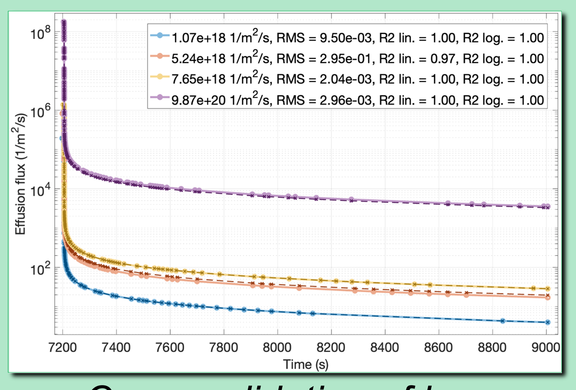


CDF-based part. flux sampling bins

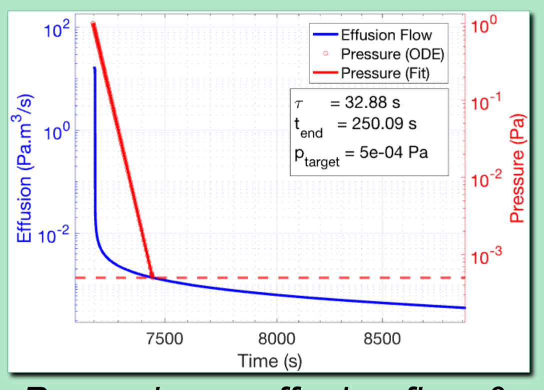


Effusion fluxes (TESSIM-X)

- **Loading:** Cumulative Distribution Function (CDF) sampling of particle flux profile from **(1)**, to limit number of (expensive) unloading simulations.
- **Unloading:** simulate diffusion & trapping with TESSIM-X [3] for all samples (*14 parallel runs*).



Cross-validation of log-interpolation model



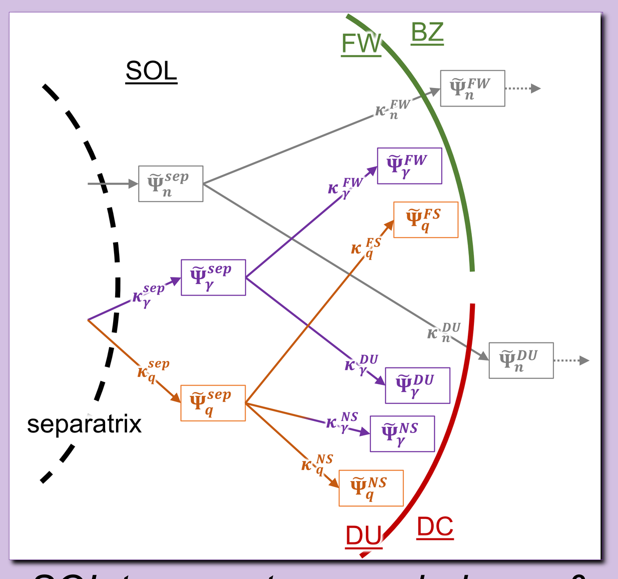
Pump-down: effusion flow & pressure decrease in time

- **Effusion fluxes**: build log-interpolation model between loading and unloading fluxes, cross-validate it against ~1/4 of simulations (*4 runs*).
- **Effusion flow** ($\Psi_{out}(t)$)**:** toroidal integral uses spline method to reduce numerical error.
- **Pump-down model:** evolve pumping until target, fit exponential to derive characteristic time of pressure decay ($p(t) \propto e^{-t/\tau}$).

$$V \cdot \frac{d}{dt} p + S_{pump} \cdot p = \Psi_{out}(t)$$

(1) SOL Transport Model

- **Goal:** compute poloidal profile of particle fluxes onto the walls (loading fluxes for outgassing).
- Literature: systemic studies apply power **balance** between (i) separatrix & (ii) wall;

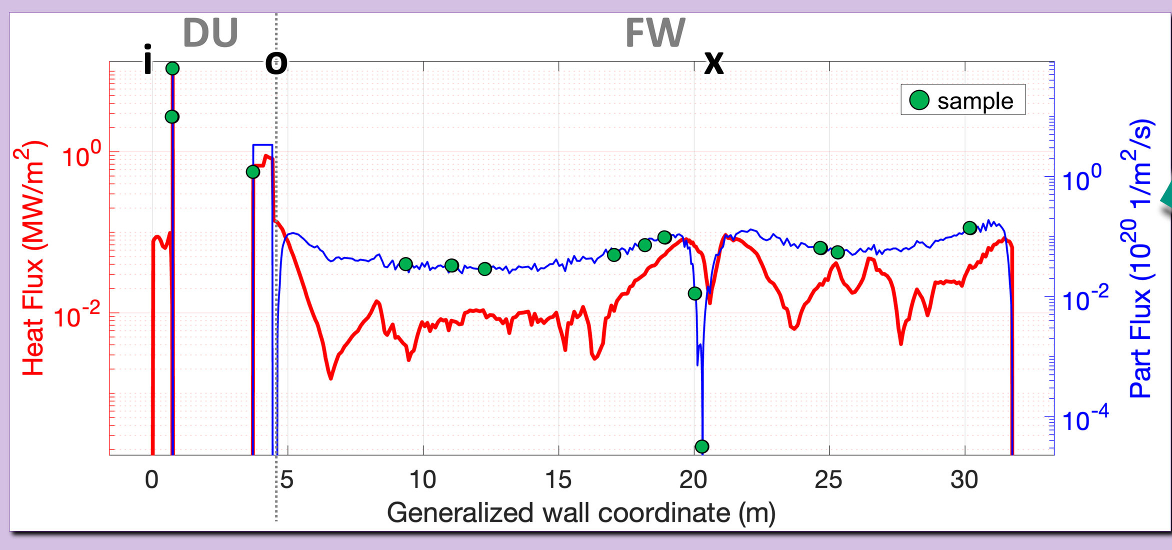


SOL transport: power balance & deposition channels

i. particles crossing (neutrons, photons, charged particles).

ii. wall deposition on First Wall (FW), Divertor Plasma-Facing Units (DU), others further (BZ, DC, VV, *etc*).

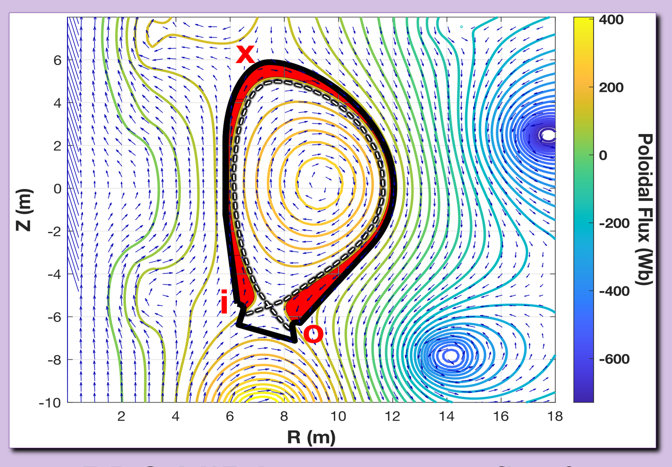
- 3 channels for charged particles:
  - Near-SOL (**NS**), diffusion through separatrix.
  - NS conversion into radiation (Argon seeding).
  - Far-SOL (**FS**), ejection of blobs/filaments.
- **Inputs** (from RDC MIRA):
  - geometry module – chamber wall contour.
  - equilibria module – magnetic configuration.
  - confined transport module (PLASMOD code) – power flow ($\tilde{\Psi}_q^{sep}$) and particles flow (Ψ_q^{sep}).
- **Expected Outputs**:
  - (poloidal) streamlines to map power and particle distribution from mid-plane points to generalized wall coordinate points.
  - Superimposed NS + FS poloidal profiles for heat and particle fluxes along wall coordinate that includes FW and DU.



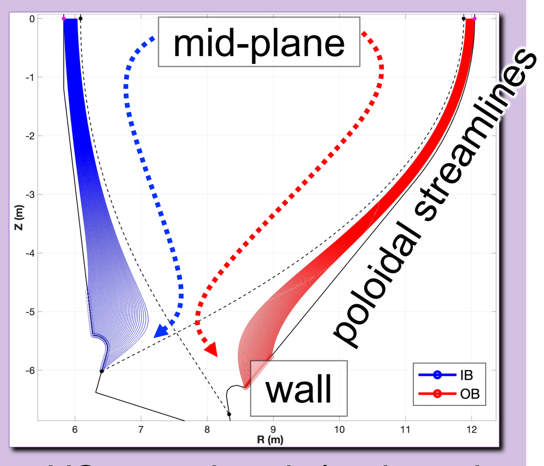
Superimposed NS + FS charged particles profiles

- **FS model:** previously developed surrogate of TOKES code to estimate heat/particle fluxes [2].
- **NS model:** transpose Eich scaling to particle fluxes and compute streamlines to map mid-plane coordinates to wall coordinates.

$$\tilde{\Gamma}_q^{NS}(d) = \frac{\tilde{\Psi}_q^{NS}}{2\pi R_0 \cdot \lambda_{NS}} e^{\frac{-d}{\lambda_{NS}}} \quad \Rightarrow \quad \Gamma_q^{NS}(d) = \frac{\Psi_q^{NS}}{2\pi R_0 \cdot \lambda_{NS}} e^{\frac{-d}{\lambda_{NS}}}$$



RDC MIRA: reactor config. & confined plasma



NS mapping: in/outboard (poloidal) streamlines

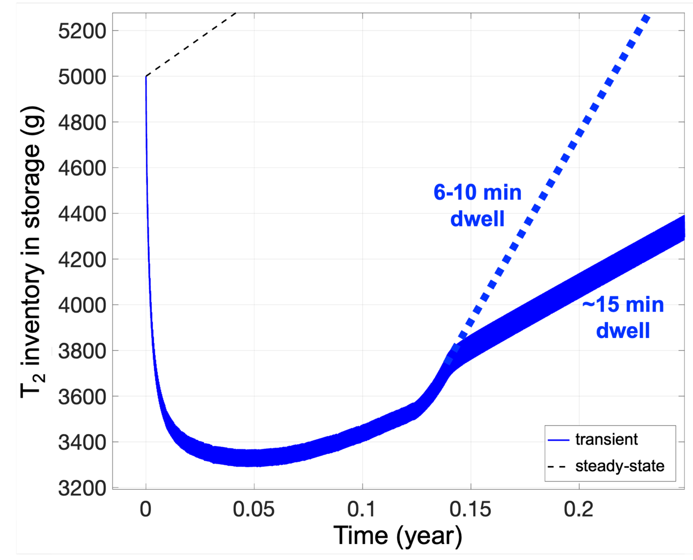
- **Approach:** assume all charged particles have the same average energy before escaping, so

power channels ≈ particle channels

$$\tilde{\Psi}_q^{sep} = \frac{\tilde{\Psi}_q^{NS}}{\kappa_\gamma^{NS} + \kappa_q^{NS}} = \frac{\tilde{\Psi}_q^{FS}}{\kappa_q^{FS}} \quad \Rightarrow \quad \Psi_q^{sep} = \frac{\Psi_q^{NS}}{\kappa_\gamma^{NS} + \kappa_q^{NS}} = \frac{\Psi_q^{FS}}{\kappa_q^{FS}}$$

Conclusions & Outlook

- **SOL Transport model:**
  - successful NS estimation of heat and particle flux poloidal profiles, matching previous 0D model in RDC MIRA, and literature reports.
  - limited precision of magnetic configuration grid precludes computation of first 20% streamlines, but not detrimental to systemic analyses due to limited deposition wall surface in NS (~12%).
- **Outgassing model:**
  - successful CDF-binning method to couple SC models through representative log. sampling.
  - cross-validated log-interpolation model to estimate integral effusion flow due to chamber wall outgassing during dwell-time, that match literature results for pristine wall conditions.
  - successful SC approach to estimate pump-down time + coupling parameter for FC models.



Preliminary coupling with Fuel Cycle

- **Preliminary coupled results:** certain design parameters lead to dwell times >10min, which significantly impacts production of electricity and fuel, such as lower net power from BOP and longer tritium doubling times at the Tritium Plant.

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[3] K. Schmid, et al., Transport of hydrogen in metals with occupancy dependent trap energies, Journal of Applied Physics 116 (2014) 134901. https://doi.org/10.1063/1.4896580.

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