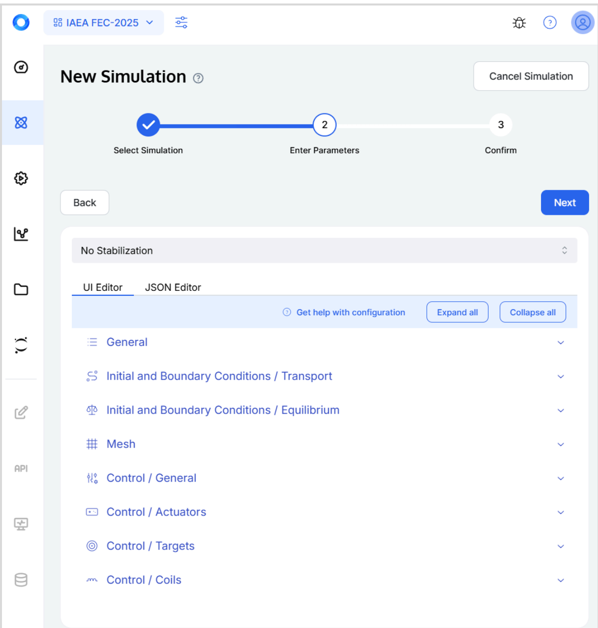
Fusion Twin Platform: An Innovative Tool for Fusion Research and Education

A. Zhurba[1], M.R. Nurgaliev[1], G.F. Subbotin[1], I. Kozlov[1], A. Asaturov[1],
D. Almukhametov[1], E.N. Khairutdinov[1], and D.M. Orlov[2]

[1] *Next Step Fusion, Luxembourg, Mondorf-les-Bains, 56A Avenue François Clément, L-5612*
[2] *Center for Energy Research, University of California, San Diego. San Diego, CA 92093*
e-mail: akz@nextfusion.org

The Fusion Twin Platform (FTP), available at https://fusiontwin.io, is a free web-based tool designed to democratize access to advanced tokamak simulations, enable collaborative research in fusion science, and enhance plasma physics and fusion engineering education. FTP allows researchers, educators, and students to use pre-built digital replicas of tokamaks, enabling precise simulations, exploration of machine learning models, visualization of plasma dynamics, and flexible data management. By leveraging NSFsim [1], a free boundary equilibrium and transport solver, FTP supports fast customizable simulations and discharge scenario development.



NSFsim is a free-boundary Grad–Shafranov and 1D transport solver for advanced tokamak simulations, plasma scenario development, device optimization, and machine learning applications. It simulates plasma evolution coupled with coil currents, induced currents in passive structures, and synthetic signals from magnetic diagnostics. NSFsim enables full scenario development, from breakdown to shutdown, predicting plasma parameter evolution, magnetic control requirements, and stability margins. It includes inverse solvers for fitting coil currents to desired plasma shapes and kinetic profiles, and linear response models for vertical stability and density control. Each simulation relies on a digital replica, built from the magnetic system's geometry and electrical properties, including poloidal coils, vacuum vessel, and limiter, all represented on customizable meshes.

NSFsim is extensively used for both current tokamak operations and future tokamak design studies [2].

FTP is a cornerstone of Next Step Fusion's mission to remove barriers to entry in fusion research, education, and collaboration. The platform supports diverse tokamak configurations, providing access to essential datasets and machine geometry while ensuring user privacy and proprietary data security. Transformative for both research and education, FTP provides tokamak simulations by offering a suite of powerful tools, including machine learning model integration, advanced visualization capabilities, and collaborative functionalities. Fully web-based, FTP requires no additional software or hardware to run, making it accessible to users worldwide. Researchers and educators can leverage these resources to conduct fusion experiments, optimize control strategies, and engage students with hands-on, interactive learning experiences, all within a secure and accessible digital environment.

In preparation for future digital twins [3], the Next Step Fusion Toolkit is presented, built around NSFsim and to be expanded with TGLF, TRAVIS, and UEDGE for advanced transport, RF heating, current drive, and edge plasma simulations.

Another piece under development is Plasma RL, the reinforcement learning-based plasma control toolkit for real-time control of plasma shape and position [4] by processing raw magnetic diagnostics data and outputting commands to adjust currents in the tokamak's magnetic coils. Presently, this is machine- and pulse-agnostic, and ongoing work aims to extend the capability to cover a wider range of scenarios and operational regimes.

One more component is Plasma Mind – a toolkit for training device-specific surrogate ML models based on historical datasets and generated synthetic data.

A new modern Plasma Control System is being developed for tokamaks, stellarators, and future power plants. The system is built on the plasma state concept – a set of key parameters that define plasma behavior for real-time control. It combines conventional and ML-based control methods within a simple yet flexible architecture with a clear separation of control layers to ensure reliability and efficiency.

All of these tools will be incorporated into FTP as components available for demonstration and full-scale real-time use. Meanwhile, the following key features available on the FTP:

- **Fast and Precise Simulations:** FTP offers tools for customizing magnetic equilibrium simulations, developing and optimizing new discharge scenarios, and evaluating plasma stability across various operational regimes with exceptional accuracy for tokamaks such as DIII-D, ISTTOK, SMART, NSF NTT, and others. These capabilities drive rapid advancements in tokamak design and operations. An example of an interface for starting a simulation is shown in Figure 1.

- **Customizable Visualization and Analysis:** FTP provides a fully integrated environment where users can plot, visualize, and analyze data, whether uploaded or generated on the platform. Advanced AI-based tools facilitate intuitive, human-like interactions for data interpretation and decision-making, streamlining research workflows. Examples of plots are given in Figure 2.
- **Comprehensive Data Management:** FTP enables seamless access to fusion datasets, allowing users to upload their data for analysis or download platform-generated outputs. This flexibility ensures efficient data management and smooth integration into broader research workflows.

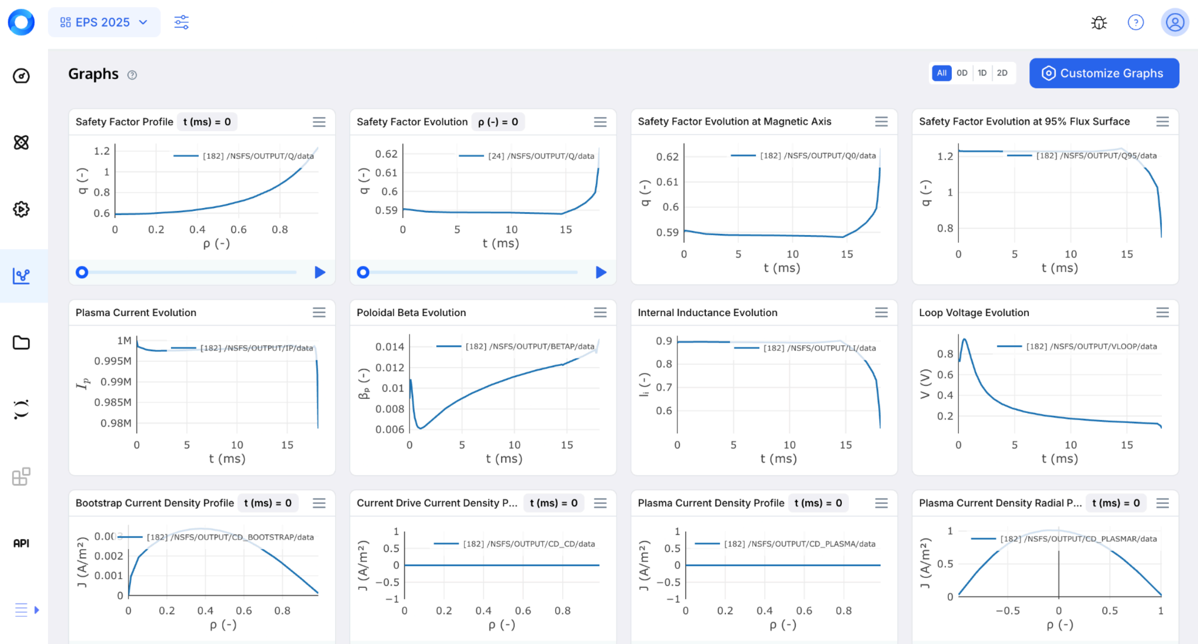


Fig. 2. Visualization of a NSF NTT discharge simulation performed using NSFsim, displayed on the FTP Graph tool

- **Collaborative Workspace Tools:** FTP includes robust collaborative features, enabling users to share workspace data with team members, create public links for wide sharing or publication, and maintain a shared context among collaborators. These tools enhance teamwork and support open science initiatives.
- **Integrated JupyterHub Environment:** FTP offers a built-in JupyterHub environment with Python notebooks and advanced extensions, such as an HDF5 viewer. This integration empowers users to perform detailed data analysis, automate

workflows, and interactively explore simulation results in a familiar coding environment.

- **ML Demonstration and Integration:** FTP serves as a showcase and integration point for machine learning tools developed by Next Step Fusion, such as a plasma boundary reconstruction ML model trained on the DIII-D experimental dataset. It also provides access to training reinforcement learning (RL) agents for plasma shape and position control, enabling users to explore cutting-edge AI-driven solutions for tokamak operations.

Besides being a powerful tool for fusion research, the Fusion Twin Platform (FTP) also has the potential to become an exceptional educational tool. It provides educators, students, and professionals transitioning from other fields to fusion with access to realistic tokamak simulations and interactive tools that bring fusion concepts to life. FTP enables hands-on learning experiences by allowing users to explore plasma dynamics, test machine learning models, and simulate real-world discharge scenarios within a secure, user-friendly environment. Furthermore, its collaborative features, such as shared workspaces and public link generation, foster teamwork among students and professionals while encouraging interaction between institutions. By integrating cutting-edge technology with practical educational applications, FTP bridges the gap between theoretical knowledge and practical understanding, inspiring both the next generation of fusion scientists and engineers and those seeking to expand their expertise into this exciting field.

References

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