

PathSim: An Open-Source Python Framework for Digital Twin Applications in Fusion Fuel-Cycle Modeling

Tuesday 9 December 2025 10:10 (25 minutes)

We present PathSim, an open-source Python framework for modular, event-driven system modeling with applications to digital twin development in fusion energy research. PathSim enables researchers to construct complex, time-dependent models through a block-based architecture that supports dynamic system topology, hierarchical modeling, and seamless integration with existing scientific computing tools.

The framework addresses key challenges in fusion fuel-cycle modeling by providing: (1) a modular component library for tritium breeding, extraction, processing, and storage systems; (2) flexible event detection and handling for operational mode analysis; (3) efficient coupling of multi-physics simulations through Python APIs; and (4) parallel execution capabilities for Monte Carlo analysis and parameter optimization.

PathSim's capabilities have been validated against experimental data from MIT PSFC's BABY tritium release experiment. A 30-component tritium bubbler model achieves simulation times of ~1.5 seconds for complete transient analysis, enabling rapid iteration and uncertainty quantification workflows.

PathSim's architecture facilitates co-simulation by wrapping external tools (FEniCS, FESTIM, and other Python-based solvers) as reusable blocks within unified system models. This approach enables researchers to combine domain-specific expertise across disciplines without monolithic software dependencies.

We are developing pathsim-fusion, an open-source toolbox of physics-informed components for the fusion community, with ongoing collaborations to expand capabilities in RF systems and plasma control.

This work demonstrates how modern software engineering practices and open-source collaboration can accelerate fusion research through flexible, accessible simulation tools that bridge experimental data, multi-physics modeling, and operational planning.

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Session Classification: Simulation and Data Integration

Track Classification: Simulation and Modelling Techniques