

NSFsim code for machine design and scenario development

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1. Introduction

NSFsim is a free-boundary Grad-Shafranov and 1D transport solver, inheriting numerical approaches developed for the DINA code [1]. Recent upgrades have expanded its application capabilities while improving performance and flexibility. Currently, NSFsim serves as a powerful tool for tokamak performance prediction, scenario development, machine learning applications, and device optimization. It is extensively used for scenario development on existing tokamaks and future projects, enabling the estimation of plasma parameter evolution, coil current dynamics, and induced currents in passive structures.

2. NSFsim as an integrated modeling framework

Figure 1 displays a schematic diagram illustrating the integration of various codes and modules around NSFsim. The NSFsim Fortran Core is a solver for transport and equilibrium and is paired with a Plant Model that includes machine-specific features. Together, they form the NSFsim Toolkit – a Python library that provides an API and tools for working with simulator inputs, outputs, and tokamak configurations. The NSFsim Toolkit is also a central place for data management between external codes. For example, simulations of heating and current drive require input data on equilibrium and plasma parameters. In return, these external codes provide current, heat, or particle sources (in the case of neutral beam injection) that are essential for accurate prediction of plasma evolution. Currently, only the electron cyclotron resonance heating and current drive code TRAVIS [2] is included in the framework.

Accurate prediction of plasma performance requires a thorough understanding of transport processes. Significant progress in this area, along with the development of fast quasi-linear gyrokinetic turbulence codes such as TGLF [3] and QuaLiKiz [4], enables the integration of these codes into a closed-loop simulation environment. At the current stage, NSFsim includes an interface for the TGLF code. Surrogate models for turbulent transport predictions, which are gaining popularity, will also be supported in NSFsim as their high computational speed is essential for control-oriented applications.

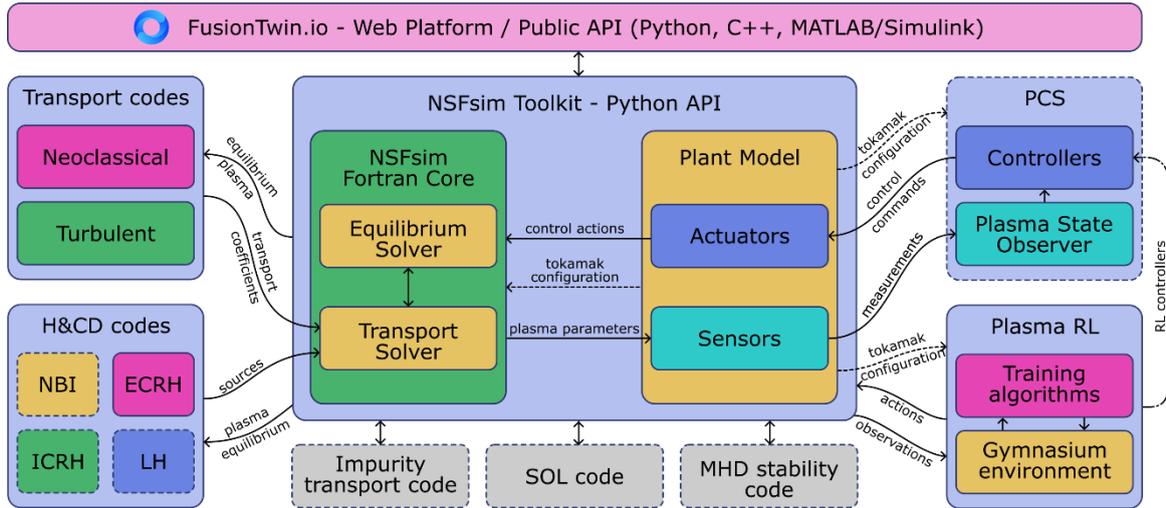


Fig. 1. NSFsim serves as the core of the integrated modeling framework. Solid arrows represent data flow during the coupled runtime execution; dashed arrows indicate loading configuration or setups; dashed-dotted lines show data offline transfer between modules. Dashed-line blocks denote simulations planned for future integration.

Regarding the control, the environment offers interfaces and tools to perform neural network training using reinforcement learning (RL). Currently, RL approach is developed and tested for magnetic control [5] and electron temperature control tasks. Sensors and the Plasma State Observer are essentially defined by the control task and the required level of detail in representing the relevant plasma parameters. For example, electron temperature control in a simulation environment can be performed by directly accessing the radial temperature profile, which may be sufficient for scenario prediction. However, for experimental applications, this would require the introduction of synthetic diagnostics and reconstruction algorithms to accurately replicate the real-time control loop and enable the development of advanced controllers.

More advanced simulation codes for impurity and scrape-off layer (SOL) transport analysis, as well as magnetohydrodynamic (MHD) stability simulations, are essential for machine design and scenario development. While these codes provide deep insights into plasma behavior, they are computationally expensive and therefore unsuitable for use in automated optimization loops or control-specific tasks. To address this limitation, we are considering the development of fast surrogate models and their integration into the overall modeling framework.

The free public access to NSFsim is provided through the web platform FusionTwin.io [6]. Users can configure simulations via a graphical user interface and analyze results using predefined plotting tools. The Platform offers a public API for Python, C++, and MATLAB/Simulink for more flexible configurations and supports user-defined simulation

setups, such as developing controllers or replays of existing experimental shots.

3. Examples

3.1. Vertical stability assessment

Vertical stability analysis using NSFsim has been carried out during the conceptual design of the Negative Triangularity Tokamak (NTT) [7]. NT configurations are known to be prone to MHD instabilities. NSFsim is capable of modelling ideal MHD in terms of vertical displacement events. An example of such simulations is shown in Fig. 2. NTT configuration without in-vessel passive plates results in a highly unstable plasma with $\gamma\tau_w = 25$ ($\gamma = 2500 \text{ s}^{-1}$). Introduction of upside-down symmetric passive stabilizing coils of HSF and LFS helps to reduce these values up to $\gamma\tau_w = 15$ ($\gamma = 280 \text{ s}^{-1}$).

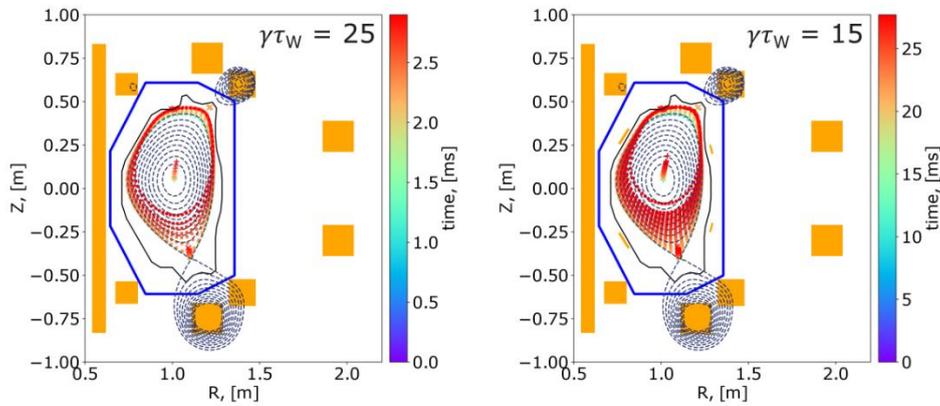


Fig. 2. VDE simulations help with stability assessment during the conceptual design of the NTT tokamak

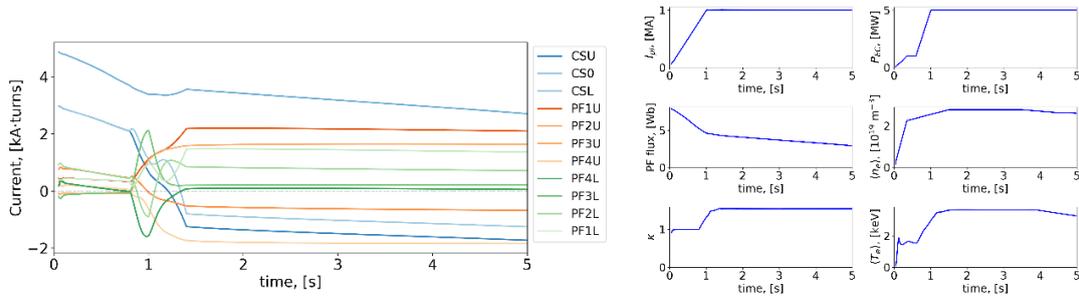


Fig. 3. Coil currents and basic plasma parameters obtained for scenario with $I_p = 1 \text{ MA}$, $B_t = 3 \text{ T}$, $P_{EC} = 5 \text{ MW}$

3.2. Scenario development

The scenario development module is a dynamical inverse solver that allows obtaining the evolution of coil currents for the given plasma current, shape, heating, and electron density waveforms. The example of such a scenario is shown in Fig. 3. A significant part of the stored poloidal flux is spent in the first second during the ramp-up phase. The next phase of active shaping is characterized by high coil current derivatives. By the end of this 5 s shot, the poloidal magnetic system still has a significant amount of the flux. This and other aspects of scenario development can be further optimized by fine-tuning the inverse solver.

3.3. Disruption simulations

In this example, a major disruption event in the DTT tokamak [8] is modeled. Some calculated quantities are shown in Fig. 4. The plasma equilibrium is allowed to evolve freely following an artificially induced thermal quench (TQ). The simulation utilizes a realistic representation of the vacuum vessel (VV) through an array of small conductive filaments, enabling accurate modeling of eddy currents and electromagnetic response during disruption phases. The system captures the dynamics of both the VDE and the current quench (CQ) phase, providing detailed 2D maps of toroidal and poloidal eddy currents induced in the VV. These eddy currents are used to evaluate the corresponding mechanical forces acting on the VV structure, which are essential for disruption load assessments and structural integrity analyses. The simulation framework also includes a model for halo current formation. It tracks the evolution of toroidal and poloidal plasma current profiles and calculates the internal plasma inductance throughout the disruption process. Key disruption features such as the I_p spike during the TQ, the generation of eddy currents caused by rapid plasma motion, and localized eddy current structures during the CQ are automatically detected and resolved.

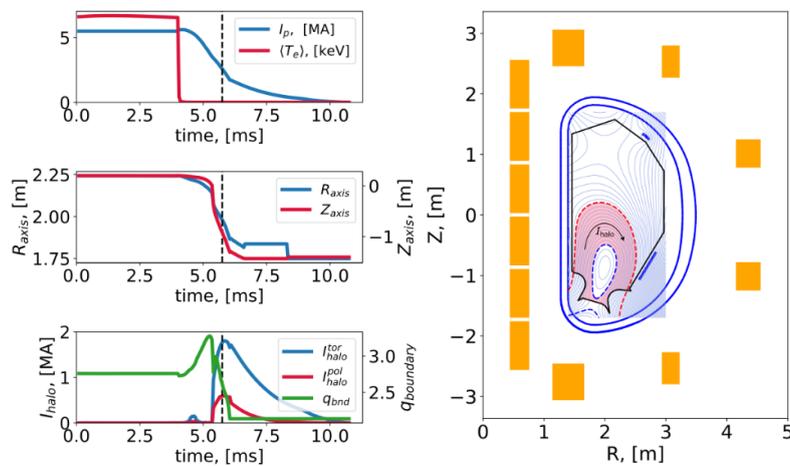


Fig. 4. Evolution of plasma parameters during major disruption on the DTT tokamak. Equilibrium at $t = 5.75$ ms is shown on the right with a shaded halo region.

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