Pulse Design & Digital Twin Capabilities of the FUSE Integrated-Modeling Framework

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The FUsion Synthesis Engine, FUSE [1, 2], is an open-source, flexible framework for integrated whole-facility modeling of fusion experiments and pilot plants (FPPs). FUSE integrates first-principle codes, reduced models, and machine learning into a unified framework, enabling comprehensive simulations that go beyond traditional zero-dimensional systems studies. This framework accelerates the design process by enabling self-consistent solutions across physics, engineering, and control systems, minimizing the need for iterative expert evaluations.

Built upon the principles of model modularity and centralized data exchange, FUSE is composed of a collection of independent "actors" each of which reads inputs and writes output to a central, hierarchical data structure based on the IMAS [3] ontology. These design choices facilitate the addition of new actors and the creation of diverse workflows. FUSE actors span from the tokamak plasma core all the way to the site boundary, with physics (including equilibrium, transport, heating & current drive, stability, and scrape-off layer), engineering (including 1D, 2D, & 3D builds, structural mechanics, neutronics, and coil optimization), balance of plant, costing, and risk.

FUSE was originally created for tokamak FPP machine design, and has broad, robust, and novel capabilities in this area. Leveraging modern software practices and parallel computing, FUSE is used to generate large databases of individual model results and complete FPP designs which are used to train neural networks efficiently (e.g., for AI-accelerated transport and equilibrium calculations). Furthermore, genetic algorithms are used to perform constrained, multi-objective optimization of FPPs. Tens of thousands of fully integrated FUSE runs can be performed in just a few hours on a small cluster. This capability is used to perform detailed trade studies (e.g., a comparison of positive versus negative triangularity FPP designs).

Building upon the same actors and workflows, FUSE has been extended to model the time evolution of both the plasma and plant, supporting simulations in both feedforward and feedback modes with controllers. Self-consistent, dynamic modeling of complete DIII-D discharges is being used for both experimental analysis of past shots and predict-first design in experimental planning. Utilizing neural-network acceleration, full-shot simulations can run in a matter of tens of seconds to a few minutes, promising to be a useful between-shot, control-room resource as well. Direct coupling to the DIII-D plasma control system is underway.

Furthermore, a modern, Grad-Hogan-like solver is being developed in FUSE, which will couple first-principle equilibrium evolution, high-fidelity transport models, and realistic plasma control. A novel algorithm for coupling coil-current evolution to internal plasma current dynamics has been developed. These coupled coil/plasma current simulations can be iterated with equilibrium calculations. This can be run as a standalone workflow for VDE modeling or with magnetic control via co-simulation with the TokSys integrated plasma control suite of tools. We will present the details of the underlying models, demonstrate the existing couplings, and discuss ongoing development. This will be a critical pulse design tool for fusion experiments and FPPs, providing a "flight simulator" that can ensure the accessibility and controllability of high-performance scenarios.

In total, FUSE is prepared to provide digital-twin tools for experimental analysis, predict-first pulse design, and FPP optimization, making it a valuable resource for bringing fusion energy to the grid. Developed in the Julia programming language, FUSE is fully open-source under the Apache 2.0 license, promoting transparency and collaboration within the fusion research community. Public FUSE installations have been deployed to NERSC's high-performance computing systems and other institutional clusters. Opportunities to collaborate for both users and developers will be discussed.

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References

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