Status and plans of the ITER Pulse Design Simulator

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The various types of plasma simulators

High Fidelity Plasma Simulators	Use high accuracy (potentially time-consuming) models to account for all possible physics to simulate the plasma behaviour	ASTRA, CRONOS, DINA, ETS, JINTRAC, TRANSP
Flight Simulators	Test and validate controllers in closed loop simulations; Strictly restricted to taking input from diagnostics, simulating plasma state from requests sent by the PCS and machine plant systems	FENIX, NEST
Pulse Design Simulators	To design scenarios → write optimal pulse schedule, using closed or open loops, with or w/o controllers; Mostly solves an inverse problem for discharge optimization; Compare to OLCs (physics and plant systems); Resulting pulse schedule can be used: 1) As input to HFPS 2) For plasma operation	METIS, JT60-SA PDS, IMAS PDS
Real-Time Simulators	Faster than real-time; Complement PCS controllers (state estimates, event detection...)	RAPTOR, RAPDENS

Speed ↓ — Complexity / accuracy ↑

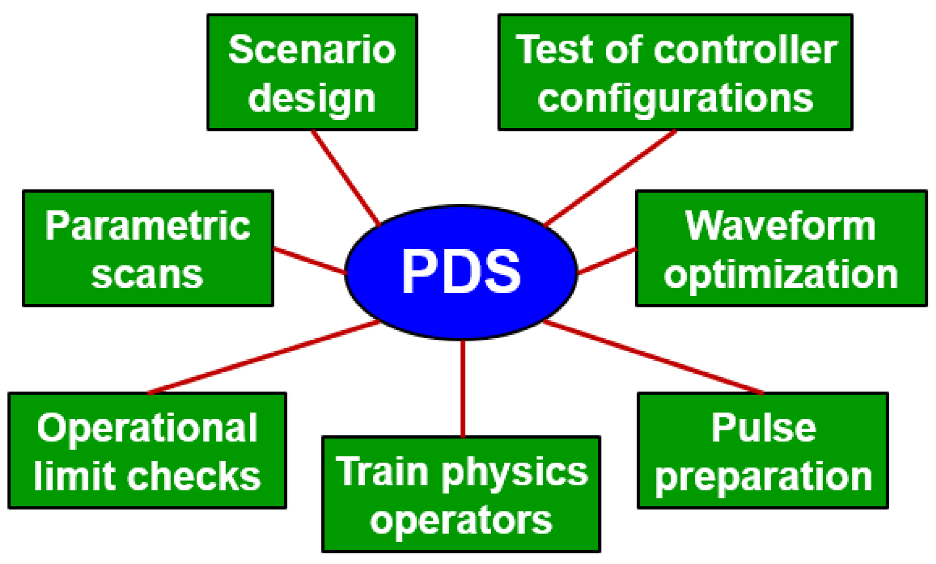
PCS: Plasma Control System *OLCs: Operating Limits and Conditions* [Felici 2023]

Goal of the ITER Pulse Design Simulator (PDS)

- **The goal of the PDS is to generate an optimal pulse schedule to design scenarios of the ITER Research Plan and prepare for ITER operation**

... With the following specific requirements:

- Check that we remain within operational limits (physics + plant systems)
- Use the IMAS standard to communicate between components
- Applicable to any tokamak (provided that they use the IMAS standard!)



In line with plans to start training future ITER Session Leaders!

- Scope of work:
  - Design the overall architecture
  - Build and test a prototype
  - Provide documentation → **Get users!**
- To be validated by comparisons to DINA and to operating devices: WEST, KSTAR, EAST, etc.

PDS pulse planner and simulator

Pulse Planner — Pulse schedule editor + inverse mode

inter-dependent

Pulse Simulator — Using direct mode

- Tool to design a pulse (with a pre-check of operational limits):
  - Plasma shape
  - Waveforms
- Including calculation in inverse mode with transport
- Graphical User Interface

→ On-going development of a Waveform Editor

Generic → compatible with any IMAS plasma simulator (HFPS, etc.)

- Tool to simulate a pulse:
  - Direct mode + controllers
  - Choose models to be launched
  - Various computational modes
  - Iteration loops
  - Actual pulse simulation

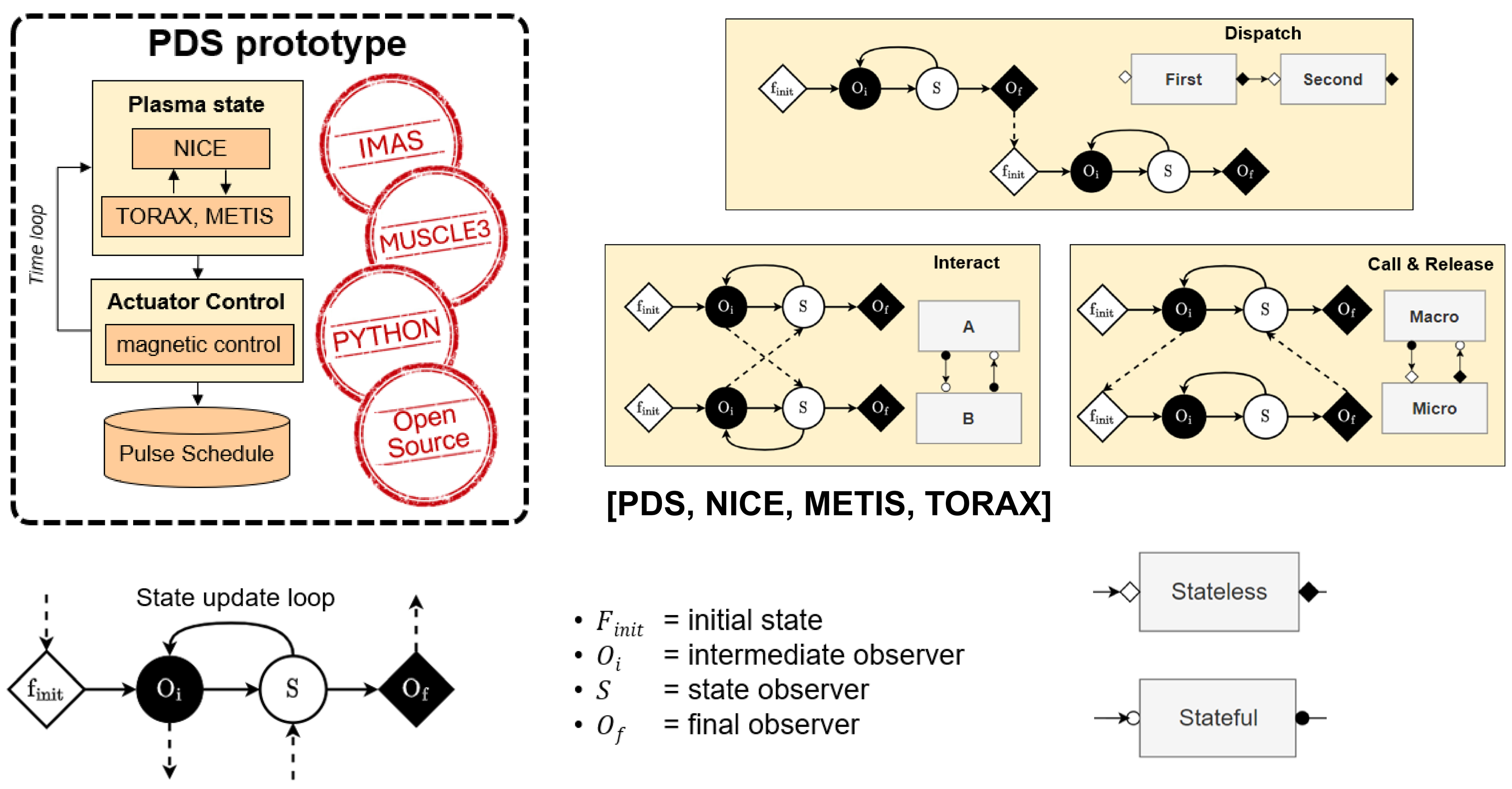
→ Focus of the PDS architecture development

Link being made with control room pulse design tools (WEST, etc.)

PDS technical choices and initial skeleton

Initial skeleton based on coupling between free-boundary equilibrium and transport code using magnetic controllers

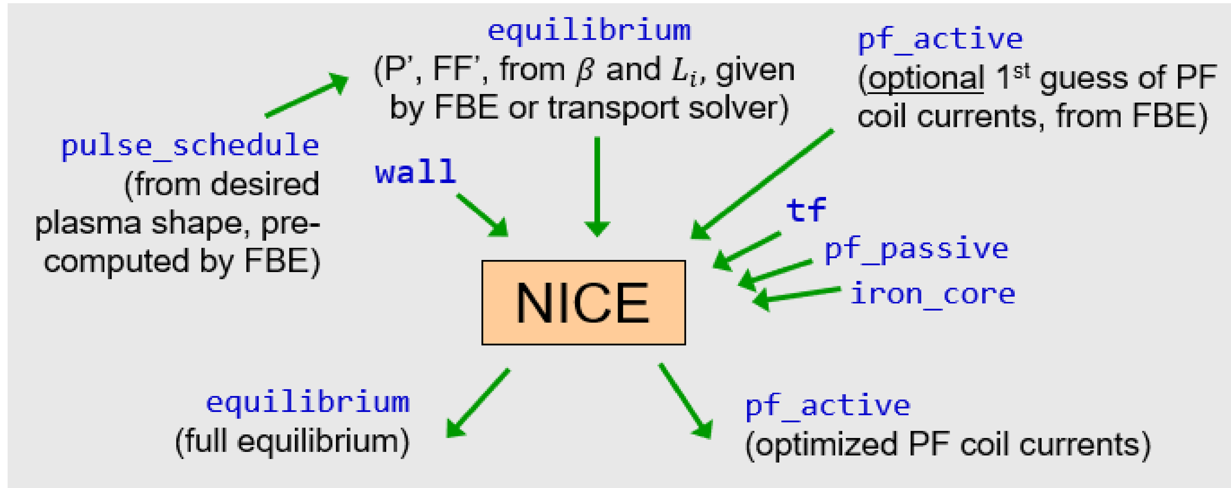
- Uses IMAS standard for data exchange **[IMAS, IMAS-Muscle3]**
- Workflow developed based on the Muscle3 Persistent Actor Framework **[Muscle3]**
- Main development language for the workflow and its tools: python!



[PDS, NICE, METIS, TORAX]

- F_{init} = initial state
- O_i = intermediate observer
- S = state observer
- O_f = final observer

Pulse planner: inverse static mode



With this mode, passive currents are not computed but can be estimated a posteriori with transport ($I_{passive} = V_{loop}/R$).

Can be used to derive a linearized model made around the equilibrium solution:

$$\frac{dX}{dt} = AX + BU \; ; \; Y = CX$$

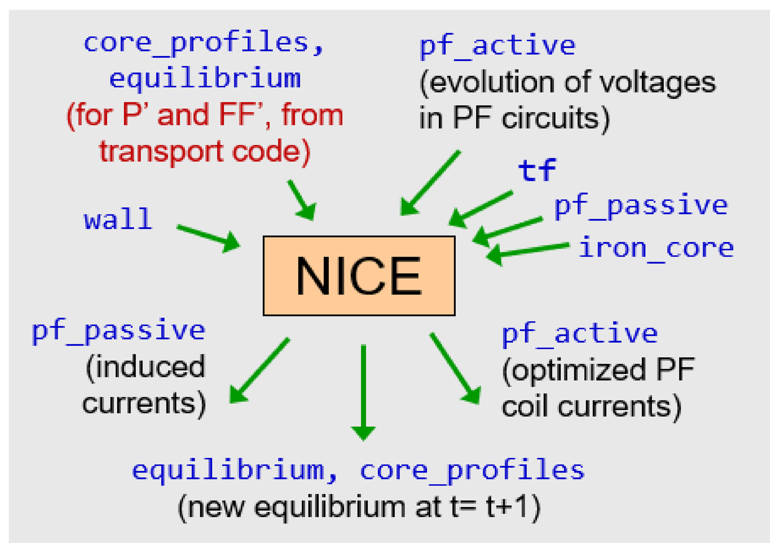
- X = current in PF coils and passive structures
- U = voltages in PF circuits
- Y = desired output (e.g. magnetic axis position, X-point, gaps)

→ A and B matrices to be calculated → Evaluation of the VDE characteristic time

Pulse simulator: direct evolutive mode

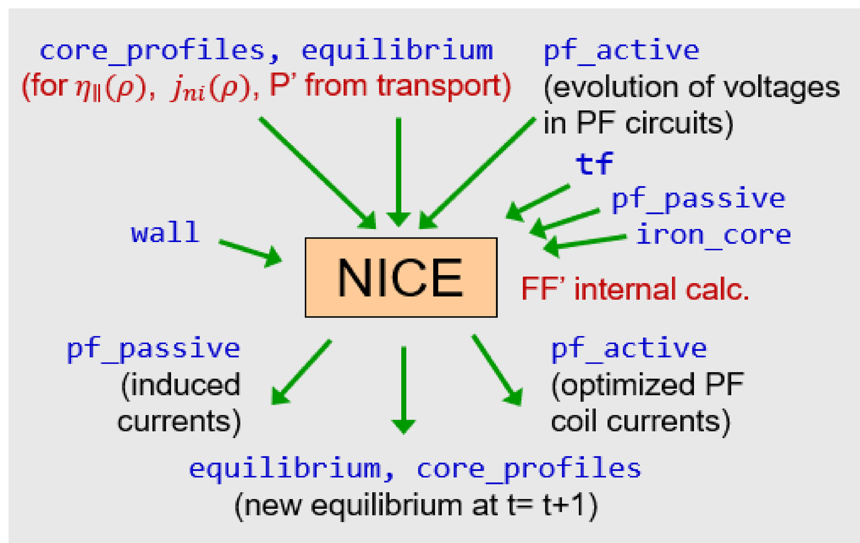
This mode uses magnetic controllers (developed by IO).

Current diffusion calculated by transport code



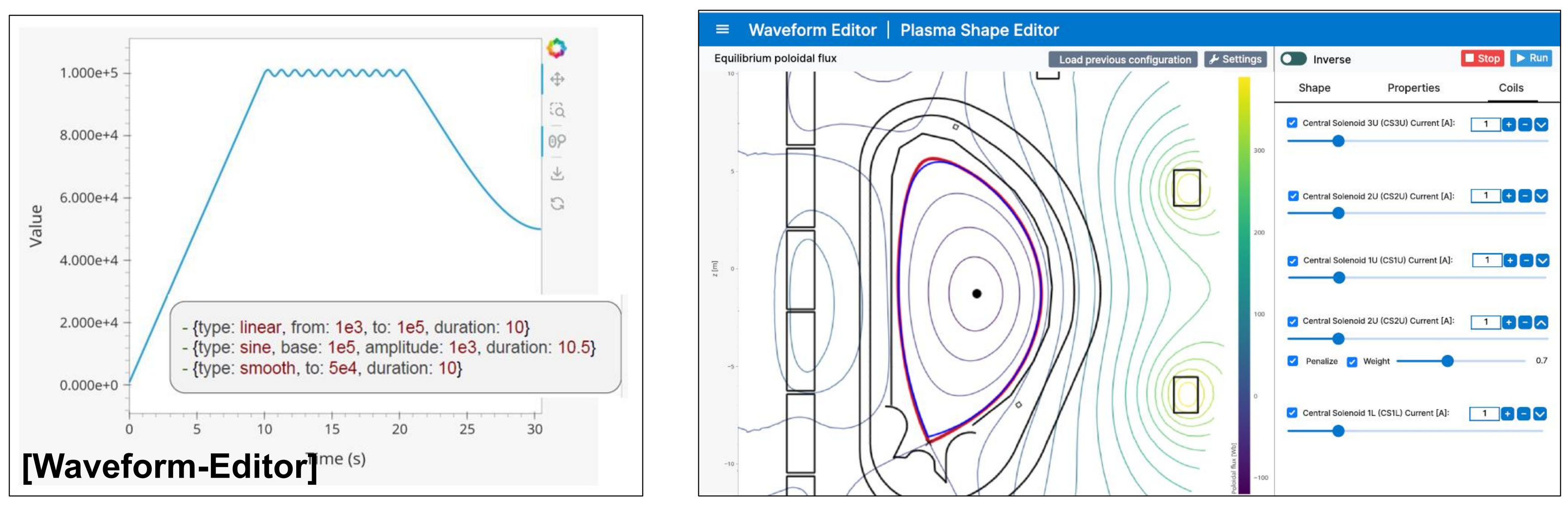
→ Easy coupling

Current diffusion calculated by FBE code



→ Accurate estimate of flux consumption

Development of the PDS pulse editor

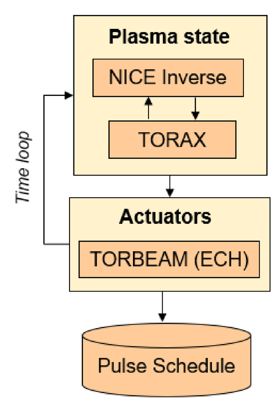


[Waveform-Editor]

Check EC dynamics at 15MA/5.3T with PDS in inverse mode

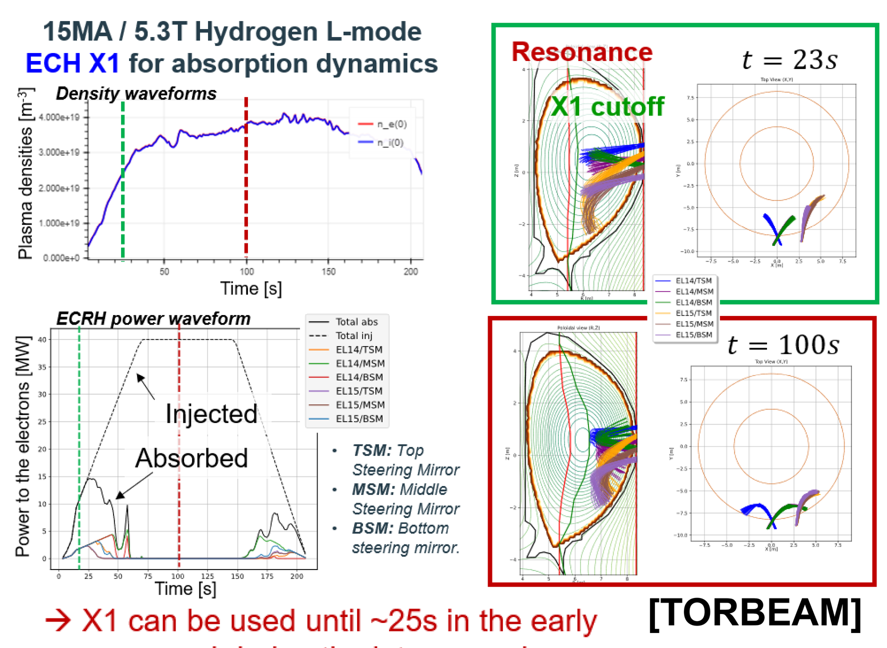
Simulation parameters:

- Heat and particle transport, current diffusion
- **Transport**: QLKNN_7_11 [QLKNN_7_11] until $\rho_n = 0.9$ with ad-hoc anomalous transport at the edge
- **Radiation**: Mavrin polynomial fits from ADAS
- Bootstrap current: Sauter model
- **ECRH:** 40MW with 2 equatorial launchers calculated with TORBEAM
- **Impurity fractions**, **initial profiles** and **edge boundary conditions** prescribed from DINA reference



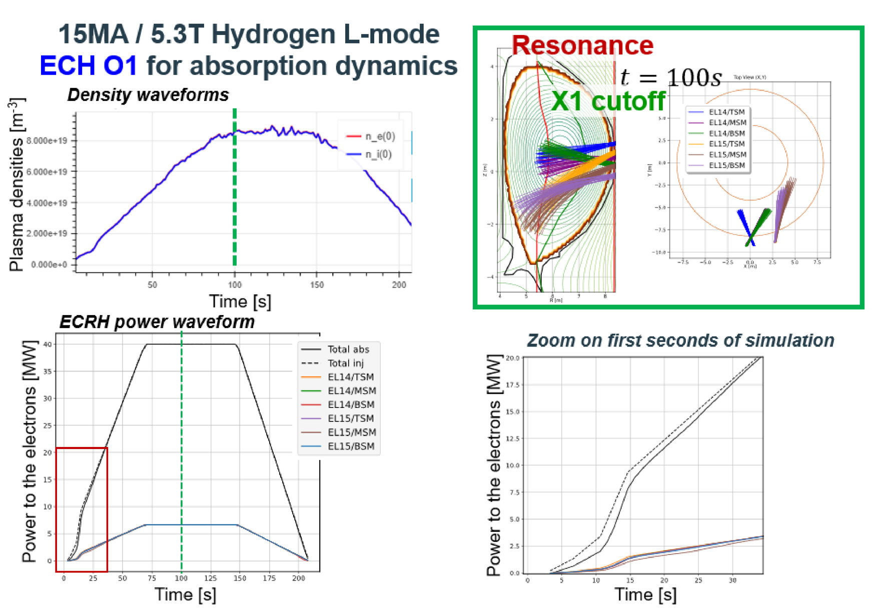
Goal: check the dynamics of ECH absorption for the two polarizations, to assess whether O1 or X1 is more appropriate early ramp-up:

- X1 should absorb since cutoff close to resonance at low density
- O1 less efficient than X1 at low density and temperature



→ X1 can be used until ~25s in the early ramp-up and during the late ramp-down

[TORBEAM]



→ O1 absorbed by 75 to 95% until ~20s

Summary and prospects

- Good agreement with DINA using PDS inverse mode
- Direct mode with magnetic control not ready yet → top priority for 2026-2027
- H&CD workflow about to be integrated [Bian 2026]
- SOLPS-NN surrogate edge model almost there [Karacsonyi 2026]
- Next steps:
  - Implement segments for the pulse planner + simulator → full integration of the two tools for PDS end-to-end simulations
  - Add fuelling and density control
  - Add W transport

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