

CONFERENCE PRE-PRINT

FUSION TWIN PLATFORM*An Innovative Tool for Fusion Research and Education*

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Email: akz@nextfusion.org**Abstract**

The paper presents the Fusion Twin Platform (FTP), a free web-based tool designed to expand access to advanced tokamak simulations, promote collaborative research in fusion science, and enhance plasma physics education. FTP integrates pre-built digital replicas of tokamaks with a fast free-boundary equilibrium and transport solver, enabling customizable simulations, scenario development, and exploration of plasma dynamics. The platform supports full discharge evolution, including plasma control requirements, stability margins, and inverse solvers for shaping and profile fitting. It provides users with interactive visualization, integrated data management, and machine learning model integration, while ensuring data security and user privacy. FTP incorporates collaborative workspace tools, allowing users to share data, maintain context, and support open science initiatives. An embedded JupyterHub environment facilitates detailed analysis, workflow automation, and integration with external research pipelines. The platform is being expanded with additional tokamak digital replicas, modules for transport, radiofrequency heating, current drive, edge plasma physics, and other relevant tools, establishing a foundation for future digital twin applications. FTP also serves as an educational tool, providing students, educators, and professionals from other fields with access to realistic simulations, interactive experiments, and collaborative learning environments. By bridging advanced research capabilities with hands-on educational experiences, FTP lowers barriers to entry, accelerates innovation in tokamak operations and design, and inspires the next generation of fusion scientists and engineers.

1. INTRODUCTION

The quest for controlled thermonuclear fusion has driven decades of research into plasma physics and advanced computational modeling. High-fidelity simulations play a pivotal role, enabling researchers to predict plasma behavior, optimize operational scenarios, and guide experimental campaigns. However, the complexity of existing codes, high computational costs, and limited accessibility have created barriers to broader participation in fusion research and education. Democratizing access to advanced simulation tools is therefore essential for accelerating innovation and training the next generation of fusion scientists and engineers.

The Fusion Twin Platform (FTP), recently launched 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 NSFsims [1], a free boundary equilibrium and transport solver, FTP supports fast customizable simulations and discharge scenario development.

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.

2. FUSION TWIN PLATFORM FEATURES

Next Step Fusion S.a.r.l., the FTP developer, is a Luxembourg-based supply chain company supporting tokamak developers in the design, simulation, optimization, control, and operation of their devices through integrated modeling and AI/ML-enabled solutions. Ongoing efforts of Next Step Fusion include the development of NSFsims, the application of reinforcement learning to various tasks in real-time plasma control [2], the development of both conventional and AI/ML-based solutions for diagnostics and control, and support for new tokamak companies through feasibility studies and device design.

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.

Key Features of 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, HBT-EP, CENTAUR, 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 Fig. 1.

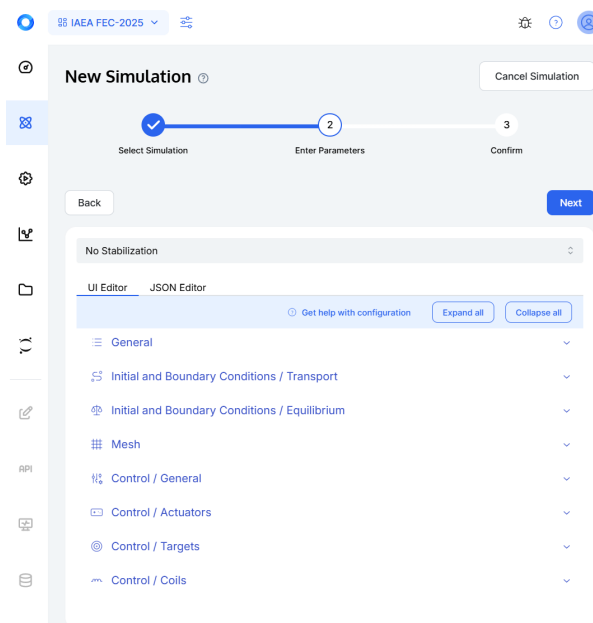


Fig. 1. Flexible configuration of new tokamak simulation using the FTP.

- **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. The system includes more than 100 pre-defined graph types and allows users to create custom visualizations tailored to their needs. Graph rendering is optimized for speed, ensuring smooth performance even with large scientific datasets. Fusion-specific elements are also supported, such as overlaying tokamak geometry on top of magnetic flux surfaces, enabling users to interpret plasma behavior in its proper machine context. Examples of plots are given in Fig. 2.

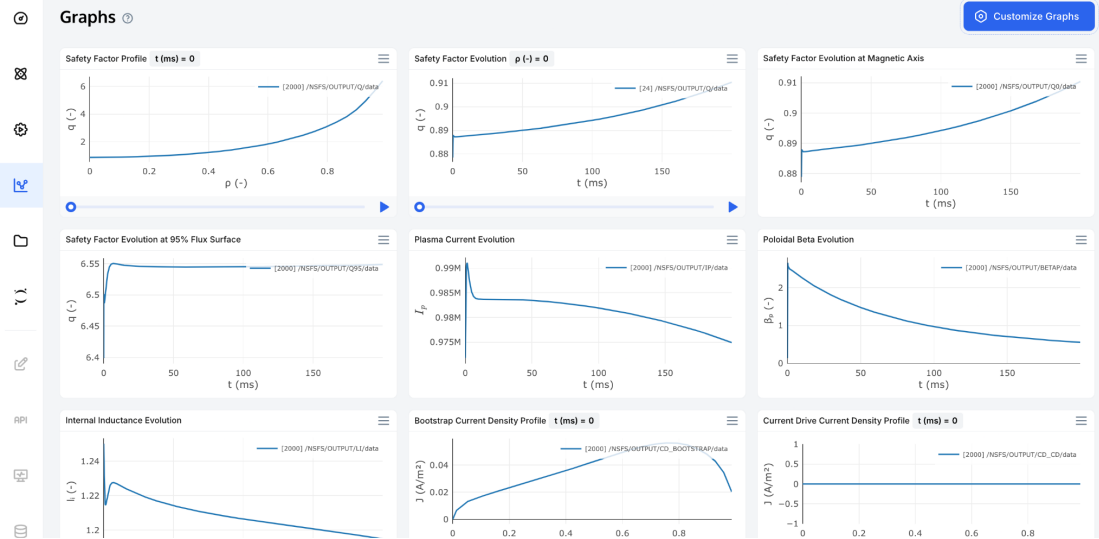


Fig. 2. Visualization of a DIII-D discharge simulation performed using NSFSim, displayed on the FTP Graph tool.

- **Comprehensive Data Management:** FTP enables seamless access to private 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.
- **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.
- **Programmatic Use via Public API:** FTP provides a public API [3] that enables programmatic access to its simulation, data management, and visualization modules. This allows researchers to integrate FTP directly into external workflows, automate large-scale studies, and connect the platform with custom research pipelines or educational tools.
- **Digital Replica Builder:** FTP includes a powerful tool that allows users to create, configure, and share virtual models of tokamaks. This tool supports importing machine geometries, defining magnetic coil systems, and specifying diagnostic layouts, enabling precise replication of both existing devices and conceptual designs. Users can customize geometry elements through an intuitive web interface or upload CAD-derived data for detailed configurations. Additionally, the Digital Replica Builder is available as a free and open source standalone tool [4].
- **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 [5].

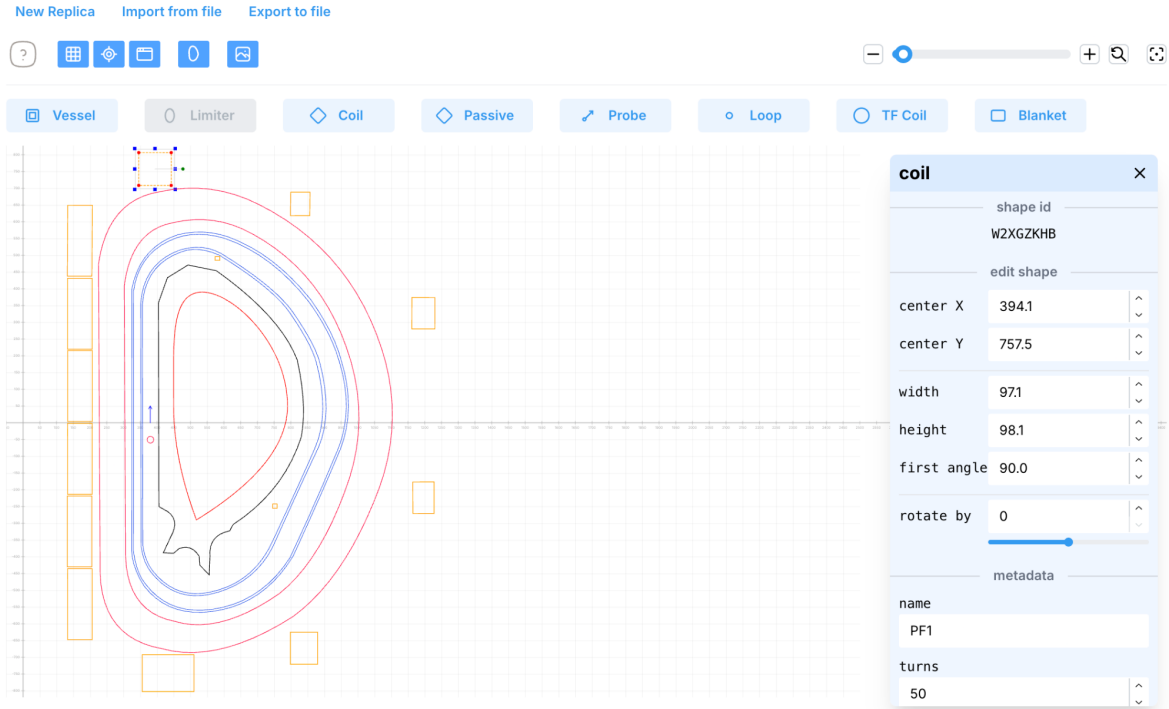


Fig. 3. Digital Replica Builder capabilities demonstration.

3. VDE SIMULATIONS EXAMPLE

One of the possible simulations that can be performed using NSFsim through the FusionTwin platform is the vertical displacement event (VDE) simulation. As an example, we present modeling carried out for the Negative Triangularity Tokamak (NTT) [6]. These simulations were conducted as part of the conceptual design of the NTT.

NT configurations are known to be prone to MHD instabilities. NSFsim is capable of modeling ideal MHD, including vertical displacement events (VDEs). The simulation is configured in feedforward mode, where the user provides general settings, initial and boundary conditions, as well as coil currents for the desired equilibrium. The simulation then runs for a sufficient number of steps until large plasma displacements develop, driven by numerical errors during the dynamic evolution. In this sense, the VDE is artificially induced.

An overview of plasma parameters during a VDE in the NTT is shown in Fig. 4. Designed plasma equilibrium is highly unstable with large instability increments $\gamma=300\text{-}500\text{ s}^{-1}$. The example demonstrates that VDE simulations capture key disruption features, such as the plasma current spike during the thermal quench and the generation of eddy currents induced by rapid plasma motion. These VDE simulations serve as a proxy for more detailed disruption studies, which are performed in a dedicated NSFsim module.

More detailed equilibrium evolution can be observed in the *Magnetic Equilibrium* plot. The maximized window is presented in Fig. 5. The user can observe poloidal magnetic flux contours and their evolution. Geometry of the machine is also plotted here, including active coils, passive stabilizing plates, and vacuum vessel grid elements.

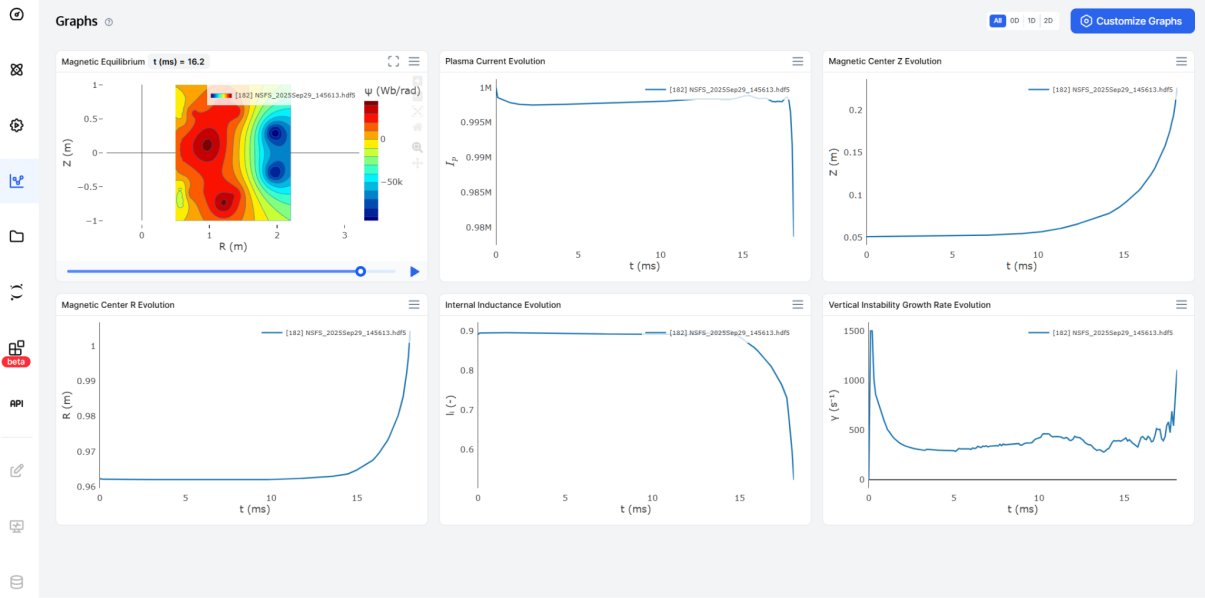


Fig. 4. Overview of the evolution of plasma parameters for VDE simulation.

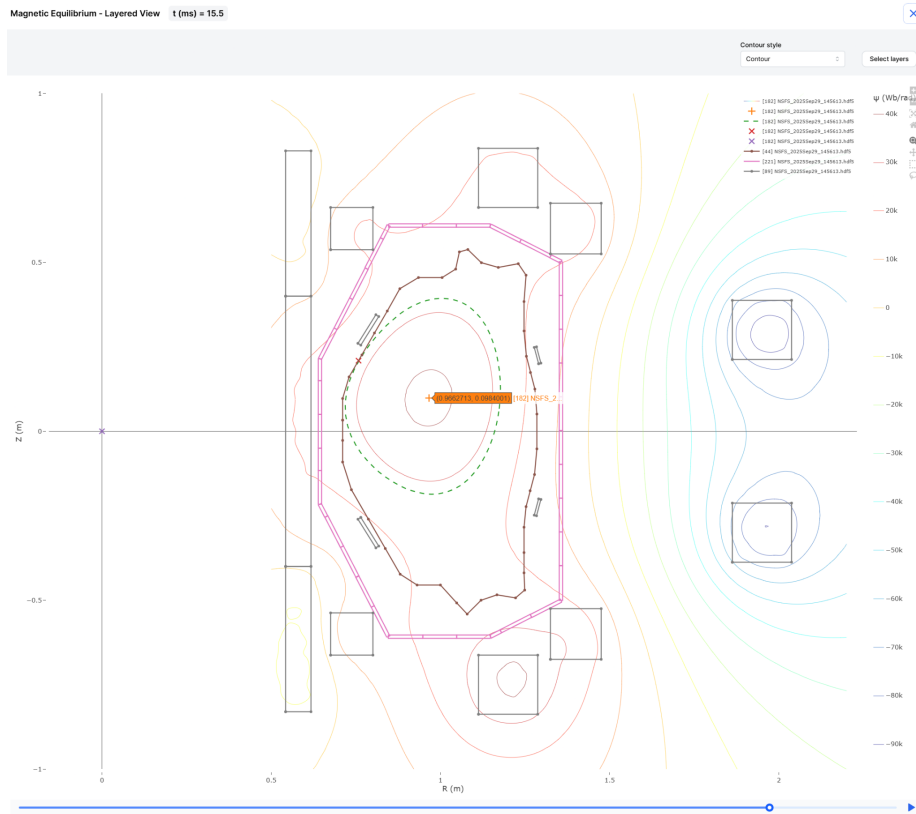


Fig. 5. Detailed view of equilibrium flux map evolution on poloidal cross-section.

To avoid uncontrolled VDE development during feedforward simulations can be run with vertical stabilization options:

- 1) Virtual vertical stabilization – a regime in which a uniform horizontal magnetic field is applied using a linear-response controller.
- 2) Active position control – a regime in which the user chooses two or four active coils and defines limits for control actions so the linear-response controller adjusts coil currents in chosen coils.

These regimes can also be used to estimate plasma stability by comparing the control variable with the poloidal magnetic field (option 1) or with feedforward coil currents (option 2). Small control actions should indicate good plasma stability.

4. FURTHER DEVELOPMENT

FTP development will continue to enhance its tokamak design, simulation, visualization, and collaboration capabilities. The following major areas of development and improvement are considered:

- **Enhance FTP simulations** with the NSFsim inverse solver and automatic discharge scenario-building modules; integrate the ray-tracing code TRAVIS [7] for more precise ECRH modeling, ASCOT5 [8] for modeling neutral beam injection in tokamak plasmas, and a surrogate model of MISHKA [9], enabling stability limit calculations in the pedestal region.
- **Further improve** the Digital Replica Builder and implement full cloud support for its collaborative use in tokamak digital replica development and testing, targeting a complete end-to-end usage scenario starting from drawing the tokamak geometry and finishing with fully functional direct and inverse solvers for the device.
- **Rework and significantly improve** tokamak experimental and simulated data representation on the platform to ensure usability and consistency between different modules, support a single representation of a tokamak digital replica throughout the platform, and enable additional data formats.

All of these developments will soon allow Next Step Fusion to provide the fusion community and its customers with an integrated modeling framework and toolset for end-to-end development and testing of tokamak digital replicas. This includes simulations, scenario development, experiment design and preparation, and experimental data analysis, ultimately enabling comprehensive tokamak design, optimization, and control across a wide range of operational scenarios.

A key feature of the Fusion Twin Platform is that it is fully web-based and does not require MATLAB/Simulink or other specialized software. This makes FTP both cost-effective and highly accessible to researchers, educators, and private companies worldwide. The platform has been developed using best practices for modern web applications, ensuring reliability, scalability, and long-term maintainability. By design, FTP guarantees data security and privacy, enabling Next Step Fusion to deliver projects for private fusion companies that prioritize intellectual property protection. This combination of accessibility, usability, and security positions FTP as a unique tool for advancing both collaborative science and industry-driven innovation in fusion.

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