EUROfusion

Simulator-agnostic Digital Twin Environment (DTE) integration - towards a consolidated framework with an ITER relevance

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Objectives

Many of the individual components that are required for a DTE are either already available or actively developed by the EUROfusion and international fusion community.

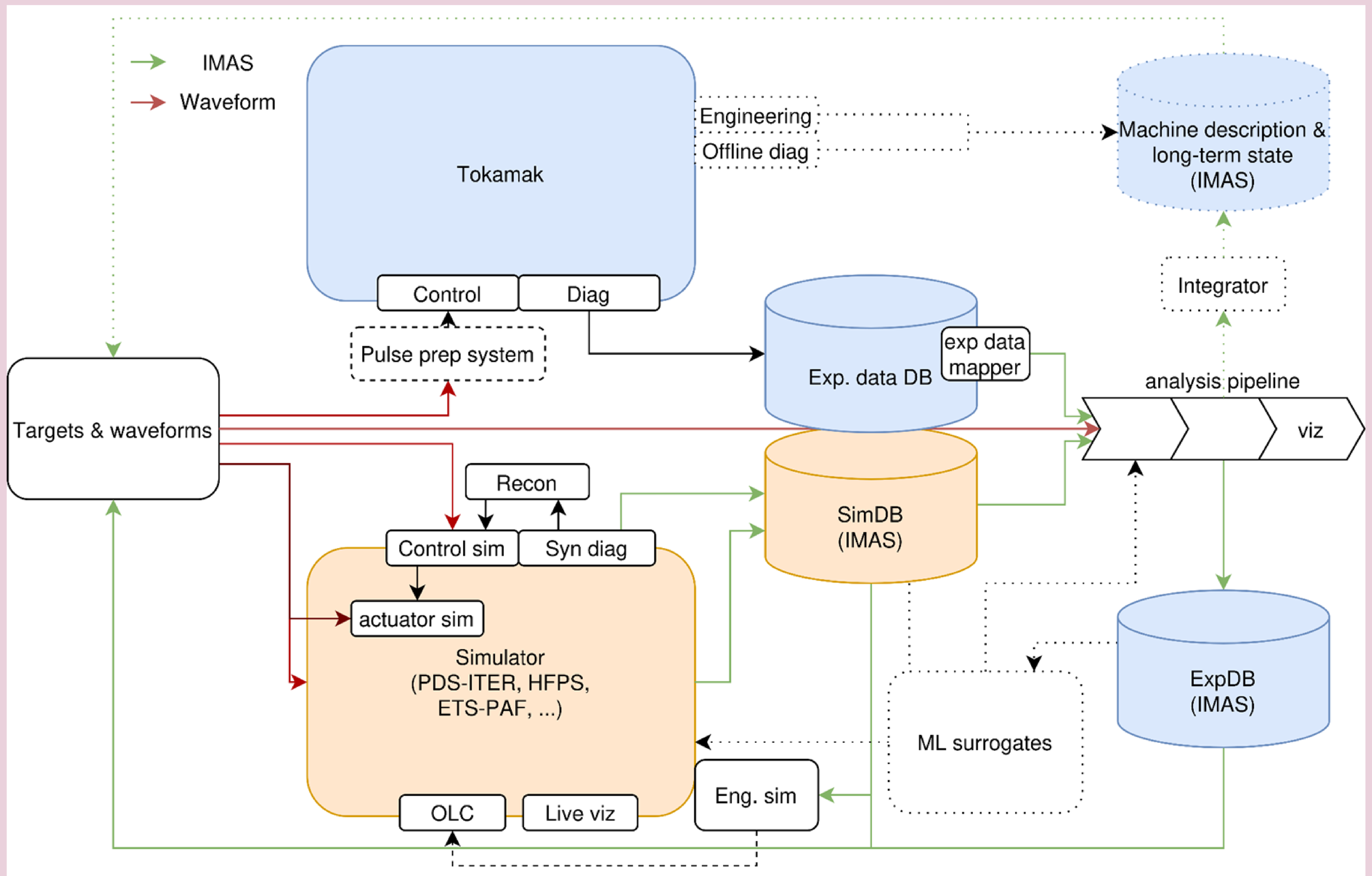
Create an integrated framework that brings these components together for a streamlined analysis, prediction, and design platform that is able to:

- Run interpretative & predictive simulations of past or upcoming experiments w/ standardized workflows.
- Provide an informed representation of the device and scenario state by synthesizing available information from observations/diagnostics, simulators, and past experience (ExpDB and SimDB).
- Enable advanced scenario planning taking into account device lifetime aspects, component degradation, and operational limits.
- Predict aging of reactor components, such as degradation caused by plasma and neutron bombardment and fatigue induced by thermal cycling.

Digital Twin Environments

Harmonize machine and simulation

- Inputs (targets, waveforms)
- Outputs (diagnostics, synthetic diagnostics)
- Simulation and experimental databases
- Analysis pipelines
- Operating limits & conditions



MUSCLE3 - the Multiscale Coupling Library and Environment

netherlands eScience center

Computational Science Lab

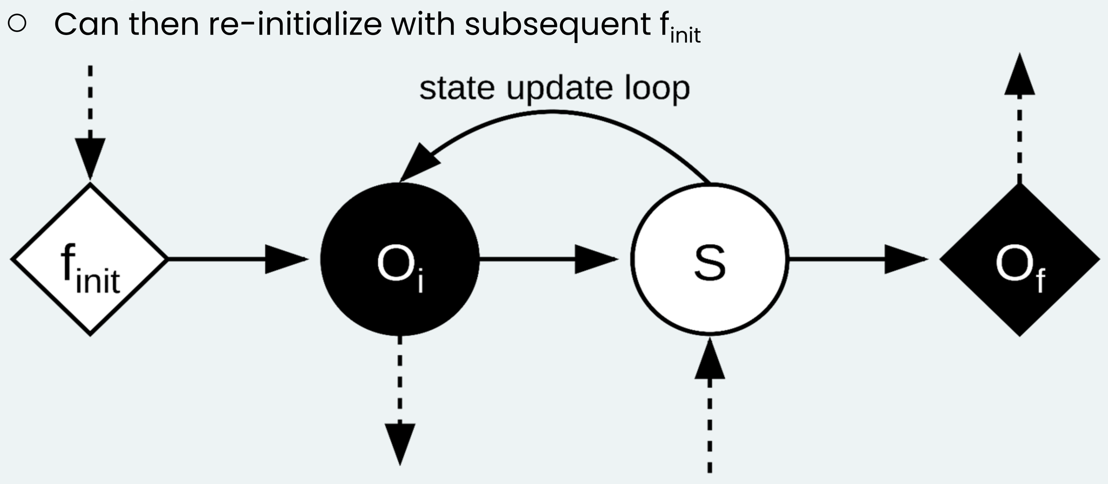
Create multiscale workflows by coupling independent simulation codes

- Allows coupling simulations codes written in different languages
- Configure multiscale models through a simple configuration file
- Communication between actors over network using messages (MPI-like)
- Allows for temporal and spatial scale separation
- Run locally or distributed
- Globally consistent local checkpointing (M. Sebregts (IC), L. Veen (NLeSC))

Actor Paradigm

- Each physical process & domain is an independent actor
  - Initialize based on inputs to their f_{init} port
  - Produce a sequence of outputs on their Intermediate Observation (O_i) port
  - Consume a sequence of inputs on their State update (S) port
  - Can produce a Final Observation (O_f)
  - Can then re-initialize with subsequent f_{init}

MUSCLE3 is publicly available on GitHub



Description and Methodology

Integration of components below into a digital twin environment is foreseen as a grant deliverable, and to demonstrate for one specific simulator:

- Harmonize simulation and experimental databases, targets and waveforms (SimDB ⟷ ExpDB).
- Support analysis pipelines for real and synthetic diagnostics (via MUSCLE3).
- Conceptualize long-term machine state databases, integrated measurements & engineering changes.
- Inherit live visualization schemes for IMAS data from simulators or analysis pipelines (MUSCLE3, ITER)
- Develop interfaces for running engin. codes (e.g FEM strain models) on SimDB, simulation or experiment
- Collaborate with VTT: training pipelines for ExpDB and SimDB (evaluate MLOps tools) & demonstrate applicability to continual learning in fusion simulations [A. Kit EPS2025].
- Develop a prototype actuator for integration of simulators with control system simulators.
- Develop prototype synthetic diagnostics.
- Develop a workflow for estimating Remaining Useful Life (RUL) of divertor tiles and instrument mirrors from experimental and simulation data over a campaign.

Integrated Modelling and Analysis Suite (IMAS)

- Universal Data model for fusion data: Data Dictionary (DD)
- Interface Data Structures (IDSs) Standardised entities for use between software components and storage
- Open-source: github.com/iterorganization

iter — china eu india japan korea russia usa

Persistent IMAS Actors

- Source - Load generic IMAS data from a database entry
- Sink - Store generic IMAS data to a database entry
- Accumulator - Accumulate time slices of IMAS data in a single IDS
- OLC - Validate IMAS data against the plant's Operating Limits & Conditions
- Visualization - Visualize IMAS data in real-time during a simulation

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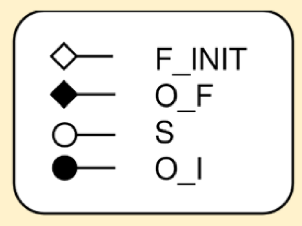
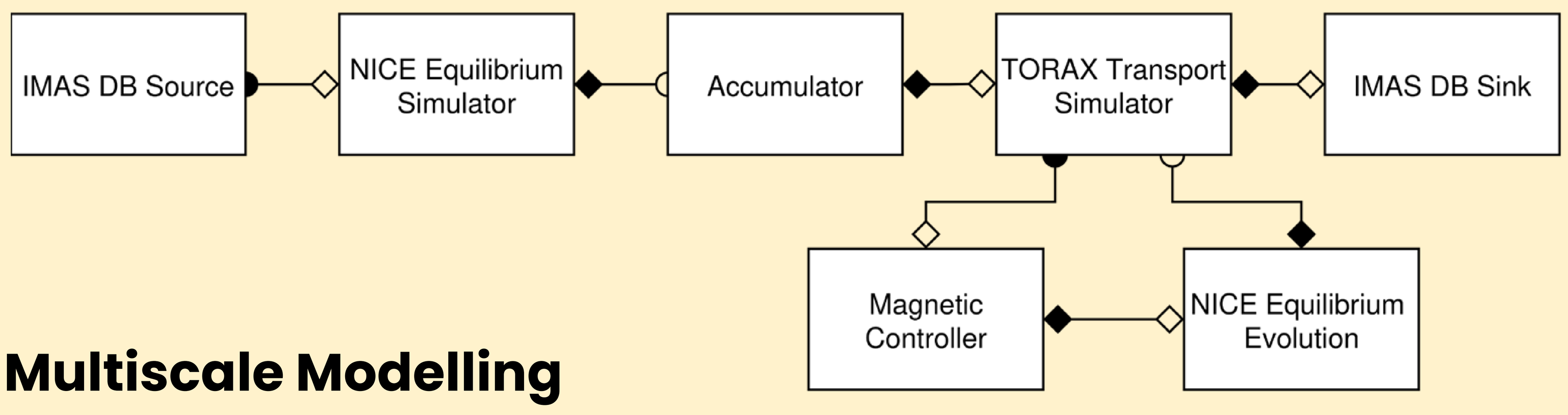
ITER Pulse Design Simulator

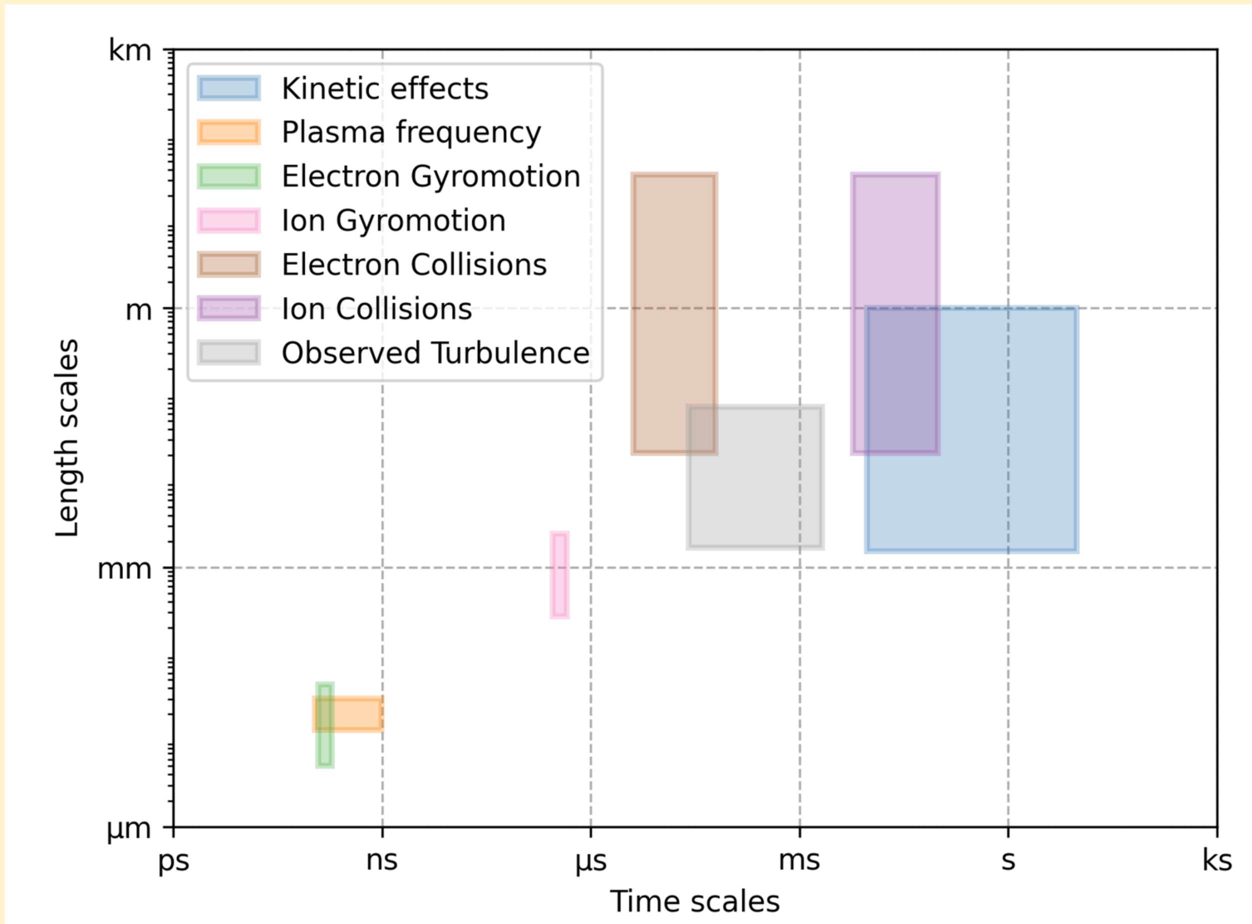
- Design optimal pulse schedules for ITER
- Forward tokamak simulation with the IMAS Persistent Actor Framework
  - Combine a free-boundary equilibrium code, transport code and Simulink controllers
  - Operational limit checking, debugging, interaction and more features





Multiscale Modelling

- Physics in a tokamak occur on many length and time scales
- Opportunity to make approximations
  - Skip over time for fast processes
  - Skip over space for local processes
- Adapt frequency of execution to physics but also to speed of codes



IMAS-MUSCLE3 is publicly available on GitHub

Towards Advanced Scenario Planning (ASP)

ASP requires synchronous coordination of multiple components in parallel, and the DTE framework provides a common platform for this.

By combining information available from individual components, risk optimized decisions about alternative scenario trajectories can be assessed. To demonstrate, the project is focused on two key example apps:

- Tracking the neutron budget and the impact on scenario planning.
- Monitoring and predicting mirror and/or PFC degradation and RUL.

Collaborations with simulator developers in Europe to facilitate broad compatibility encouraged. Interaction with EUROfusion DTE collaborators: CEA, IPP-CAS, EPFL, JINTRAC team, ETS-PAF team, ITER-PDS team.

Outcomes (2026, 2027)

Develop the necessary software infrastructure and to demonstrate:

- A software environment to link simulators to experiments.
- Describing planned plasma scenarios in format both control systems & simulators are compatible with.
- Link scenario schedule and waveforms through the analysis pipeline.
- Synthetic diagnostic implementation to mimic real diagnostics.
- The capability to conduct linking for databases of experimental observations and simulated scenarios.
- Software infrastructure for operating limits and consumption, such as neutron budget to estimate Remaining Useful Life (RUL) of components.
- Conceptualization of a long-term machine state database in addition to ExpDB.
- Compatible visualization tools between simulation and experiment.

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