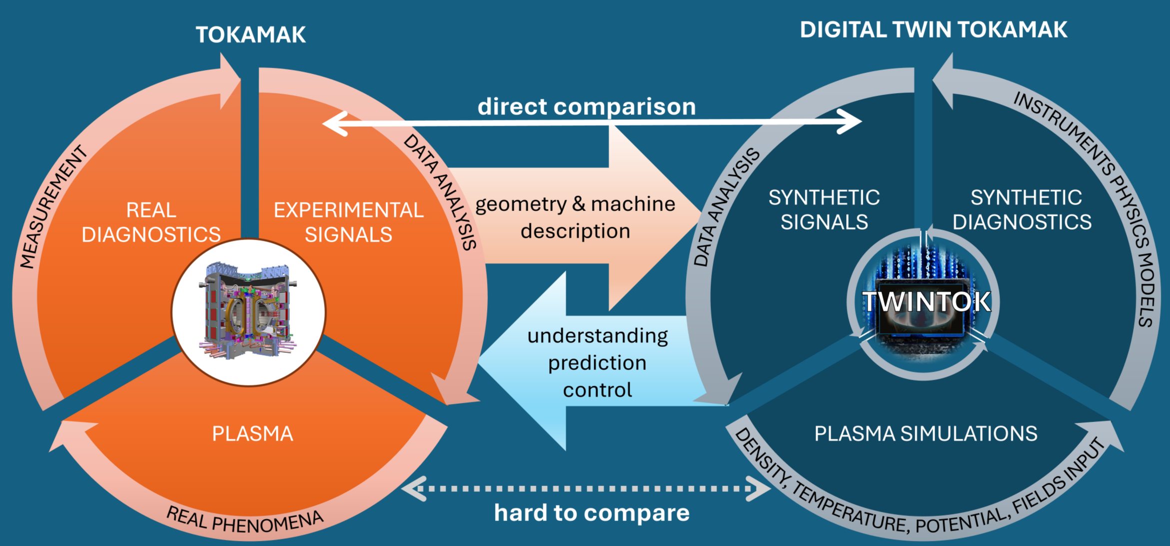
TWINTOK-IDA: Integrated Validation & Benchmarking Framework for the EUROfusion Digital Twin Environment

A. Glasser (M2P2) R. Fischer (IPP)
I. Kudashev (M2P2) J. Morales (CEA) F. Clairet (CEA)
Z. He (M2P2, IUSTI) S. Mazzi (CEA) G. Dif-Pradalier (CEA) O. Krutkin (EPFL)

Aix-Marseille University, CNRS, Centrale Méditerranée, M2P2, France
IRFM, CEA Cadarache, France
Max-Planck Institute for Plasma Physics, Garching, Germany
EPFL, Lausanne, Switzerland

The Challenge: Bridging Simulation & Reality

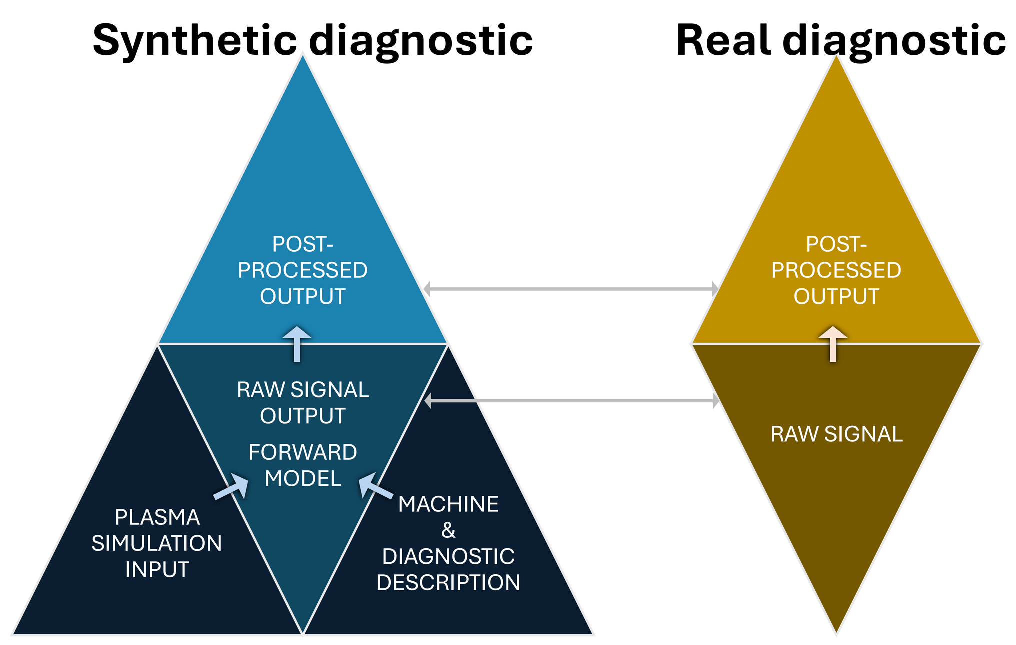
This project combines the TWINTOK digital twin framework with Integrated Data Analysis (IDA) tools to enable quantitative validation of plasma physics models. IDA provides robust Bayesian plasma profiles and equilibria from sparse, noisy diagnostics, while TWINTOK supplies synthetic diagnostics for benchmarking simulations against experiments. The integrated TWINTOK–IDA framework will automate synthetic diagnostics, generate validated plasma parameters with quantified uncertainties, and use them to assess physics and engineering models using AI/ML-assisted discrepancy detection and advanced visualization.



Gap: Digital Twins (DTs) are often sophisticated simulators but lack a robust framework for validating physics models against experimental data.
Problem: "Ground truth" in fusion is difficult to establish due to sparse, noisy experimental data and fragmented synthetic diagnostics.
Solution: Create a self-consistent validation loop. TWINTOK-IDA merges two synergistic efforts:

- TWINTOK (M2P2+CEA+EPFL): A digital twin framework for benchmarking simulations using synthetic diagnostics.
- IDA (IPP): Integrated Data Analysis tools using Bayesian inference for reliable plasma profiles.

Validation engine that transforms the Digital Twin Environment into self-correcting "living model" of the physical device



Forward models

- Interferometry: TIP model for ITER adapted to WEST geometry, strong match with experiment
- Visible & Spectroscopy: Raysect + Cherab simulate impurity emission lines and radiated power
- Bolometry: reproduces effects of plasma composition and wall reflections on measured signals
- Reflectometry (FeDoT): 2D full-wave simulations of microwave propagation in turbulent plasmas
- Camera imaging: ongoing development using advanced ray-tracing differentiable tools
- ECE: developing and benchmarking ECE code.

WP1: DTE Integration and Framework Expansion

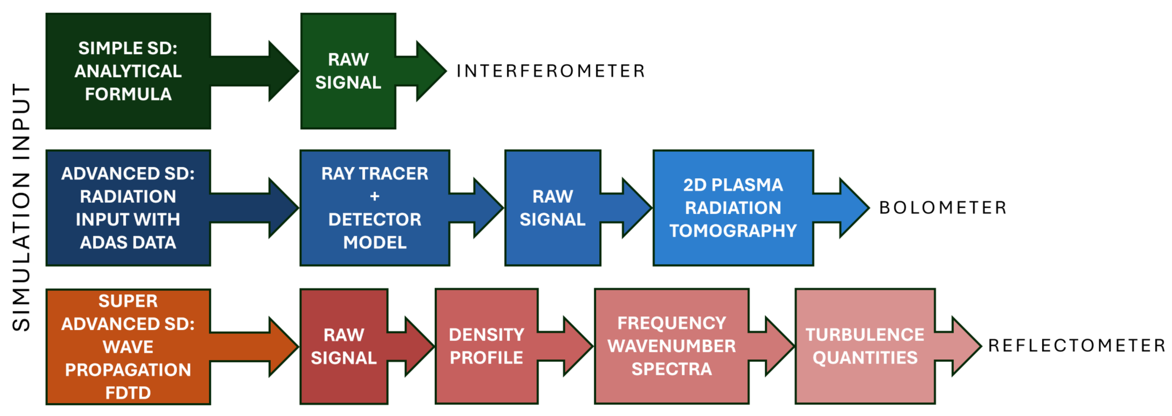
Architect the foundational infrastructure of the validation service, creating a modular platform that translates simulation outputs into synthetic signals for consistent, "apples-to-apples" comparisons.

T1.1 Data Aggregation and Standardization

Simulation outputs from key EUROfusion codes (SOLEDGE-HDG, GYSELA, HFPS workflow) and corresponding experimental data (reflectometry, interferometry, bolometry, camera imaging, ECE, spectroscopy, Thomson scattering) from multiple devices - WEST, ASDEX Upgrade and TCV.

T1.2 Synthetic Diagnostics Automation

Building on TWINTOK, we will finalize an automated, modular workflow and expand it with new diagnostics, including visible range camera imaging for divertor heat loads and magnetic configuration detection, ECE for temperature profiles, CECE and ECEI for temperature fluctuations.

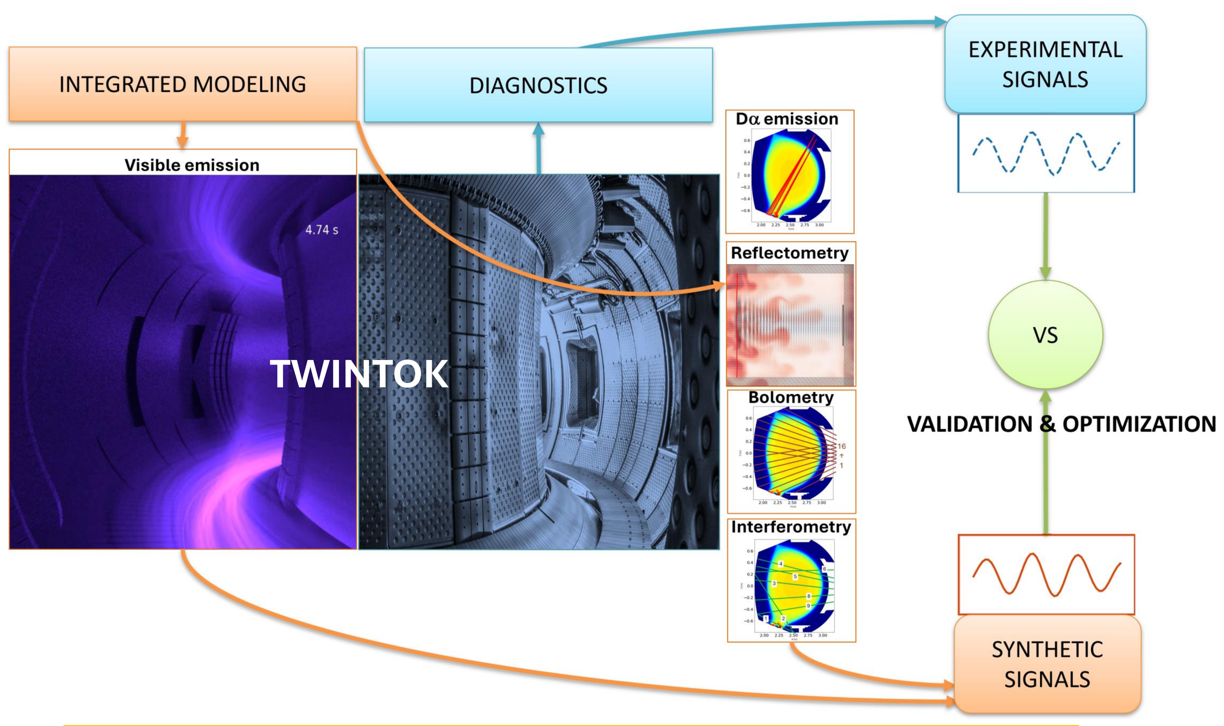


WP2: IDA and Equilibrium Reconstruction

This WP, led by **R. Fischer**, forms the core analysis engine of the framework based on Bayesian probability theory, combining measurements, forward models, and physical constraints. SDs from WP1 act as the forward models, linking plasma parameters to measurable experimental quantities. The framework will use both reduced-fidelity models for fast routine estimation and high-fidelity models for benchmarking and validation studies.

T2.1 IDA for Profiles The Python IDA package will be developed to full maturity. The use of robust likelihoods will mitigate outliers, producing reliable electron density and temperature profiles with full uncertainty quantification.

T2.2 IDE for Equilibrium The Integrated Data Equilibrium (IDE) code will be developed and made IMAS compatible. This free-boundary Grad-Shafranov solver, coupled with the current diffusion equation, will provide consistent equilibrium reconstruction. The IDE results will be validated against existing codes (e.g., NICE) at WEST.



Neverov PPCF 2020
Carr 44th EPS 2017
Medvedeva 15th IRW 2022
Fischer FST 2010
Kudashev ICFDT6 2022
Scotto d'Abusco NF 2022
Di Genova NF 2021
Meister SOFE 2023
Kudashev AS 2022

WP3: AI/ML-Enhanced Predictive Modelling and Analysis

Move beyond qualitative validation toward statistically rigorous, quantitative assessment.

T3.1 Quantitative Scoring System Develop multi-metric scoring - MAE, RMSE, Pearson correlation, spectral overlap, and SSIM for 2D data - weighted to prioritize agreement in critical plasma regions.

T3.2 AI/ML for Discrepancy Detection Quantify experimental uncertainties (noise, calibration) as a baseline. Apply surrogate AI/ML models to classify discrepancies in near real-time, distinguishing measurement artifacts from missing physics.

WP4: Advanced Visualization and User Interface

Ensure usability and broad adoption across the EUROfusion community.

T4.1 GUI Development Create a user-friendly Python interface to visualize synthetic and experimental signals side-by-side, automate comparisons, and generate reports.

T4.2 User-Oriented Deployment Design with a user-centric philosophy, supporting both modelers and experimentalists. IMAS compatibility enables integration with community tools like IDA. Full documentation, tutorials, and best-practice guides will promote sustained use within EUROfusion DTE.

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