NEXT STEP FUSION

Overview of NSFsim application for plasma simulations and integrated modelling

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nextfusion.org

Team

MADE IN LUXEMBOURG

At Next Step Fusion, we believe recent and upcoming progress will soon launch the fusion energy industry, providing safe and affordable energy for humanity

Private EU company established in April 2023 in Luxembourg:

- **Unique, interdisciplinary team** of 20+ based in Luxembourg (HQ), Spain, and Portugal
- **Deep expertise in tokamaks** design, simulation, control, and diagnostics
- **Dedicated teams** for simulation software development and AI/ML
- **Vast experience** with ITER, KTM, T-10, T-15MD, COMPASS, DIII-D, ISTTOK, and TJ-II stellarator
- **Proven track record** in the public and private fusion sectors

Columbia Engineering

Consorzio RFX
Ricerca Formazione Innovazione

FUSION INDUSTRY ASSOCIATION

MARITIME FUSION

UC San Diego

CER
Center for Energy Research

European Fusion Association

COSYLAB

DIII-D
NATIONAL FUSION FACILITY

VTT

NVIDIA Inception Program

NDA
Medical isotopes FNS

MAX PLANCK INSTITUTE FOR PLASMA PHYSICS

TUSCIA RESEARCH UNIVERSITY SMALL TOKAMAK

FuseNet

NDA
Tritium breeding FNS

ISTID

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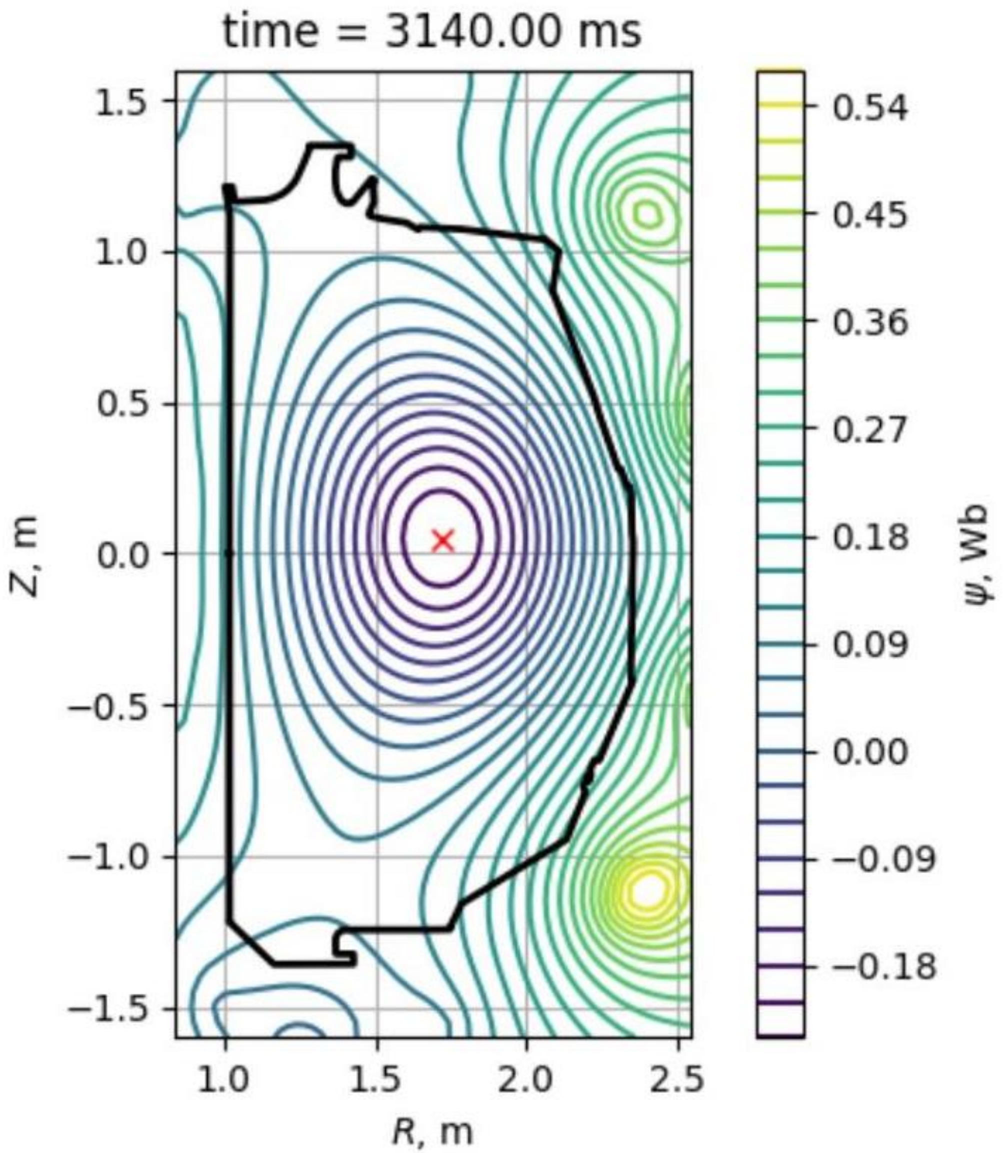
NSFsim

NSF simulator (NSFsim) is an IMAS-compatible advanced Grad-Shafranov 1.5-D axisymmetric (2D solver with a 1D kinetic component), time-dependent, transport-modeling, free boundary in external magnetic field tokamak plasma simulation code.

NSFsim is based on the renowned **DINA** simulation approach with more than 30 years of experience in numerous tokamak experiments and control.



Simulation capabilities

- Direct calculation
- Scenario calculation
- No-plasma calculation
- Inverse solver for ML datasets
- Disruption (MD/VDE)
- Equilibrium reconstruction
- Integrated modelling
- Online simulation platform
- API interface for online calculations
- ML-based controllers

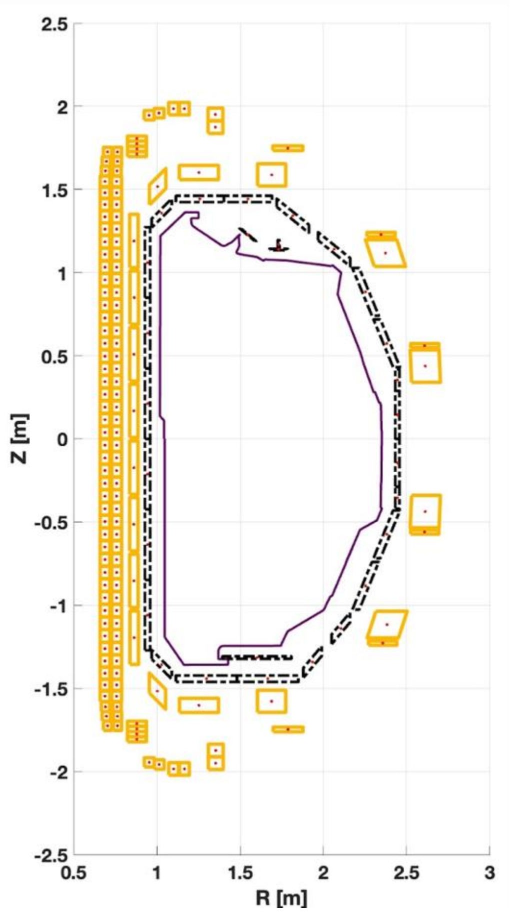
NSFsim is IMAS-compatible for data storage and coupled simulations with external codes

Grid structure: Green function

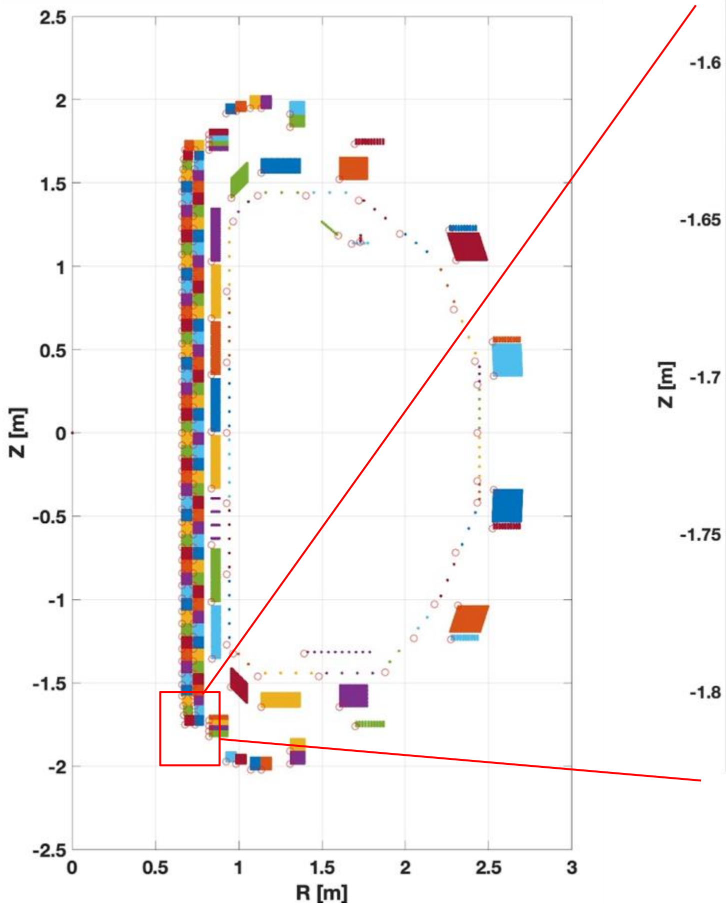
- Conductive elements are represented by parallelograms

- Each element is represented by a grid of regularly spaced dot objects

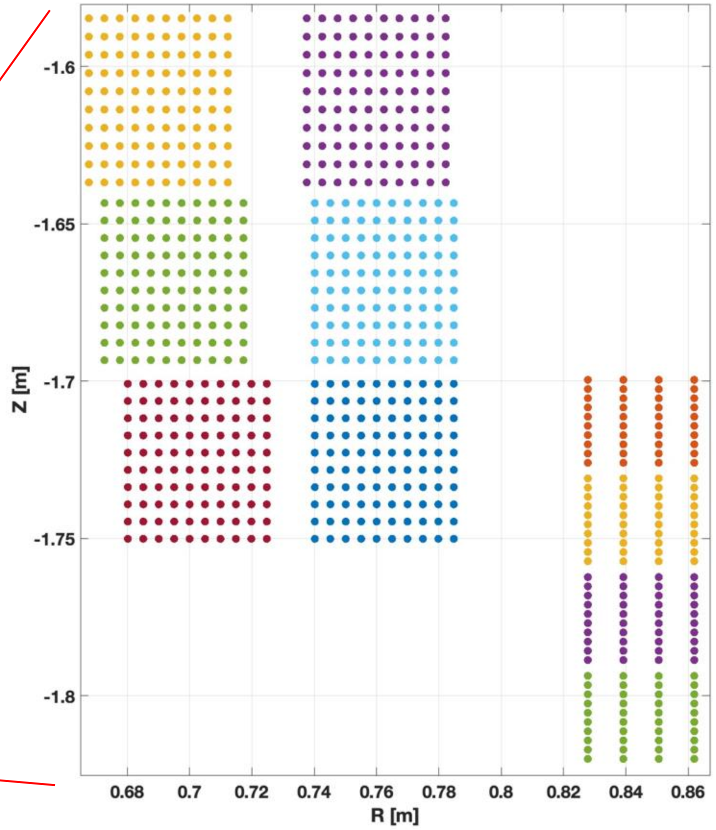
Device representation



Grid representation



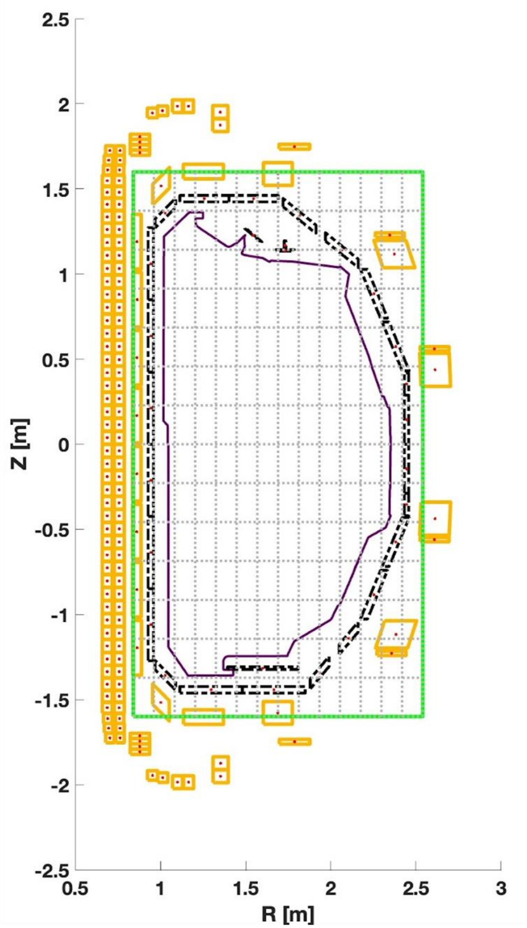
Grid representation
(zoomed)



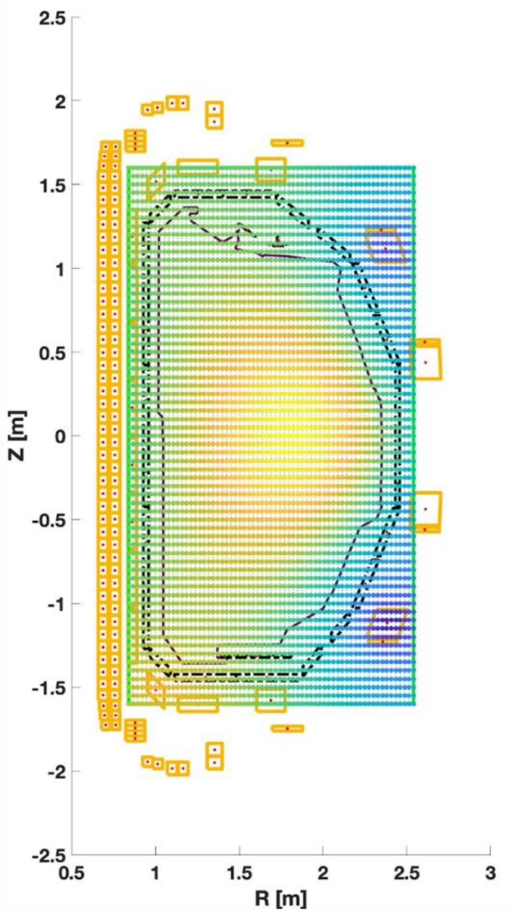
Grid structure: PSI

- The poloidal flux Ψ(R,Z) is computed on a uniform rectangular grid in the (R,Z) plane.
- Each grid node stores a scalar value of the Ψ, obtained from the equilibrium solver.
- Post-processing of the discrete Ψ is used to reconstruct flux surfaces and separatrix

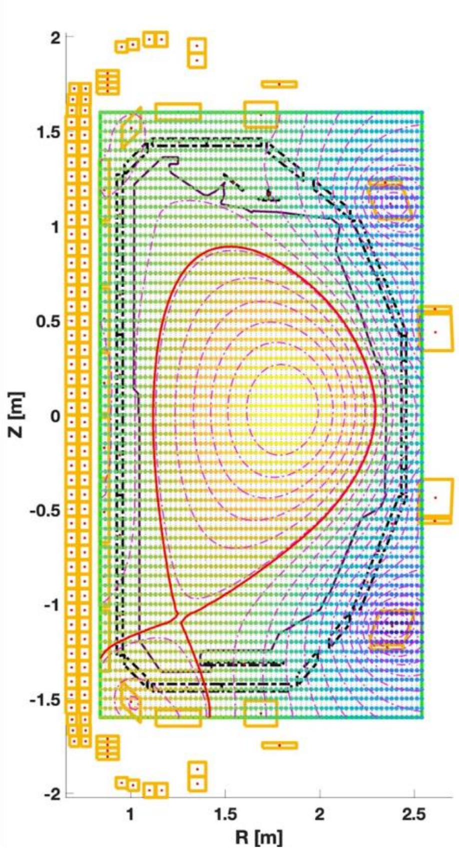
Grid representation



Ψ values on grid



Processed results to obtain Ψ level lines

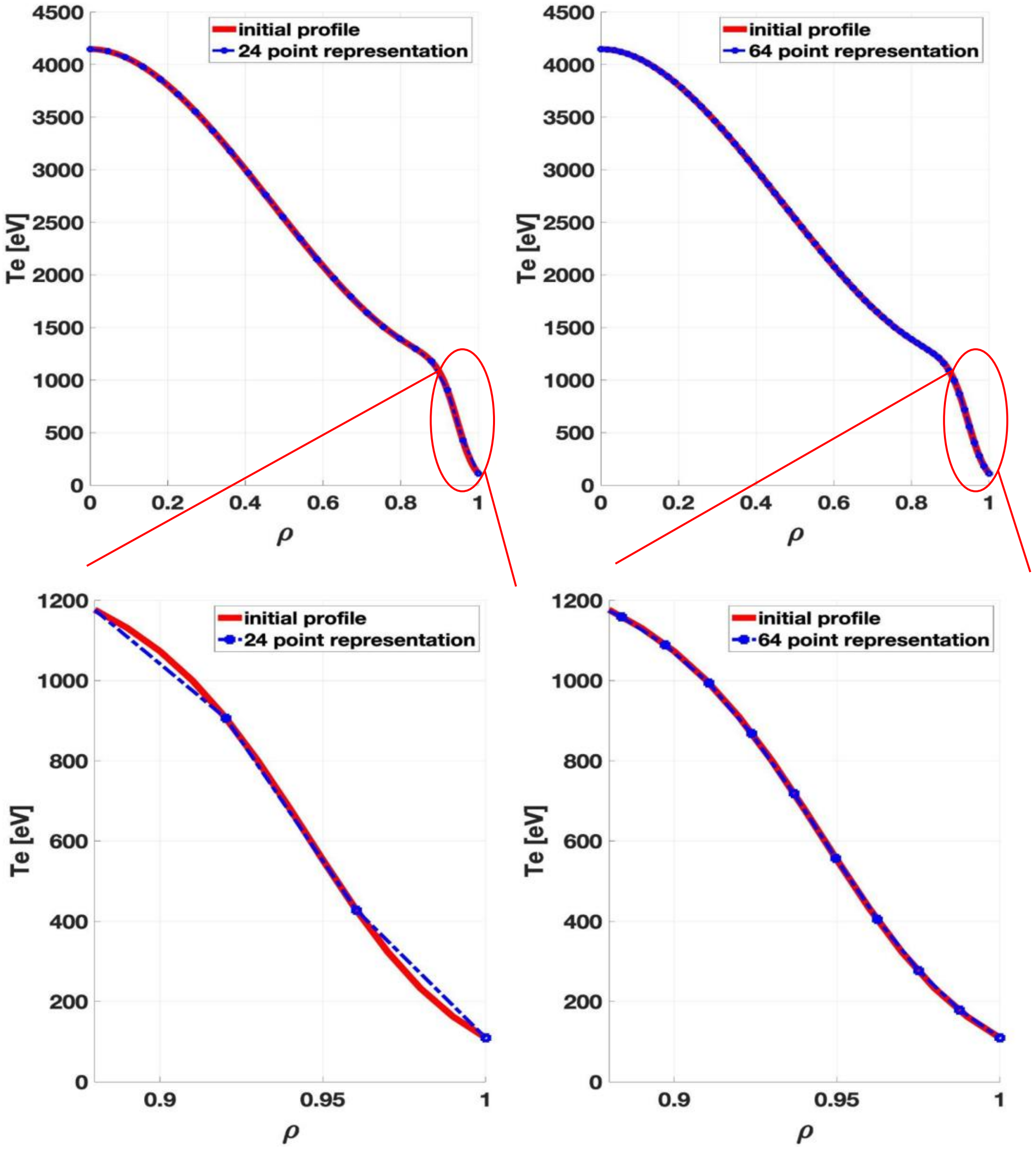


Grid structure: 1D kinetic profiles

- Kinetic quantities (temperature, density, current drive, etc.) are computed on a 1D radial grid.
- The number of radial grid points is configurable and can be adapted to the physics of interest.
- Higher number of grid points – better accuracy of profile reconstruction, at the cost of higher computational time.

Fine resolution is crucial when profiles include localized physics:

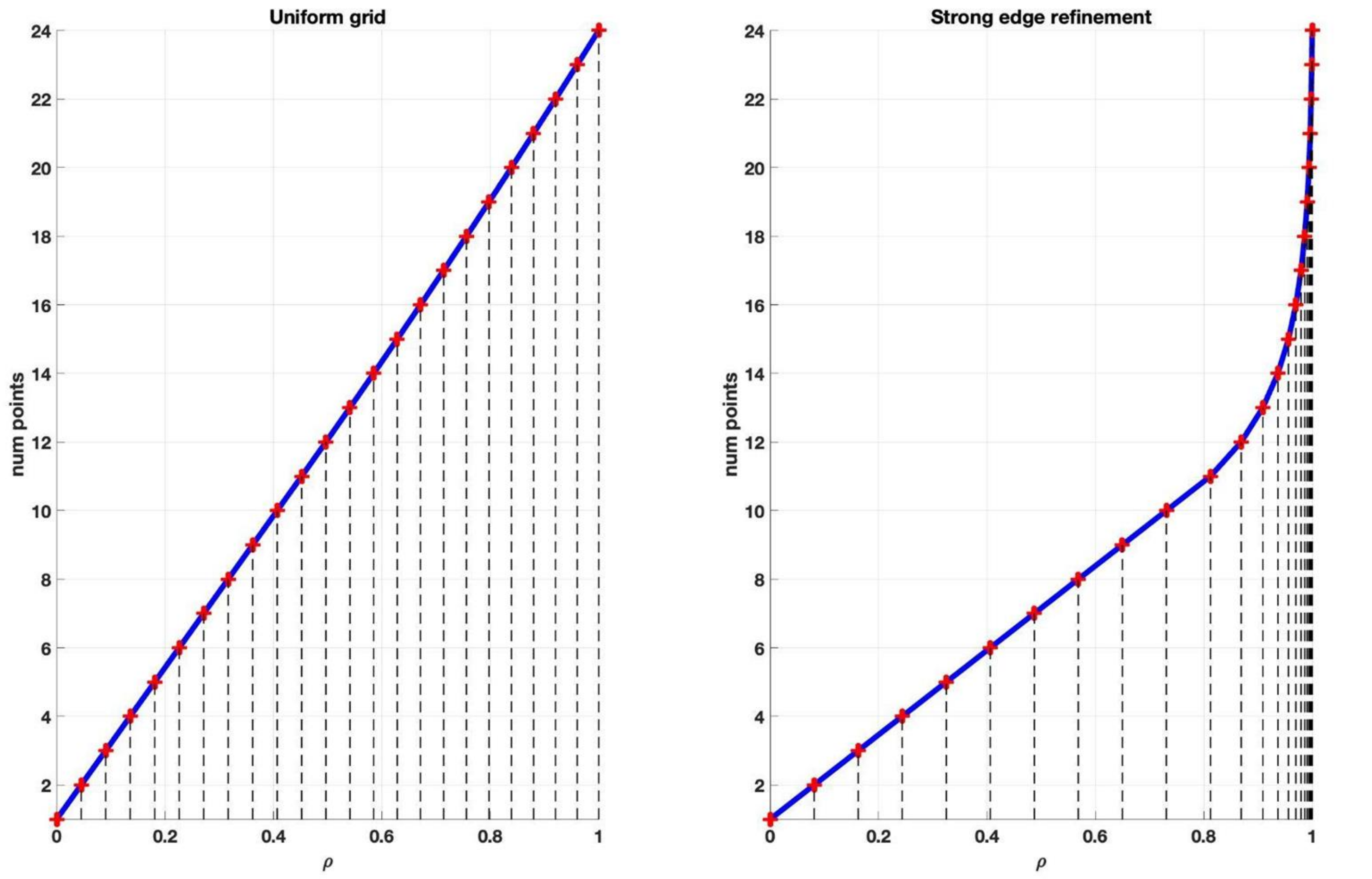
  - transport barriers
  - heating & fuelling sources
  - current drive deposition
  - sharp gradients



Grid uniformity adjustment 1/3

- Non-uniform radial grids are used to concentrate resolution in regions of dominant physics activity.
- Enhanced edge resolution enables accurate treatment of localized physics.
- Grid resolution and distribution are configured prior to each simulation run and remain fixed during the run.

Example of different grids

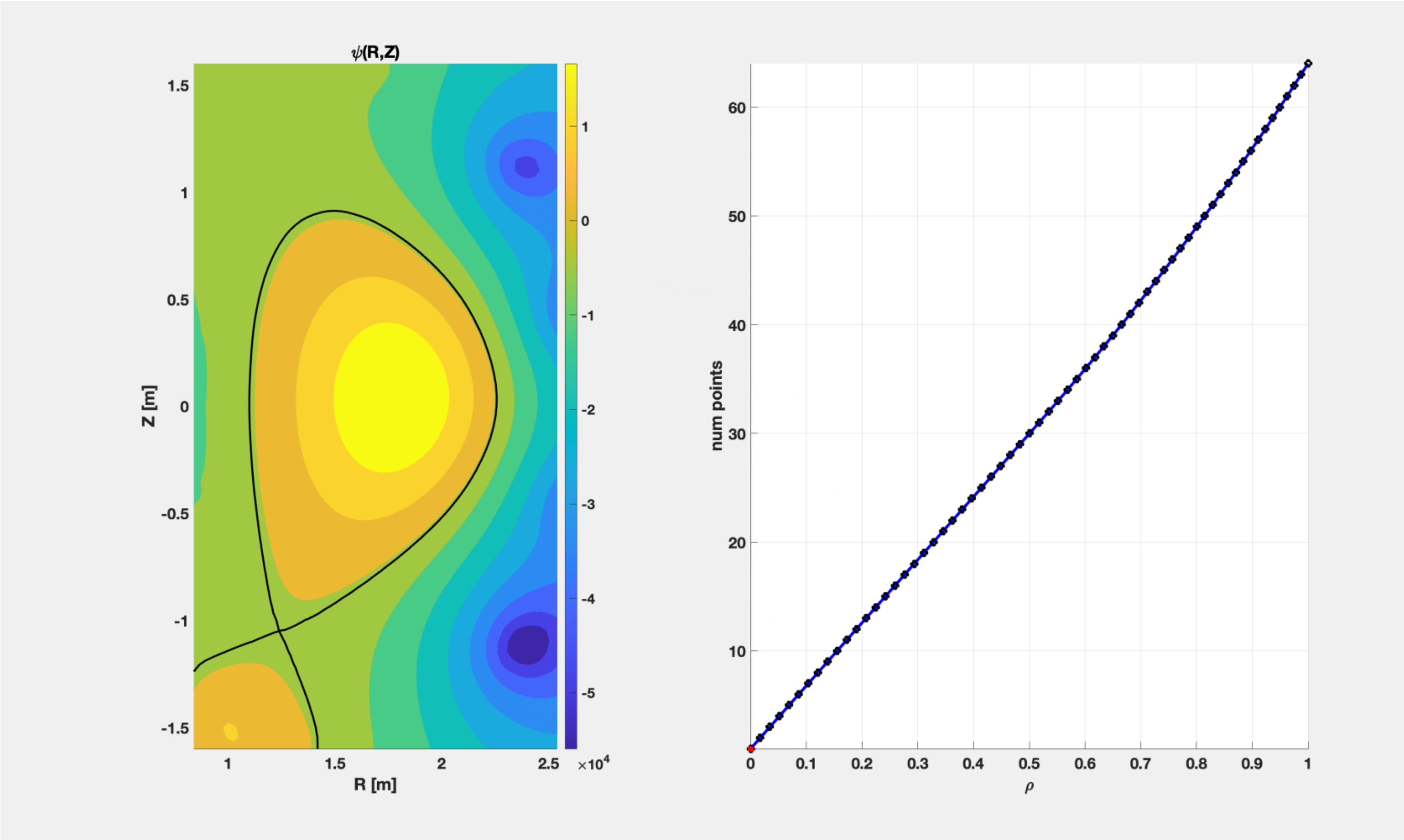


Grid uniformity adjustment 2/3

1D profile sampled on 64 uniformly spaced points

Many important effects are edge-dominated

- Changes in current profile → shifts in separatrix / X-point position
- Boundary conditions strongly affect global equilibrium evolution
    - Fueling
    - ELMs
    - BS current



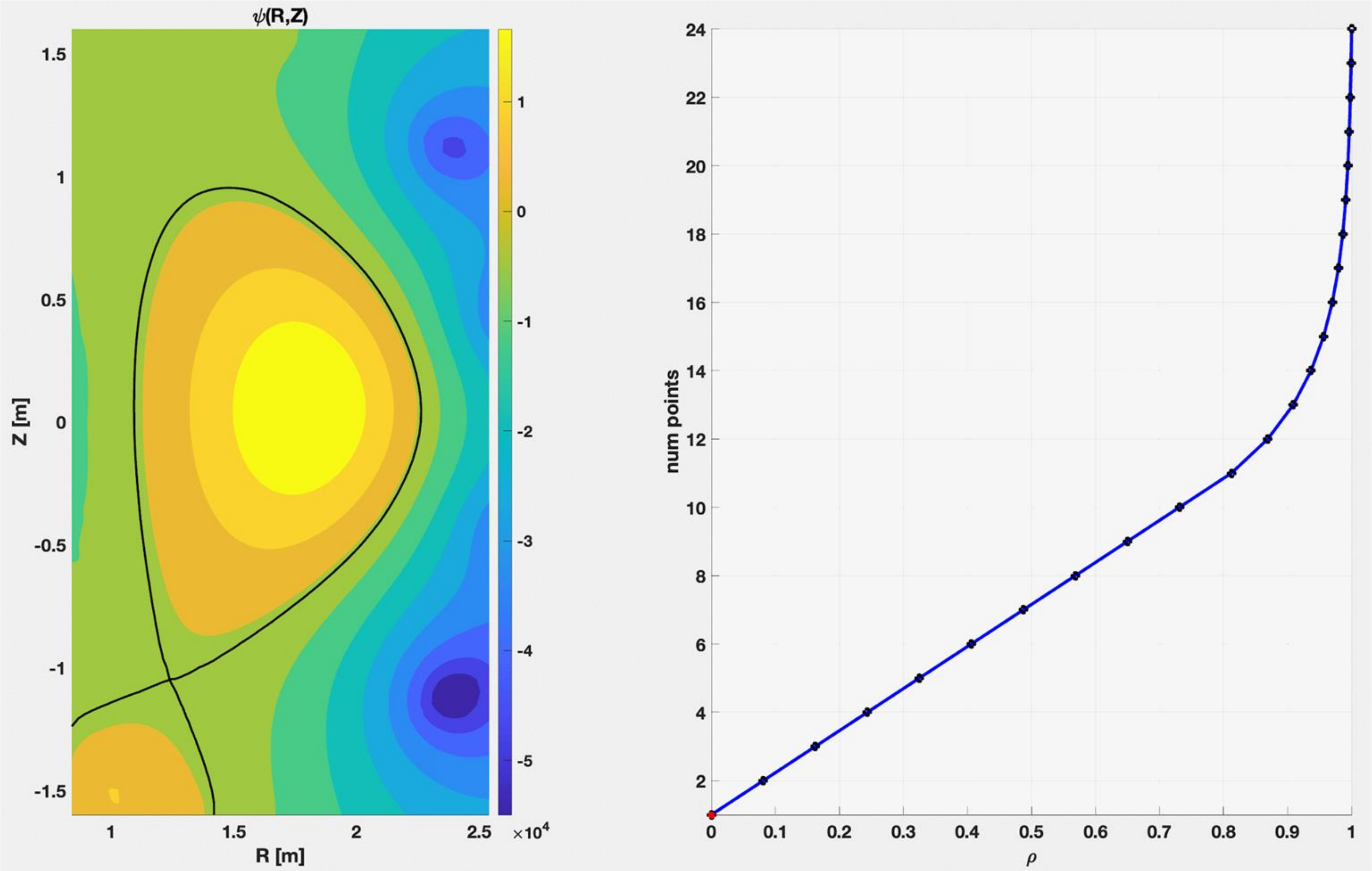
Grid uniformity adjustment 3/3

1D profile sampled on 24 points, with increased point density near the edge

Good trade-off: non-uniform radial grid

- Refined mesh at the edge, coarser in the core
- Preserves accuracy where it matters most
- Preserves computational efficiency

Comparable accuracy can be achieved with less non-uniform grid points, rather than with a uniformly refined grid



Advanced kinetic simulation settings

Change type of boundary conditions calculation between

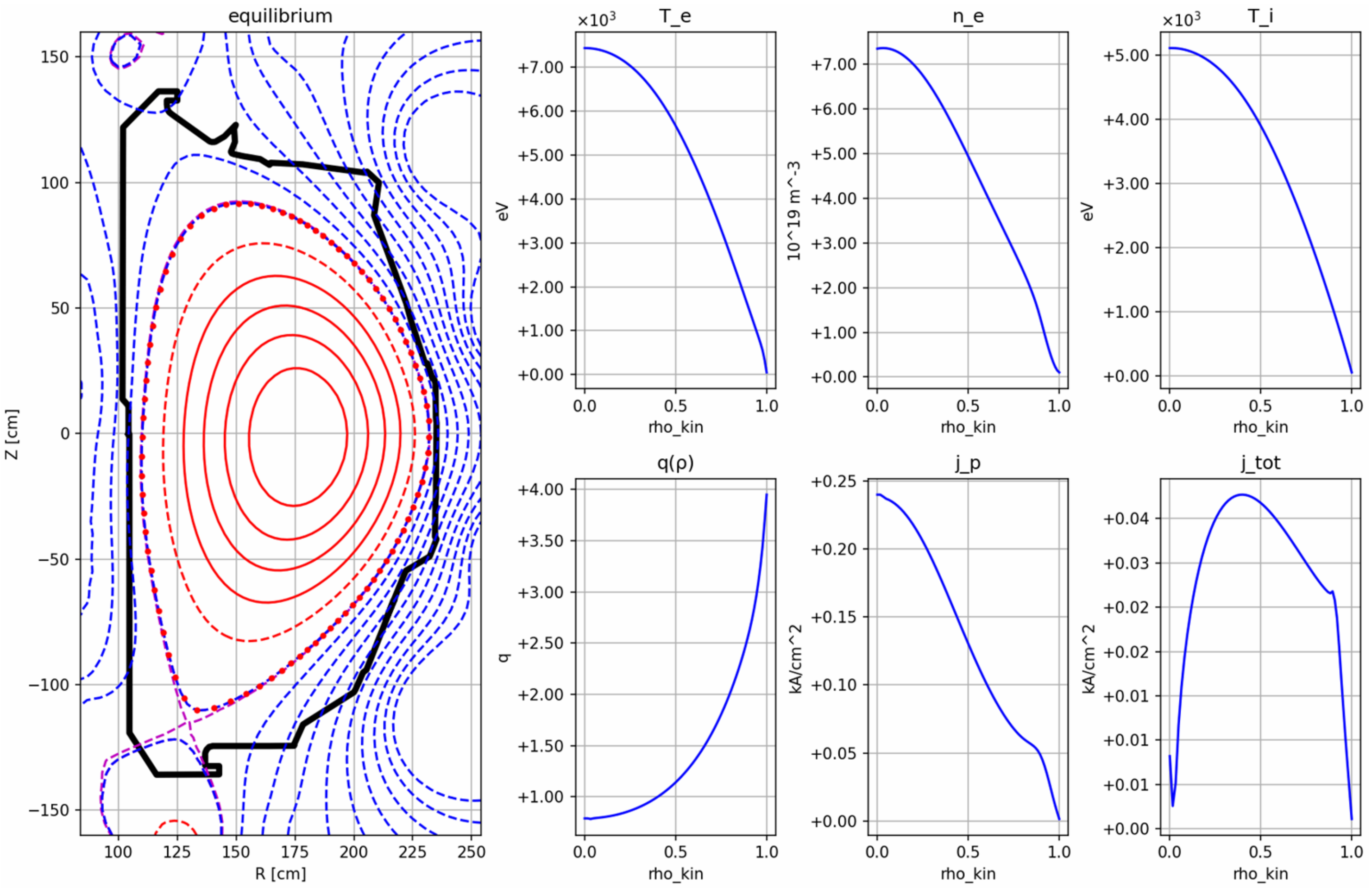
- ➔ **Dirichlet** (where X(ρ) for ρ= 1 is constant)
- ➔ **Robin** (where X(ρ) calculates self-consistently from the balance between transport and edge losses)

External profiles of **heating power**, **current drive** and **particle sources** can be prescribed as input profiles.

Sources are consistently coupled to the kinetic equations to compute their contribution to:

- temperature evolution
- total plasma current profile
- density evolution

Example of direct calculation with active external sources for heating, current drive and particles



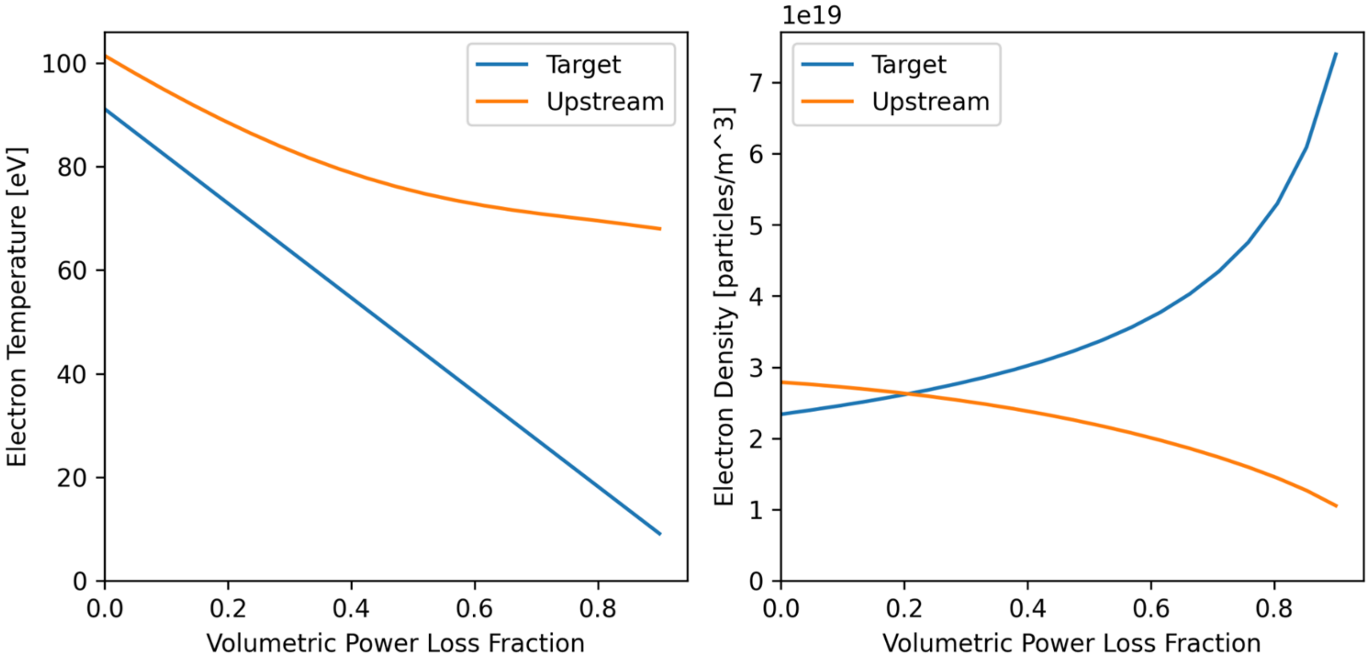
Key features

Integrated SOL modelling (0D SOL)

Fast reduced 0D Box-Model (modified 2-point model) developed by [Zhang_2023] is implemented in NSFsim

Key features:
- Input - particle and heat fluxes from core to SOL
- Heat and particle transport
- Analytical evaluation – extremely fast
- Parallel connection length is taken from equilibrium with real geometry
- Flux expansion effects are included
- SOL width is obtained from Heuristics Heuristic drift-based model [Goldston_2012]

CENTAUR-like (negative triangularity, Q>1, high-field tokamak) plasma and equilibrium: P_{SOL}=13.5 MW, λ_q=1.3 mm



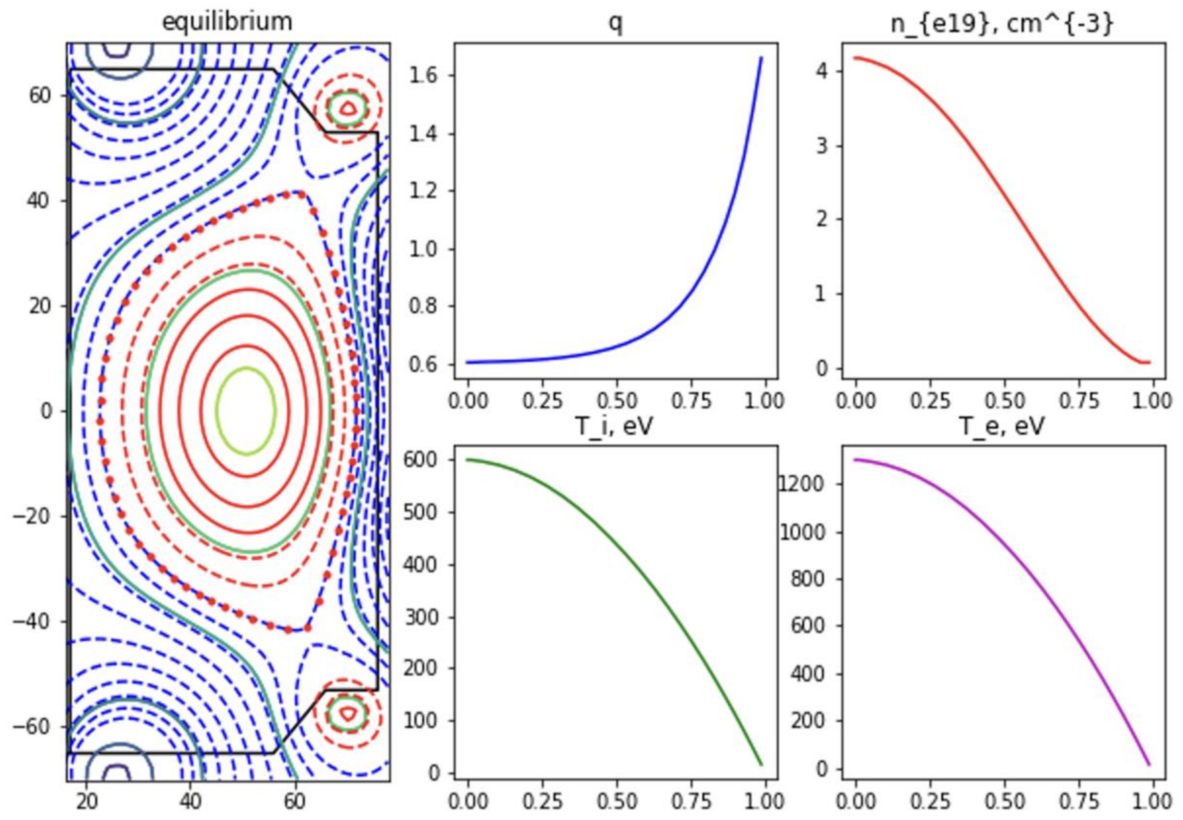
Direct calculations

Currents in poloidal field coils → **Plasma parameters**

Set currents, voltages, or both currents and voltages for different active coils as the input

Options for kinetic mode in calculation:

- Temperatures and density fixed as profiles
- Density fixed as profile
- Temperatures fixed as profiles
- Density fixed as average value



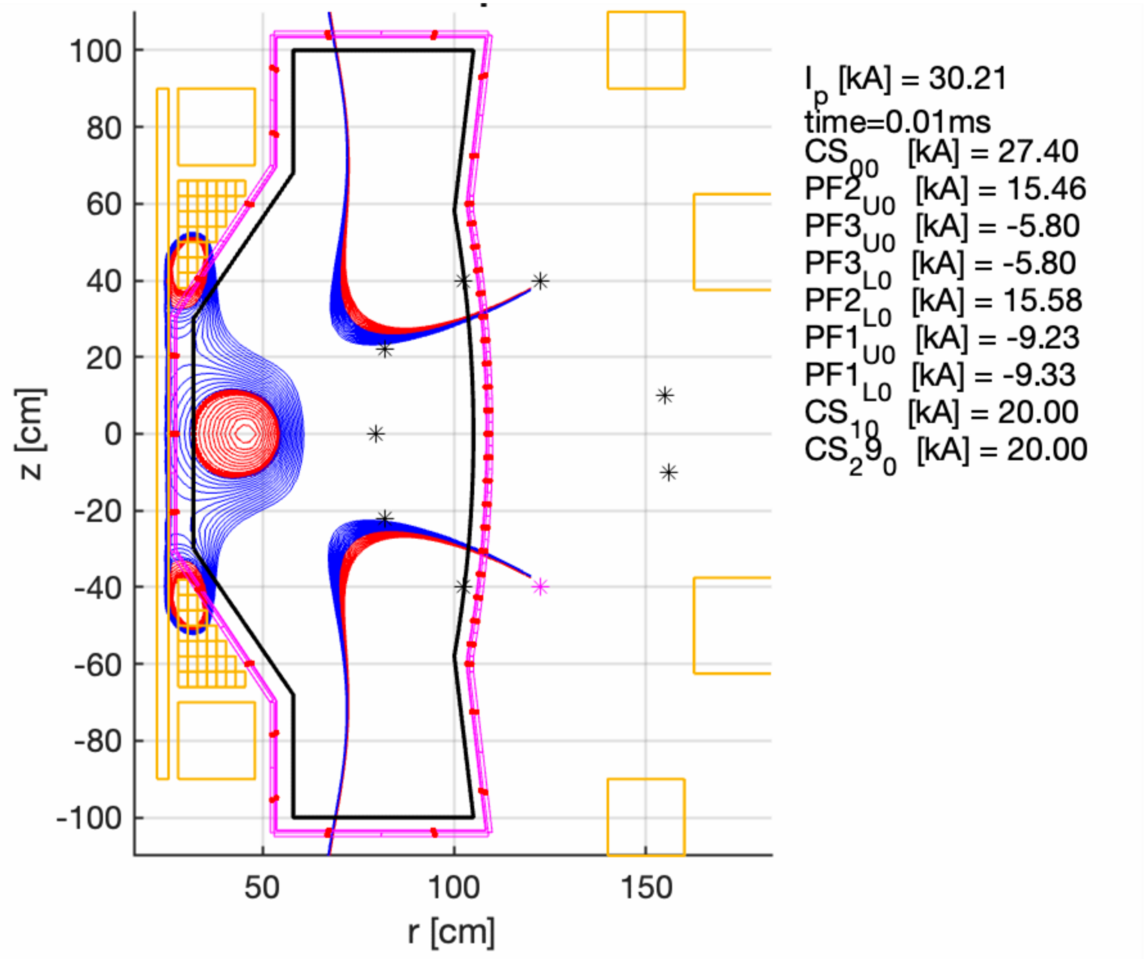
Scenario calculations

Plasma parameters evolution → **Scenario for coil's currents**

Include ion/electron heating with current drive generation or just pure ohmic heating

Choose kinetic mode for calculation:

- Prescribed evolution for Ne, Te, Ti
- Prescribed evolution for Ne, calculate Te, Ti



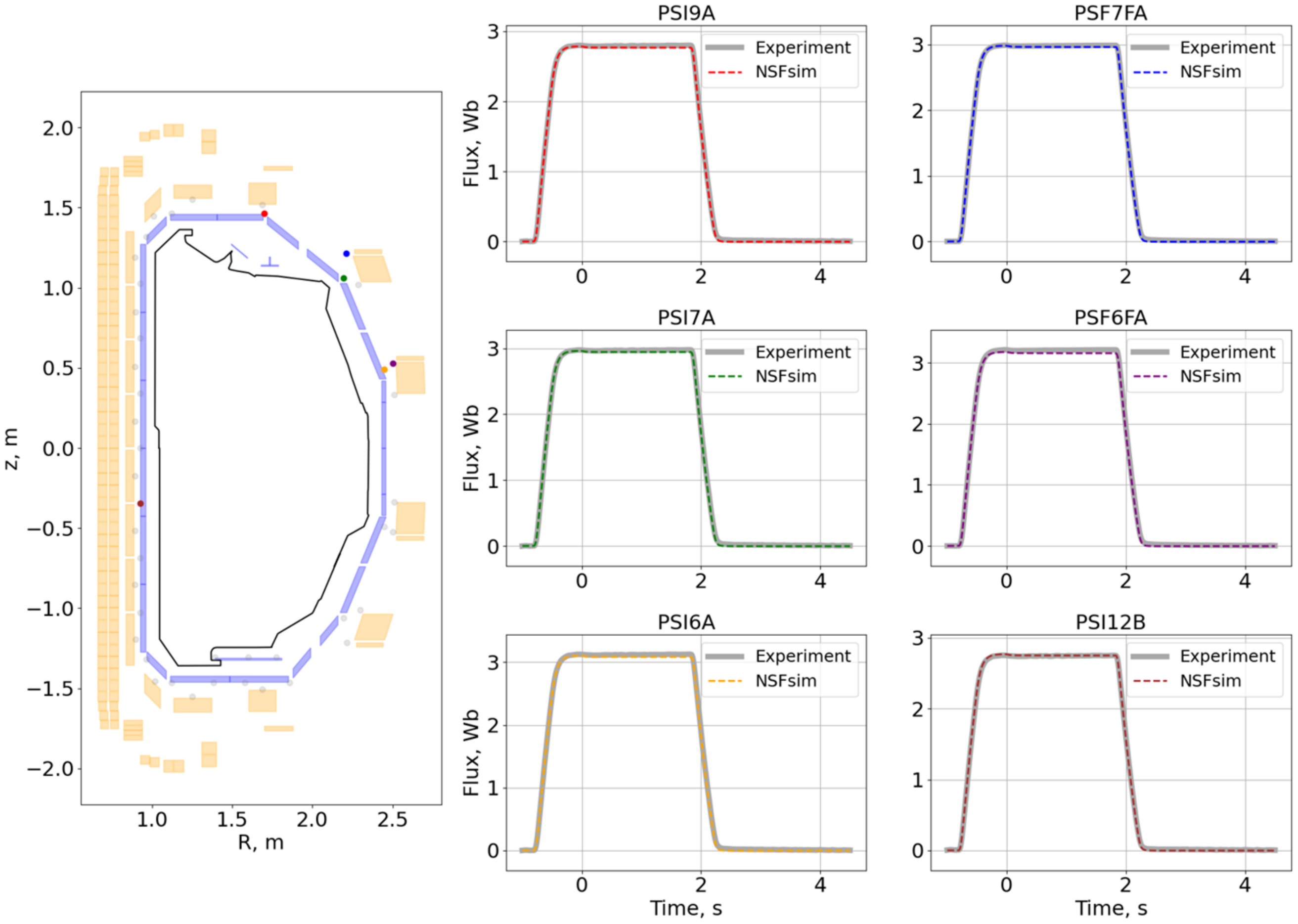
ST VNS machine example

Plasma–free calculations

Currents in poloidal field coils → **Passive currents, EMD signals**

Use cases:

- Validation of the 2D electromagnetic model used for other calculations
- Selection of reference magnetic diagnostic channels during alignment with real device



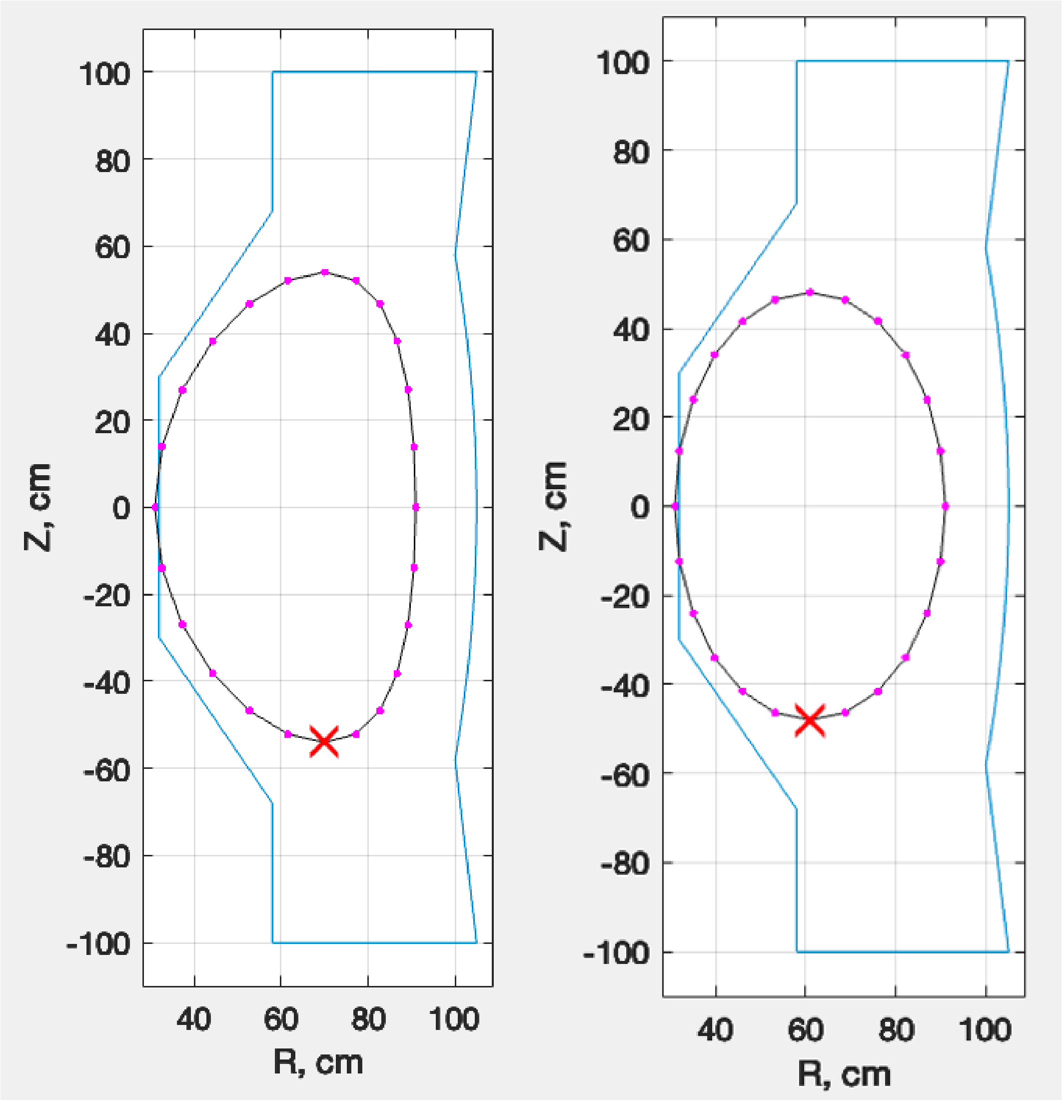
Inverse solver

Plasma parameters → **Parameters for direct calculation initialization**

Calculate set of different "start points" in discharge scenario or for Machine Learning datasets

Inputs:

- Plasma shape
- Plasma current
- Coil currents constraints
- Temperatures and density as profiles
- Psi on axis



Major disruption and VDE

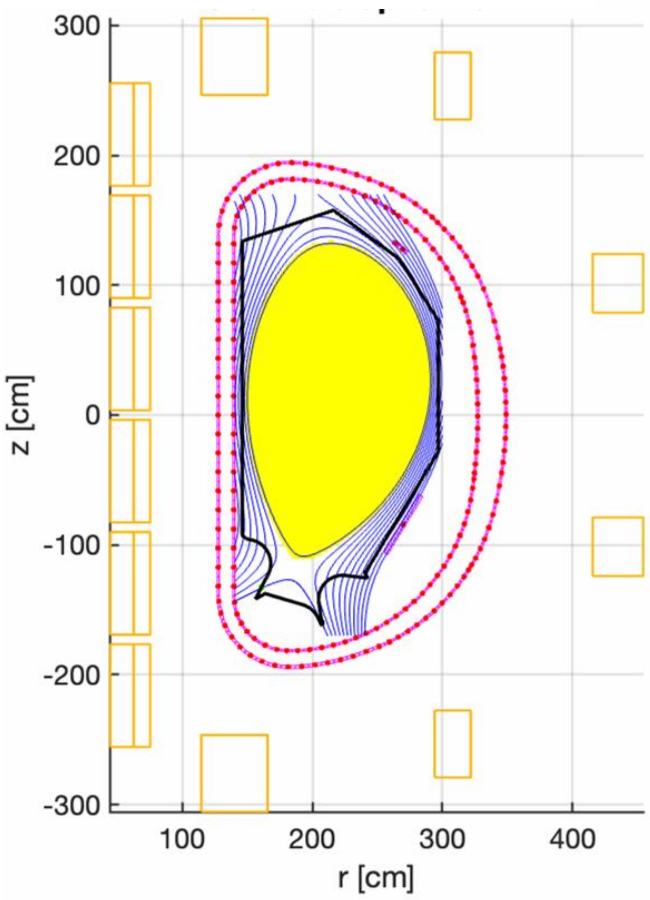
Artificial triggering or self-consistent evolution of disruption conditions

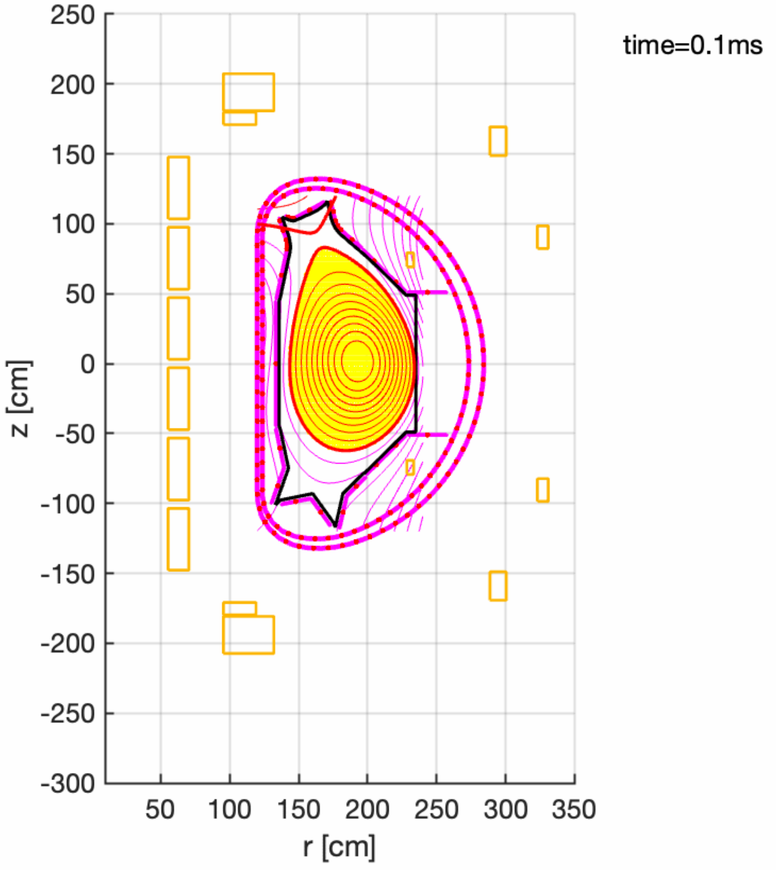
Two stages:

- Thermal quench
- Redistribution of the current profile after mixing

Features:

- Characteristic Ip spike
- Calculate Halo area with poloidal/toroidal currents
- RE current
- Eddy currents in passive structures
- Forces distribution in passive structures





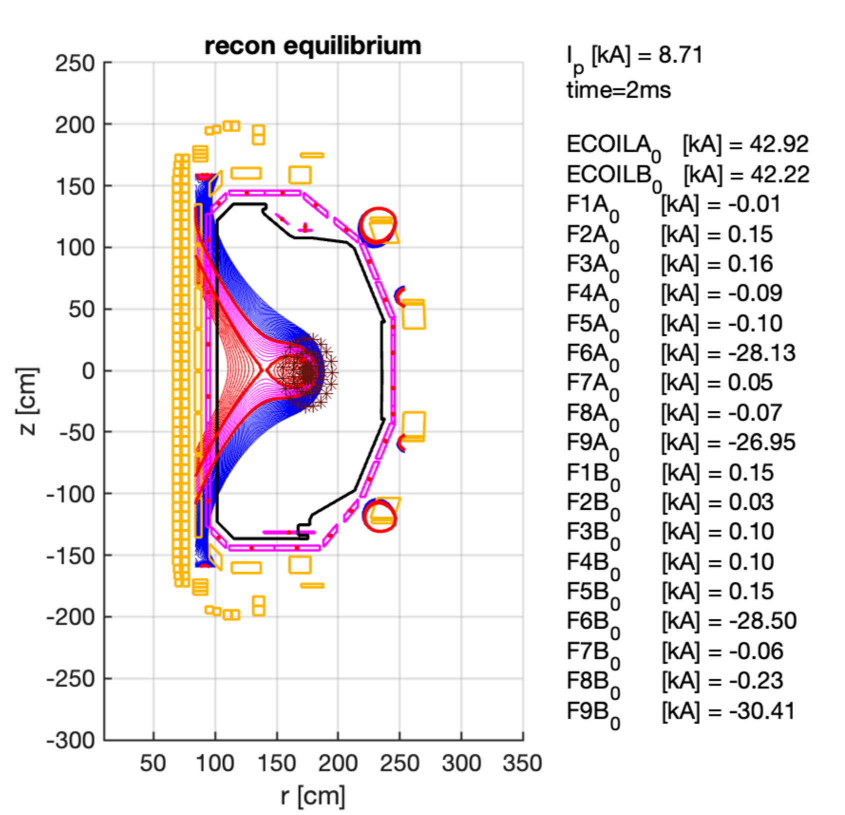
Equilibrium reconstruction

Reconstruction based on:

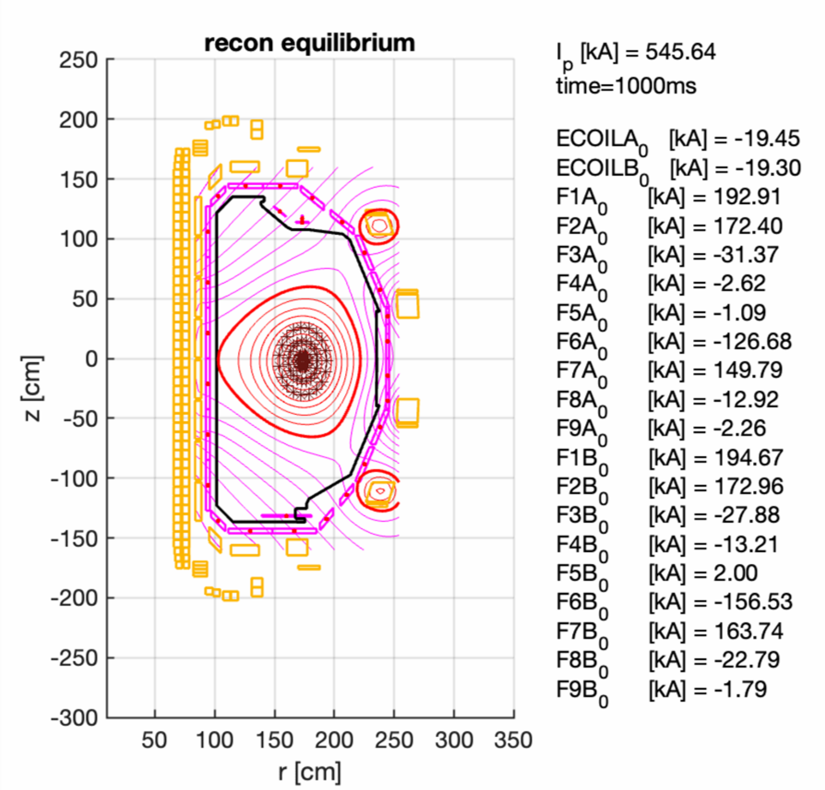
- Plasma current
- EMD signals with 'valid' mask
- Coils current

Two types of reconstruction:

Fixed filaments

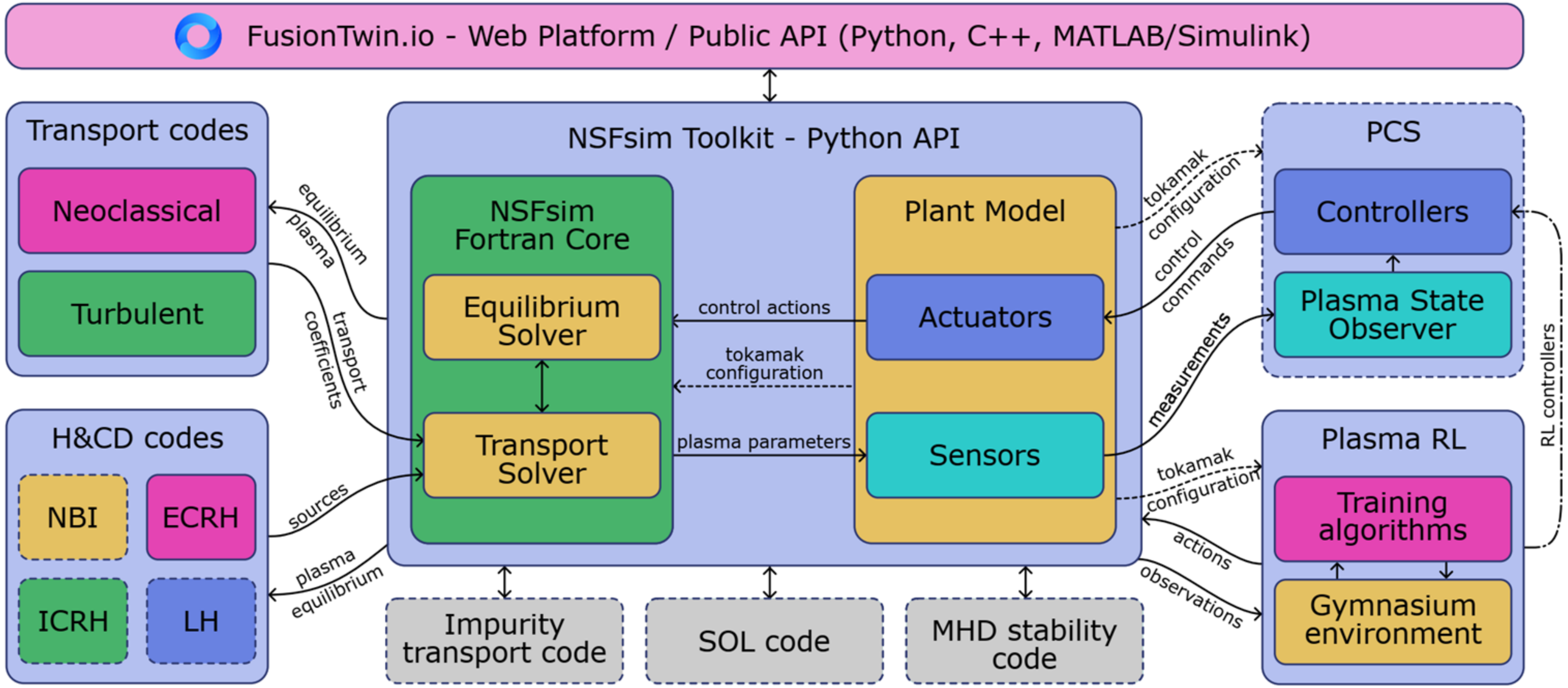


Floating filaments



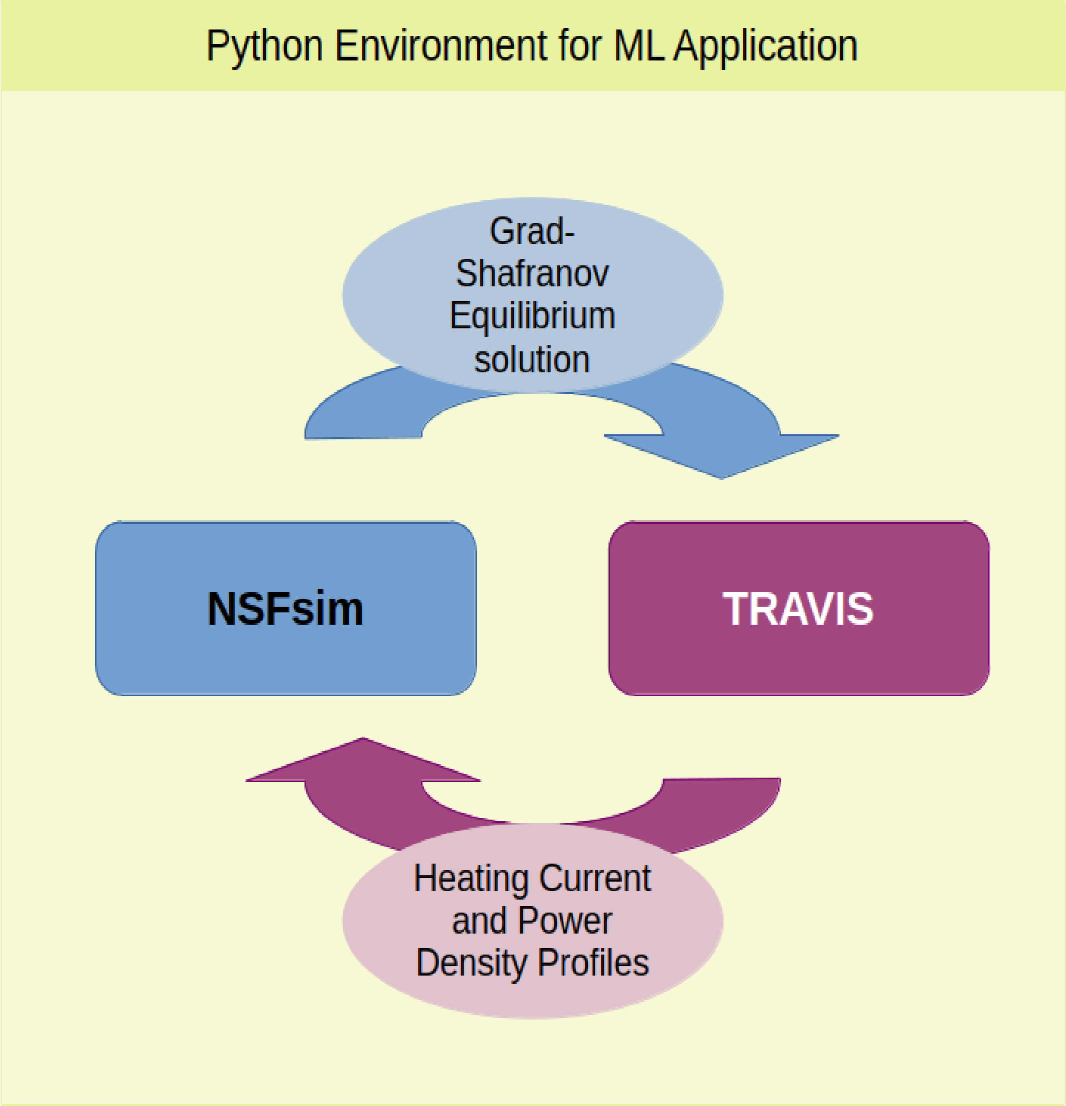
Integrated modeling framework

Ongoing projects on integrating codes around **NSFsim** for self-consistent plasma simulations for design and control (a.k.a. flight simulator)



TRAVIS – ECRH and ECCD ray-tracing code | **ASCOT5** – NBI and fast-particles
TGLF – turbulent transport | **MISHKA** – NN surrogate model for pedestal region

Integrated modeling: ECCD with NSFsim



TRAVIS is a multi-beam and multi-pass ray-tracing code for electron cyclotron resonance heating (ECRH).
Courtesy of IPP Max Planck.

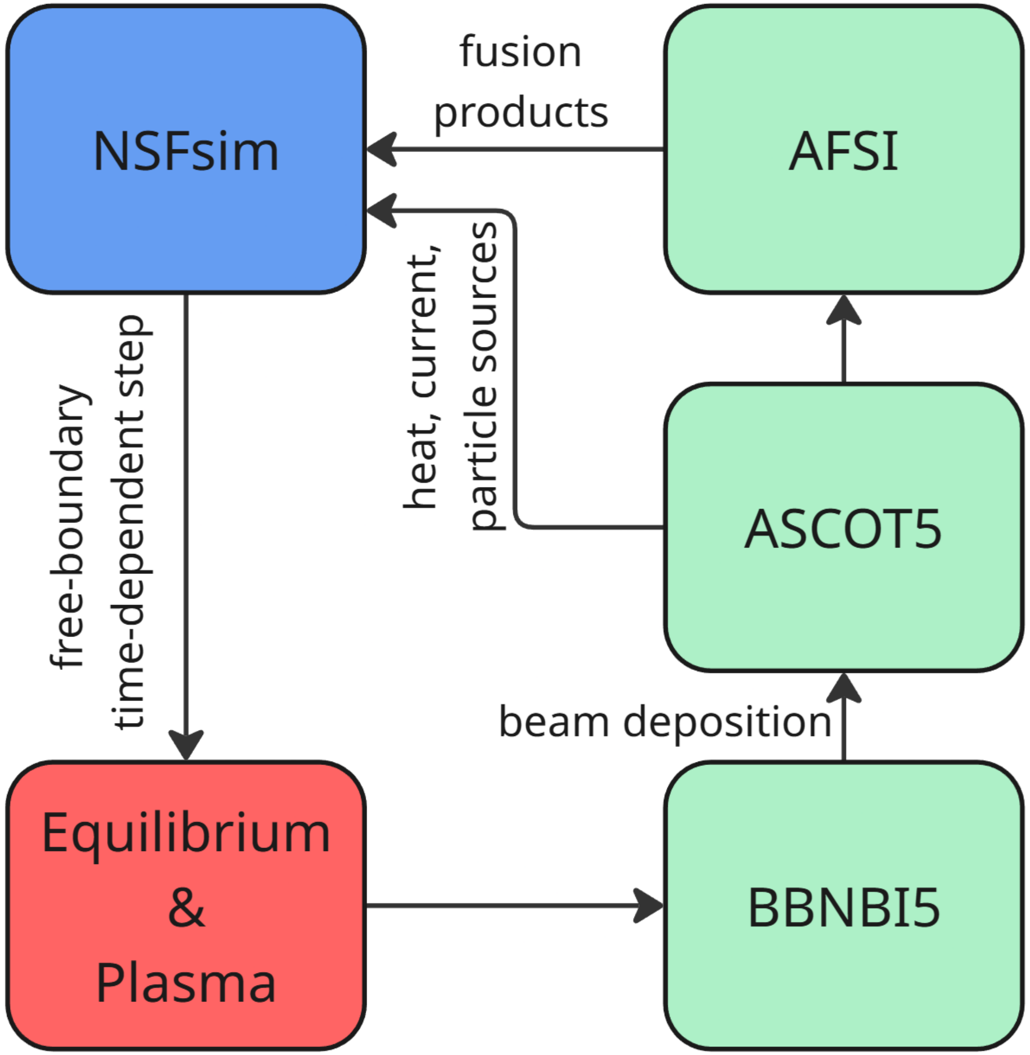
Key features of TRAVIS:

- TRAVIS works with an arbitrary 3D magnetic equilibrium being applicable for both stellarators and tokamaks.
- The equations for ray tracing are taken in the weakly relativistic approach with thermal effects taken into account.
- Absorption, current drive and emissivity are calculated in the fully relativistic approach.
- For the calculation of ECCD, an adjoint technique with parallel momentum conservation is applied.

[N.B. Marushchenko, Y. Turkin, H. Maassberg, *Computer Physics Communications* 185-1, 2014]

We use a combination of **NSFsim** and **TRAVIS** as a simulation core within our ML plasma control pipeline.

Integrated modeling: NBI with NSFsim



ASCOT5 is is a test-particle orbit-following Fokker-Planck solver.

Key features of ASCOT5:

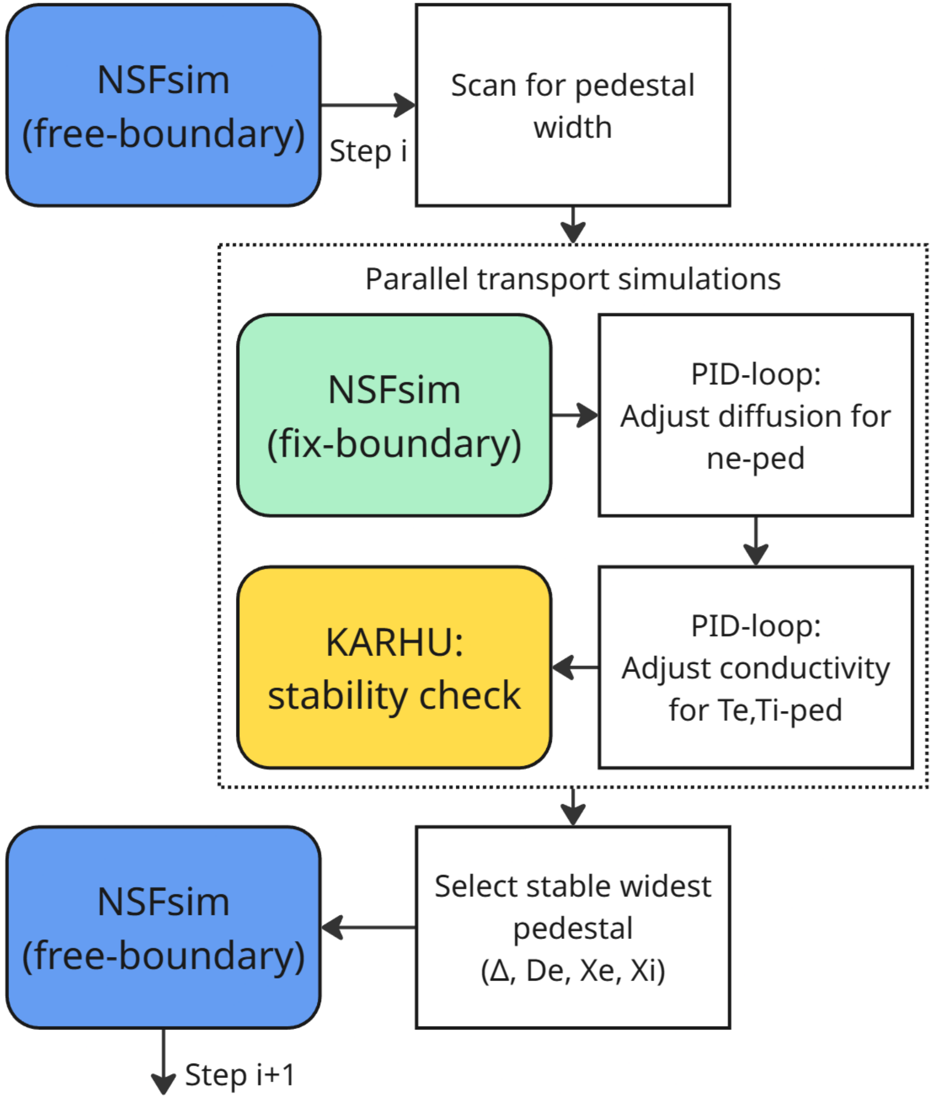
- Extensively parallelized (OpenMP, CPU/GPU).
- Includes BBNBI5 code for calculations of beam birth profile and shine through.
- Includes AFSI for fusion product source calculations from thermal plasma and fast ion slowing-down distributions.

NSFsim-ASCOT5 coupling implementation:

- Shared-memory data management.
- Between step calls for BBNBI-ASCOT5-AFSI.

Integration of ASCOT5 has been developed in collaboration with VTT – transport coupling scheme will be available in ASCOT5 open-source repository.

Integrated modeling: EPED-like pedestal with NSFsim



KARHU v2.0 neural network is employed for stability analysis and physically constraint pedestal simulations

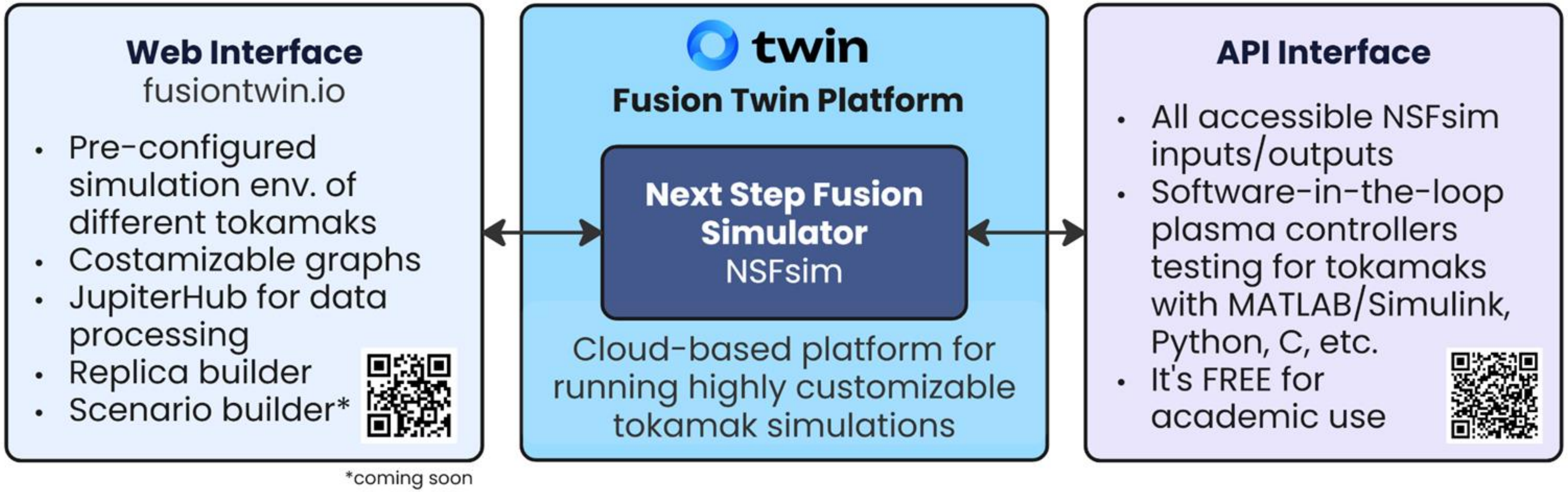
Key features of KARHU:

- Uses HELENA and MISHKA codes for dataset generation
- Currently includes JET and DIII-D-like dataset

EPED-like workflow:

- Select n_e^{ped} as input
- Scan for pedestal width:
  - Adjust particle diffusion for n_e^{ped}
  - Adjust heat conductivity for $T_e^{ped} = T_e^{KBM}$
  - Check stability with KARHU
- Maximum pedestal width is applied
- (In progress) Fix-boundary parallel runs for pedestal selection loop

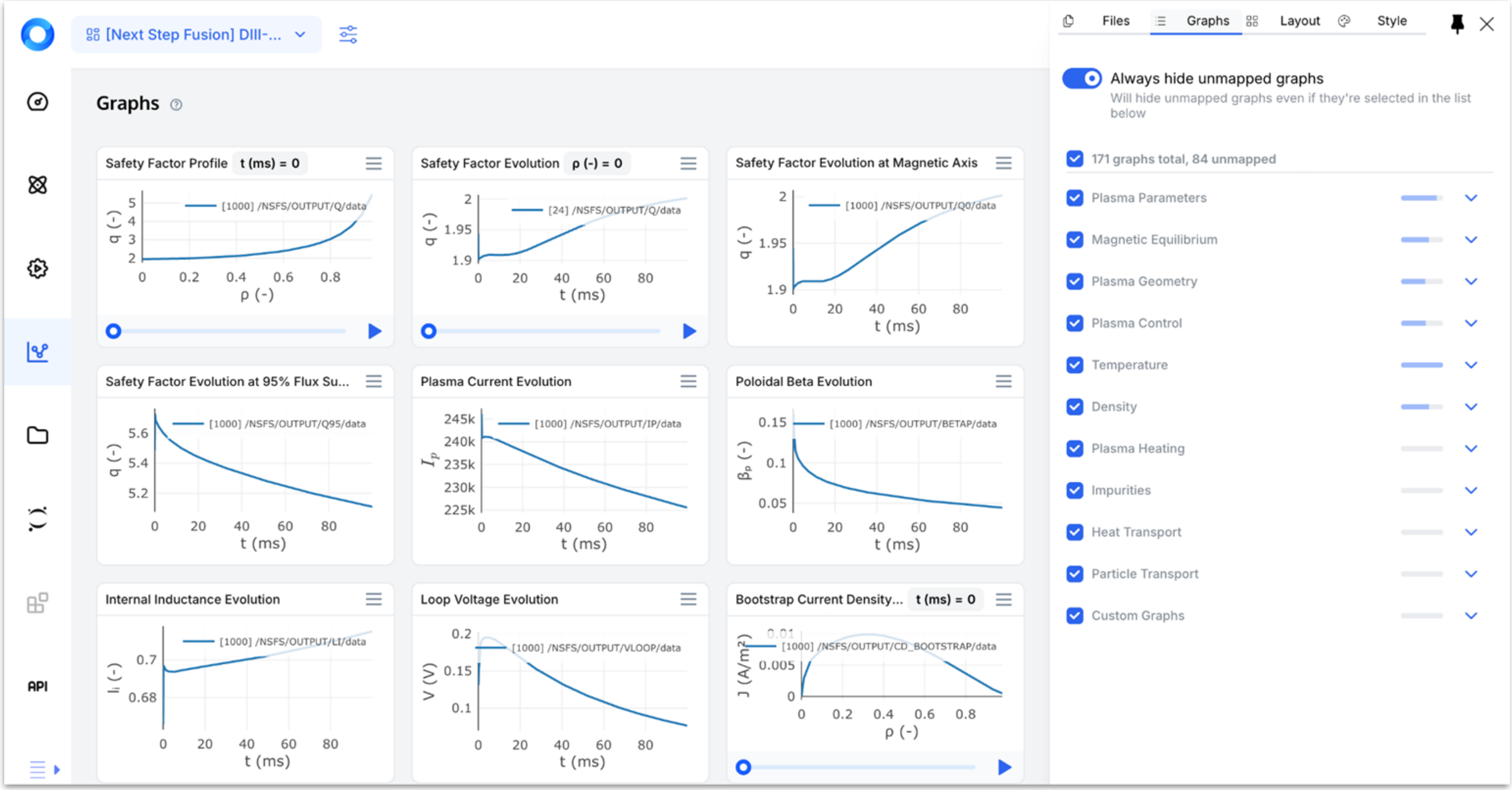
Online simulation Platform



Fusion Twin Platform https://fusiontwin.io is a cloud-based platform for running highly customizable tokamak simulations, uploading and visualizing fusion data, collaborating and sharing with others, and more. To run realistic simulations, the Platform utilizes digital replicas of tokamaks, including DIII-D, ISTTOK, SMART, and NSF NTT.

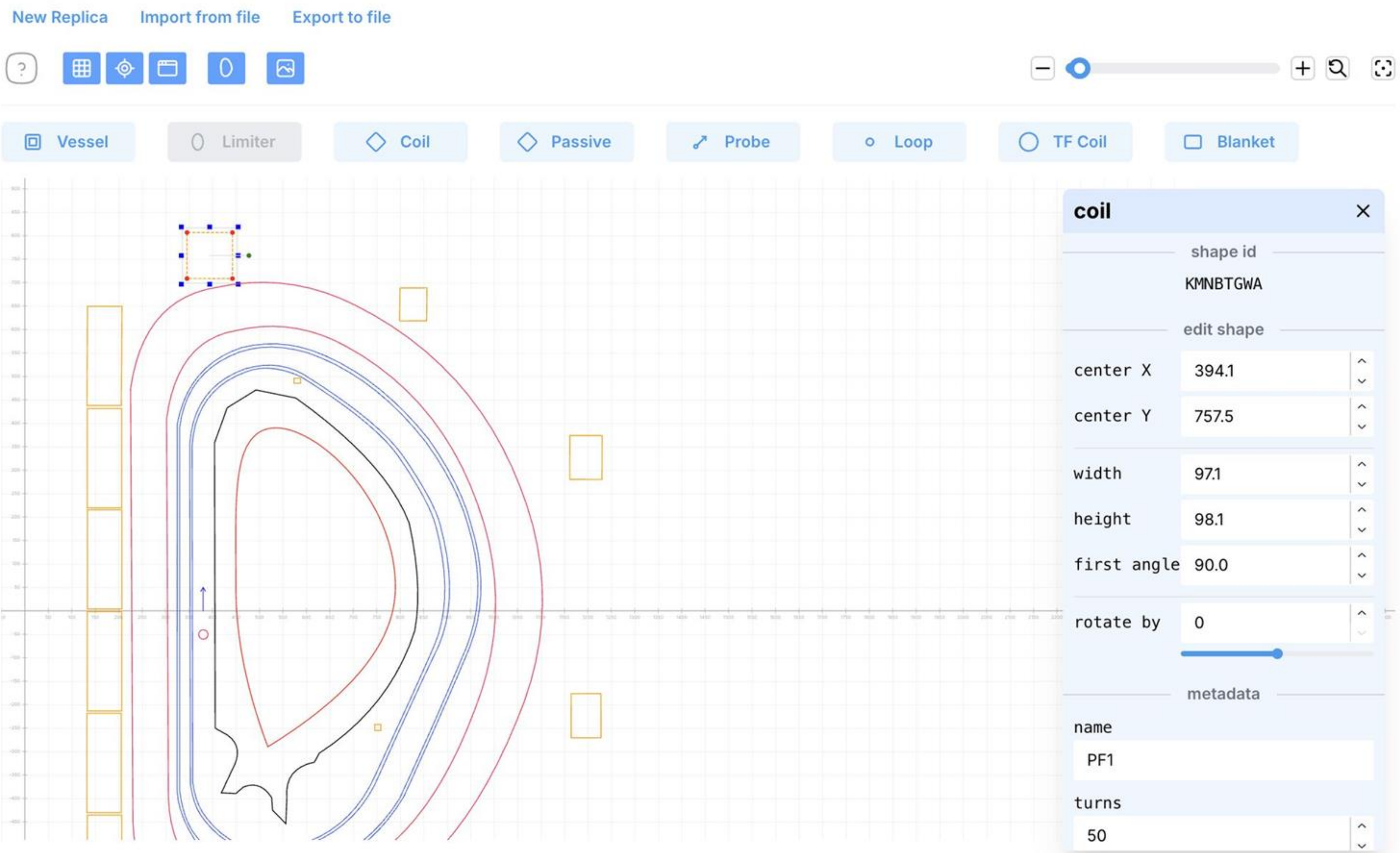
Platform API facilitates software-in-the-loop testing of tokamak plasma controllers. It integrates with NSFsim via MATLAB/Simulink, Python, C, and other languages, exposing all simulator inputs and outputs. The API is freely available for academic use.
https://github.com/Next-Step-Fusion/platform-api-examples

Online simulation Platform



Replica builder

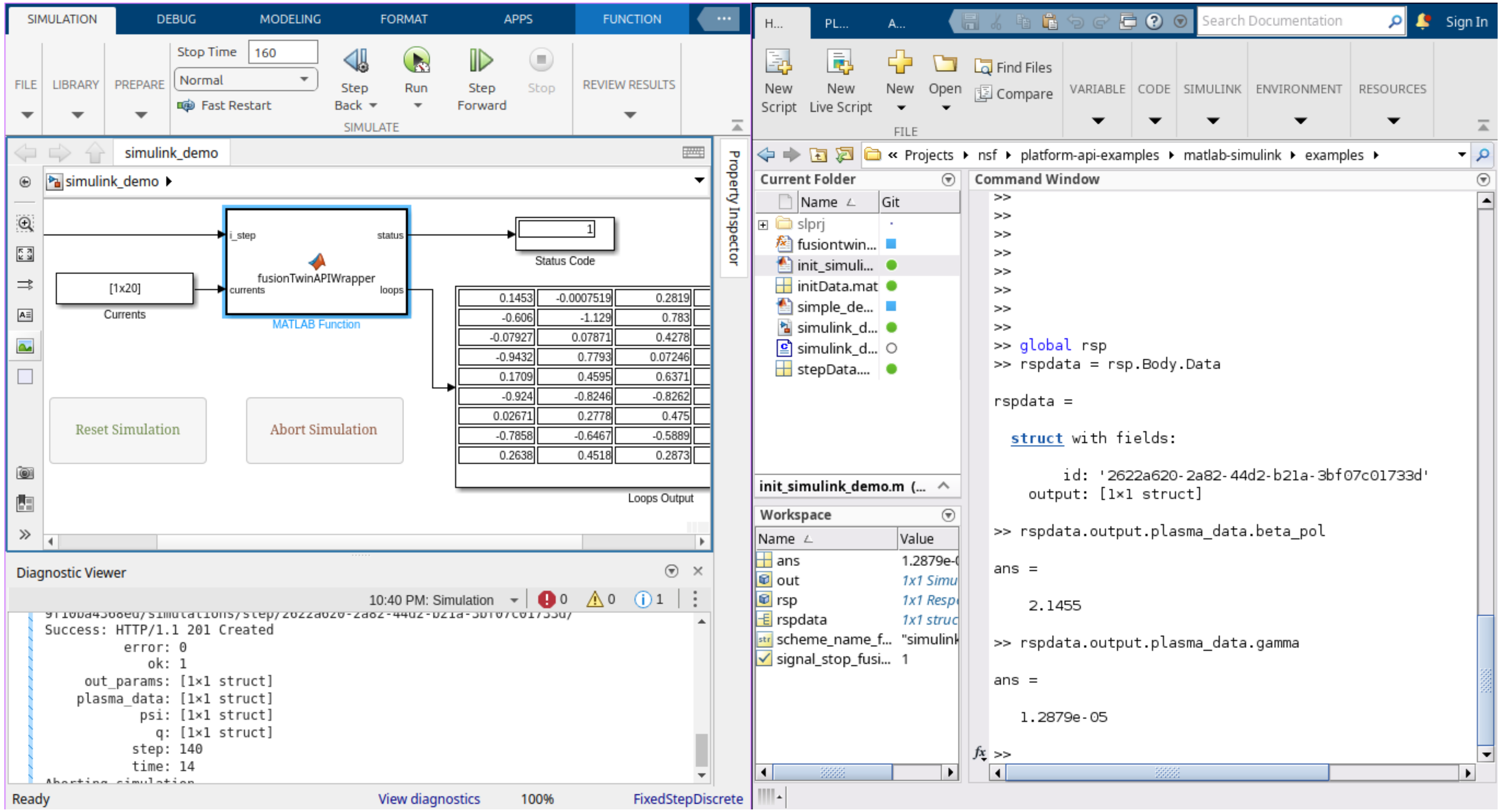
Replica Builder by Next Step Fusion is a browser-based editor for creating a 2D cross-section "digital twin" of a tokamak, including components such as the vessel, coils, and limiter. Users create and edit the replica by placing and adjusting component parameters on a grid. It supports importing and exporting designs and standardizes geometry and configuration data for easy sharing and deployment (as a static build). This enables faster simulation and scenario development in **Fusion Twin Platform**.



https://github.com/Next-Step-Fusion/replica-builder

Public API

Next Step Fusion's **Platform API** provides ready-to-run scripts to start and control cloud tokamak simulations. Users need an account, an API key, and a workspace ID to initialize, run, abort, and save results (HDF5 + metadata) by modifying the **run.py** script and the **JSON** inputs. This facilitates the integration of automated pipelines (including external controllers in **Simulink**) with standardized digital replicas to improve reproducibility, sharing, and visualization.



Use cases can be found at poster and in our publications at nextstepfusion.org

Thank you for your attention