DTE: TWIN4RTF A Machine-Agnostic Digital Twin Framework towards Fast Simulation and Real-Time Plasma Prediction and Control

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Introduction & Motivation

The European fusion programme is entering a transformative phase where the integration of advanced modelling, AI, and real-time control will determine the success of **ITER operations** and accelerate the design of **DEMO**.

Key challenges:

- **Limited diagnostics** in reactor-grade tokamaks with strongly self-regulated burning-plasma dynamics
- **Tightly coupled physics** — magnetic control, transport, impurities, MHD, core and edge
- **Need for data-driven & model-based observers and controllers** operating in real time

TWIN4RTF addresses the missing link: **a standardized ecosystem tailored to reduced fast plasma simulators and real-time control, leveraging multi-fidelity approaches, integrated data analysis, and AI/ML surrogate modelling.**

TWIN4RTF Architecture & end-to-end workflow

DATA SOURCES & DIAGNOSTICS
TCV • AUG • → MDSplus • IMAS • HDF5

DEFUSE / DEFUSE++ – Data Sandbox
FAIR data curation • ML data-loaders • Benchmarking • Plasma State & Event detection

GPU AI/ML Surrogates | IDA Inference engine
CXRS (Ti, rotation) • Bolometry • ECE • … • ONNX | Probabilistic profiles • UQ

RAPTOR/TORAX + MEQ + EKF – State Observer
Transport + equilibrium prediction • EKF assimilation • AI outputs as "measurements"

CONTROL-READY OUTPUTS & RT-inference
Real-time kinetic & equilibrium profiles with uncertainty → Feedback control • ITER extrapolation

Core Components

RAPTOR & TORAX

Physics-based reduced 1.5D transport codes. RAPTOR: real-time capable, current + heat + particle diffusion with Extended Kalman Filter (EKF) for dynamic state estimation. TORAX: JAX-based, differentiable, GPU-accelerated, open-source.

GPU AI/ML Surrogates

Deep Learning models with computationally trivial inference for real-time deployment. Ensembling provides uncertainty quantification. Physics-informed ML and transfer learning for cross-machine applicability. ONNX export for deployment.

Integrated Data Analysis (IDA)

Bayesian inference framework combining heterogeneous diagnostics with physics models. Principled uncertainty quantification and processing. IMAS-compatible for broad interoperability.

MUSCLE 3 Orchestration

MUltiScale Coupling Library and Environment engine for modular workflow orchestration. Ensures machine-agnostic interoperability via fully IMAS-compliant pipelines aligned with FAIR data principles.

DEFUSE++ Sandbox

Disruption & Event analysis framework for FUSion Experiments. Multi-machine data pipeline with standardized data loaders, signal processing, event detection, and ML-ready dataset generation with full traceability. ++ extension for dataset curation, benchmarking, ML library integration, rapid prototyping of surrogates, and off-normal event observer testing.

Objectives & Work Packages

WP1 O1 GPU AI/ML Pipelines (IPP + SPC)

Standardized, reusable GPU-accelerated pipelines for AI/ML surrogate modelling. Physics-informed ML, transfer learning, ensemble uncertainty. ONNX export and IMAS integration. Tested on AUG and TCV for generic interfaces.

WP2 O2 DEFUSE++ Data Infrastructure (SPC)

FAIR-compliant automated multi-machine data infrastructure and sandbox. Dataset curation, benchmarking, ML libraries, standardized data-loaders, and off-normal event observer testing. Primary training/testing environment.

WP3 O3 Surrogates & Synthetic Diagnostics (SPC + IPP)

GPU-accelerated surrogates for real-time kinetic, Ti and rotation profiles (TS, CXRS, etc.) on TCV and AUG. DL models trained on comprehensive datasets. Ensemble-based uncertainty. Validated against IDA (AUG) and TS & CXRS profiles (TCV).

WP4 O4 RAPTOR+MEQ with EKF (SPC + IPP)

Dynamic real-time estimation and prediction of kinetic profiles and equilibrium. Extended Kalman Filter assimilation of AI surrogate outputs as measurements. Consistent coupling with LIUQE equilibrium solver.

WP5 O5 Hybrid Multi-Fidelity Workflows (IPP + SPC)

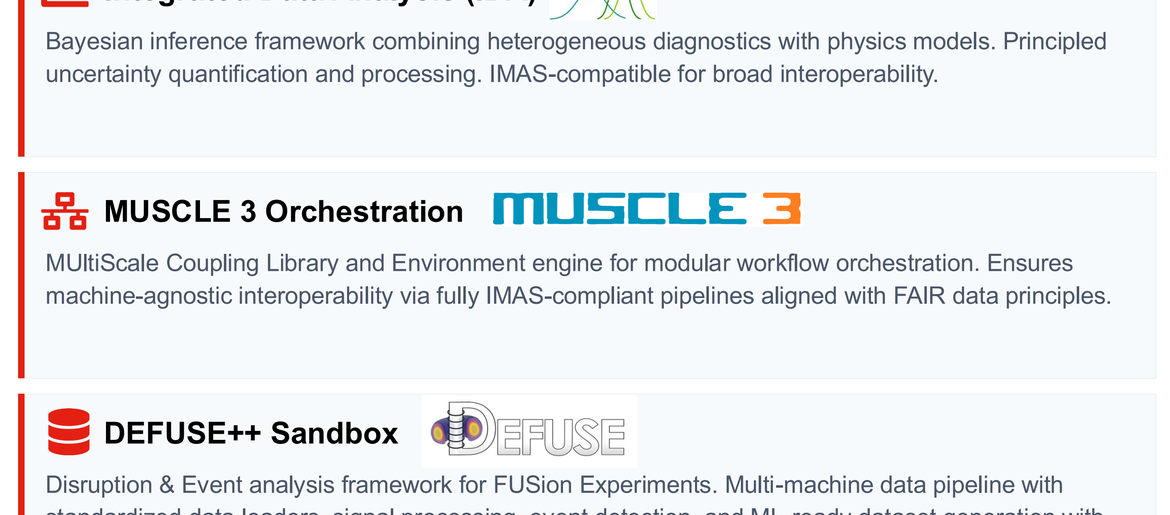
Combine RAPTOR+MEQ+EKF (fast physics) with GPU-ML surrogates (accelerated inference) and IDA (rigorous validation). Balance speed for real-time control with rigor for post-shot analysis.

WP6 O6 Integration & Deployment (SPC + IPP)

MUSCLE 3 service orchestration with strict IMAS compatibility. TORAX (JAX) for rapid differentiable solver prototyping. Deployable AI-assisted plasma proximity monitors for ITER/DEMO scenarios. Community extensibility.

Hybrid Multi-Fidelity Workflows & Orchestration

TWIN4RTF balances **speed** and **accuracy** towards fast **simulations** and **RT inference**



Deliverables & Key Differentiators

2026 **D1** – AI/ML frameworks: ONNX+IMAS **D2** – DEFUSE++ sandbox **D3** – CXRS surrogates (TCV/AUG)

2027 **D4** – RAPTOR+MEQ+EKF **D5** – Hybrid workflows **D6** – Integration + proximity monitors

- Fast, uncertainty-aware internal diagnostic estimates when full analysis is not feasible in real time
- Machine-agnostic interfaces (IMAS / ONNX) supporting extrapolation to ITER
- Composable Digital Twin services (MUSCLE 3) reusable by the EUROfusion community
- EKF fusion of data-driven "measurements" with first-principles dynamics; TORAX (JAX) for differentiable solvers

References

[1] F. Felici et al., Nucl. Fusion 58 (2018) 096006 • [2] M. Moret et al., Fusion Eng. Des. (2015) • [3] A. Pau et al., IAEA FEC (2023)
[4] J. Illerhaus et al., Fusion Eng. Des. 220 (2025) 115274 • [5] R. Fisher et al., arXiv:2411.09270v1 • [6] J. Citrin et al., arXiv:2406.06718v3

This work was supported in part by the Swiss National Science Foundation.
Validation: TCV (SPC-EPFL) and ASDEX Upgrade (IPP Garching).
Design intent: portability and extrapolation to ITER.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.