NEST and its use for WEST plasma operation

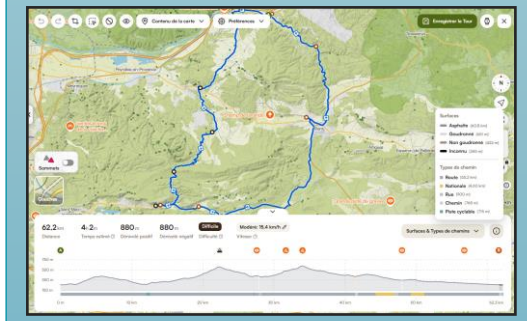
Rémy Nouailletas[1], Guillaume Gros[1], Jean-François Artaud[1], Flore de Cossé Brissac[1], Clement Egot[1], Blaise Faugeras[2], Theo Fonghetti[4], Agnieszka Hudoba[3], Philippe Moreau[1], Mark Lafferty[3], Elisa Lascar[1], Mireille Schneider[4]

September 2026

[1]*CEA, IRFM, F-13108 Saint Paul-lez-Durance, France.*
[2]*LJAD, UMR 7351. Université Cote d'Azur. Parc Valrose. 06108 Nice cedex 2. France.*
[3]*UKAEA, Culham Campus, Abingdon, UK, OX14 3DB*
[4]*ITER Organization, 13067 Saint Paul-lez-Durance, France.*

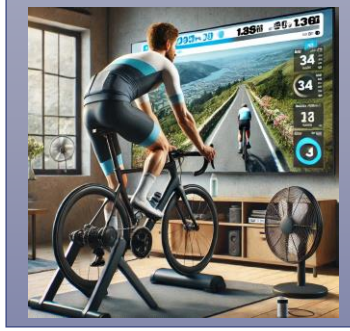
Concepts definition

Pulse design tools



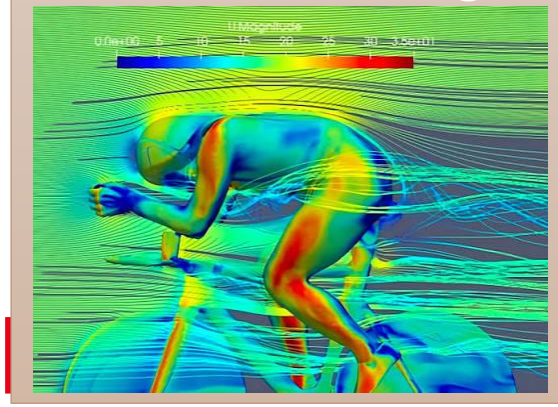
- Plasma scenario preparation
- Evaluation of operational limits

Flight simulator



- Couple the scenario simulation with available controllers

Digital twin



- Tokamak design and optimization
- Post-pulse analysis

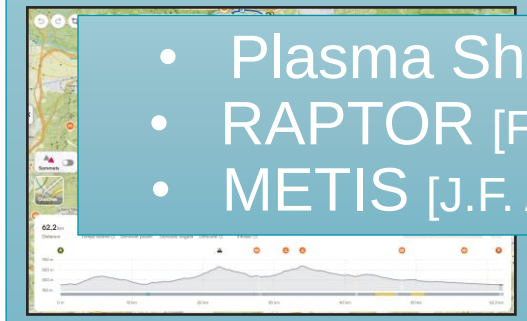
Tokamak



- Run plasma scenario
- Plasma commissioning Installation of new components

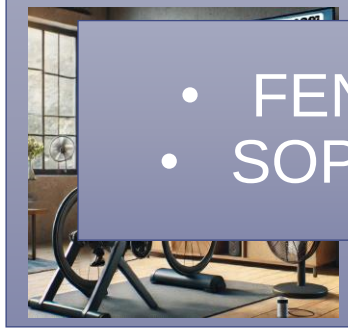
Concepts definition

Pulse design tools



- Plasma Shape Editor
- RAPTOR [F. Felici, 2018]
- METIS [J.F. Artaud, 2018]

Flight simulator



- FENIX [E. Fable, 2022]
- SOPHIA [F. Janky, 2026]

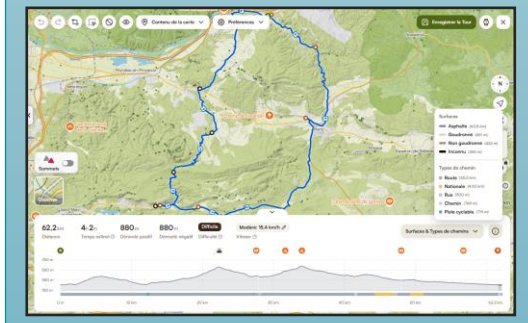
Digital twin



- V-KSTAR [J.M. Kwon, 2024]

- ITER Pulse Design Simulator [M. Schneider, SOFT 2026]
- JT-60SA Pulse Design Simulator [E. Joffrin, IAEA 2025]

Pulse design tools



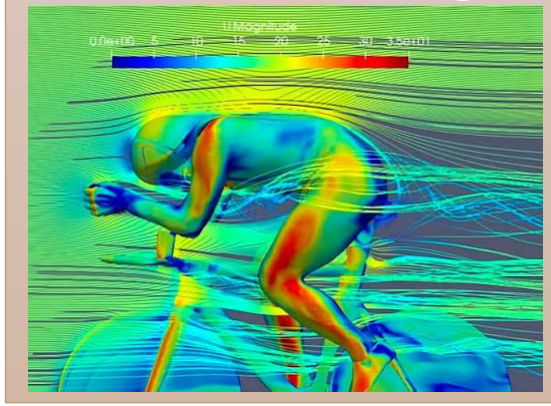
- Plasma scenario preparation
- Evaluation of operational limits

Flight simulator



- Couple the scenario simulation with available controllers

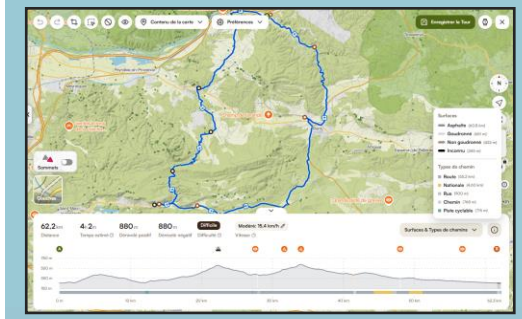
Digital twin



- As closed as required of the real plant
- Tokamak design and optimization
- Post-pulse analysis

NICE Environment for Simulated Tokamak

Pulse design tools



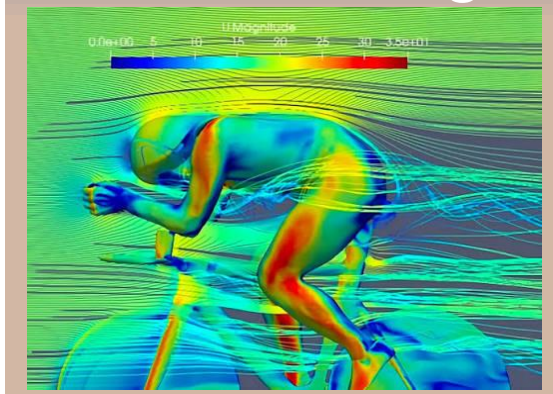
- Plasma scenario preparation
- Evaluation of operational limits

Flight simulator



- Couple the scenario simulation with available controllers

Digital twin



- Tokamak design and optimization
- Post-pulse analysis

1. NEST operating modes

Two available operating modes of NEST

Production mode

- Interfaced with the WEST pulse schedule editor Xedit
- Use same controllers as WEST PCS (MATLAB Simulink)
- Power/current drive source modules for LHCD and ECRH
- Synthetic magnetic diagnostic + reconstruction code

Development mode(s)

- Python magnetic controllers
- Plasma target reference given by configuration files (YMMSL)
- Modules list function of the studied problem

Common features

- **NICE:** free boundary equilibrium code with resistive diffusion and 1D transport (time evolution mode)
- Empirical heat transport model (Bohm/Gyro-Bohm module)
- Averaged time-varying density is prescribed
- Interfaced with the WEST pulse IMAS database
- Use of MUSCLE3 inter-processes communication library for data exchange

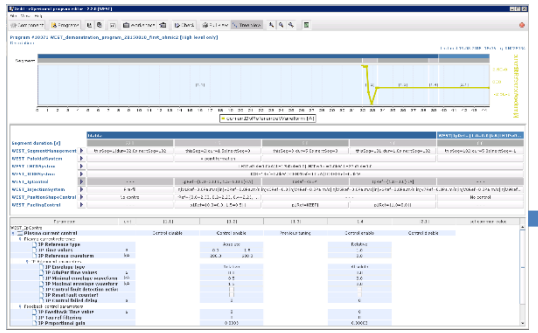
} shared with other tokamak integrated modelling platforms

2. NEST production mode

- Negative triangularity scenario preparation

NEST architecture is fully integrated in WEST environment

WEST Pulse Schedule editor Xedit



WEST IMAS database

DP.xml Sup.xml

Mapping Scripts

Xml files for PCSSP TimeSeriesGen.

TOP (Former WEST database)

Top2Simulink

Controllers configuration

NICE
Free Boundary direct code with evolution
diffusion and 1D transport model

Bohm/Gyro Bohm Transport Core model

Source Core Merge

TORBEAM

LH_antennas model

EC_launcher model

Equilibrium reconstruction

Wall model

PF_active model

Core_profile model

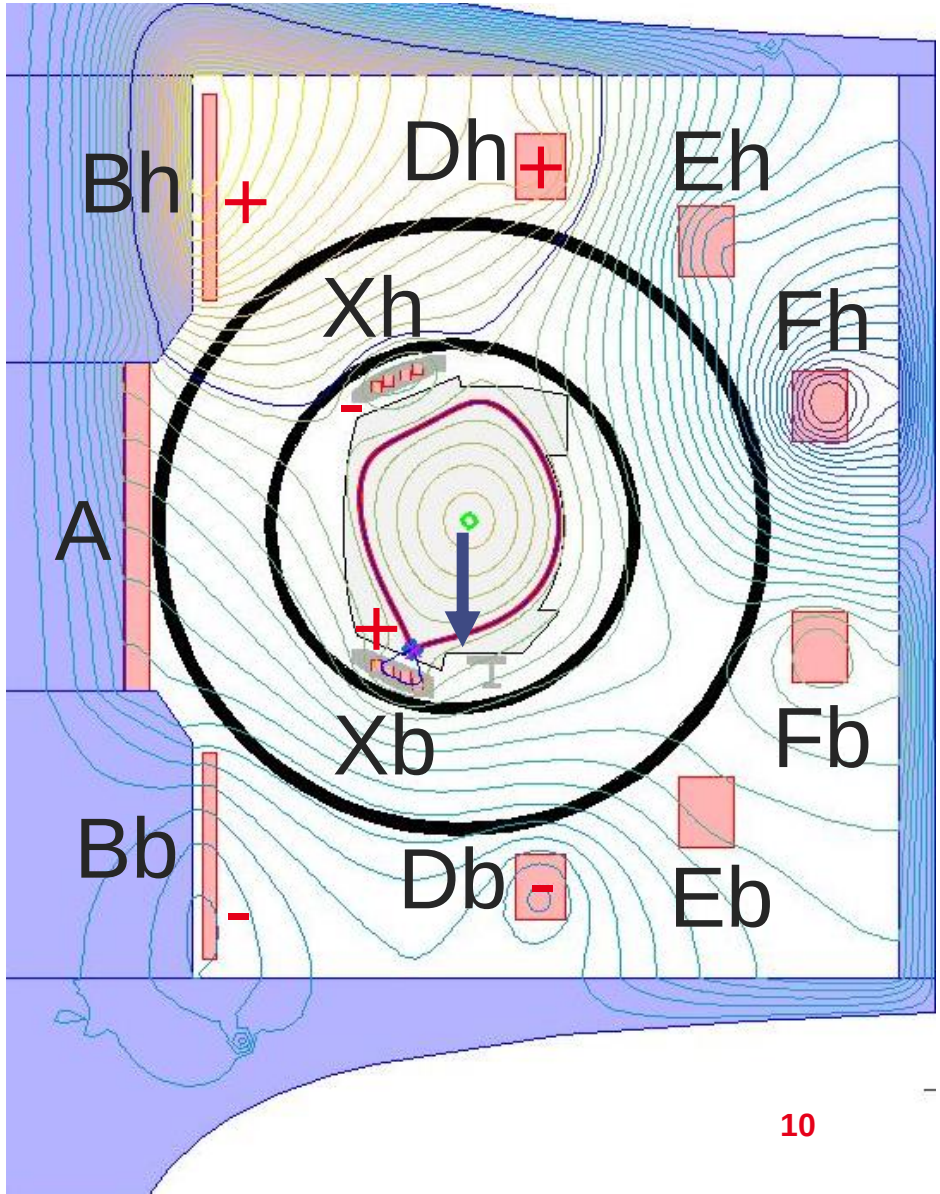
Plasma Control System + CODAC
- Segment Manager
- Magnetic control
- Heating control

Python
Fortran
IMAS IDS message
C++
MATLAB Simulink
Python list message

Present limitations:
- Zeff, Ti/Te ratio constant scalar
- No modeling of the LH coupling
- No density time evolution modeling, no fueling control

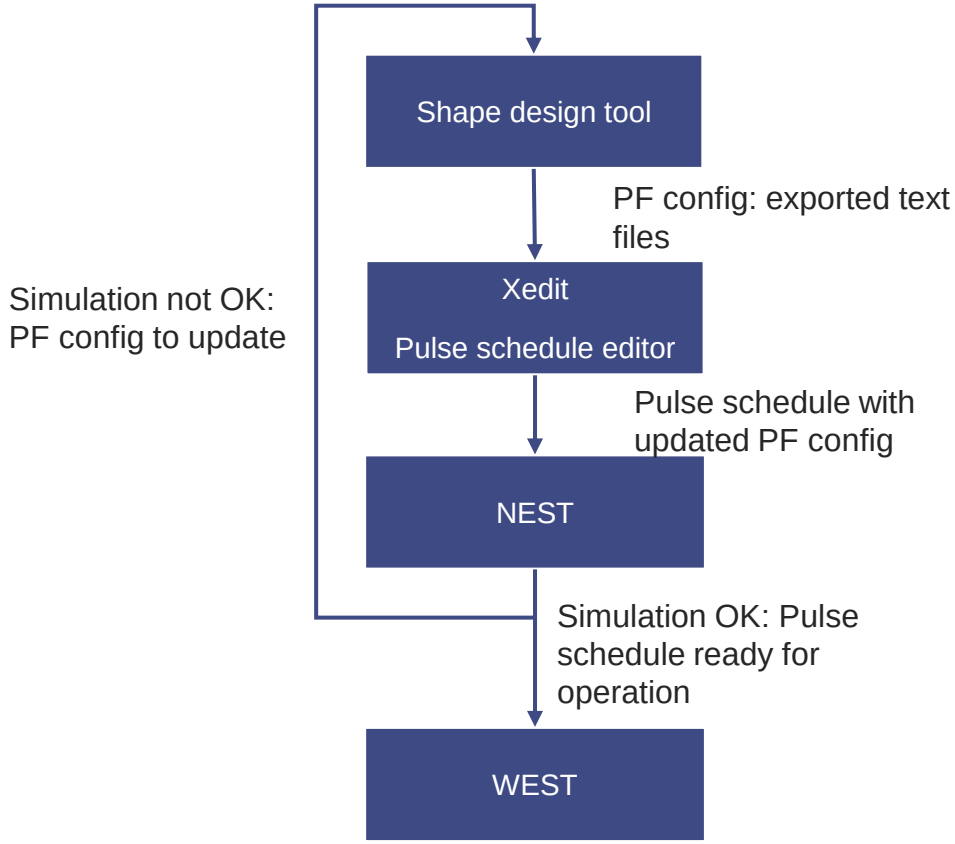
Negative triangularity scenario was developed for WEST with NEST in production mode

- Upper negative triangularity on WEST can be achieved with reversed upper divertor coil current
- **Challenges:**
  - The PF coil reference currents are very closed to the thermal limits
  - The magnetic controller is not originally designed to control negative current in the upper X coil
  - The X-point formation should be totally redesigned
  - Plasma commissioning in 3 days

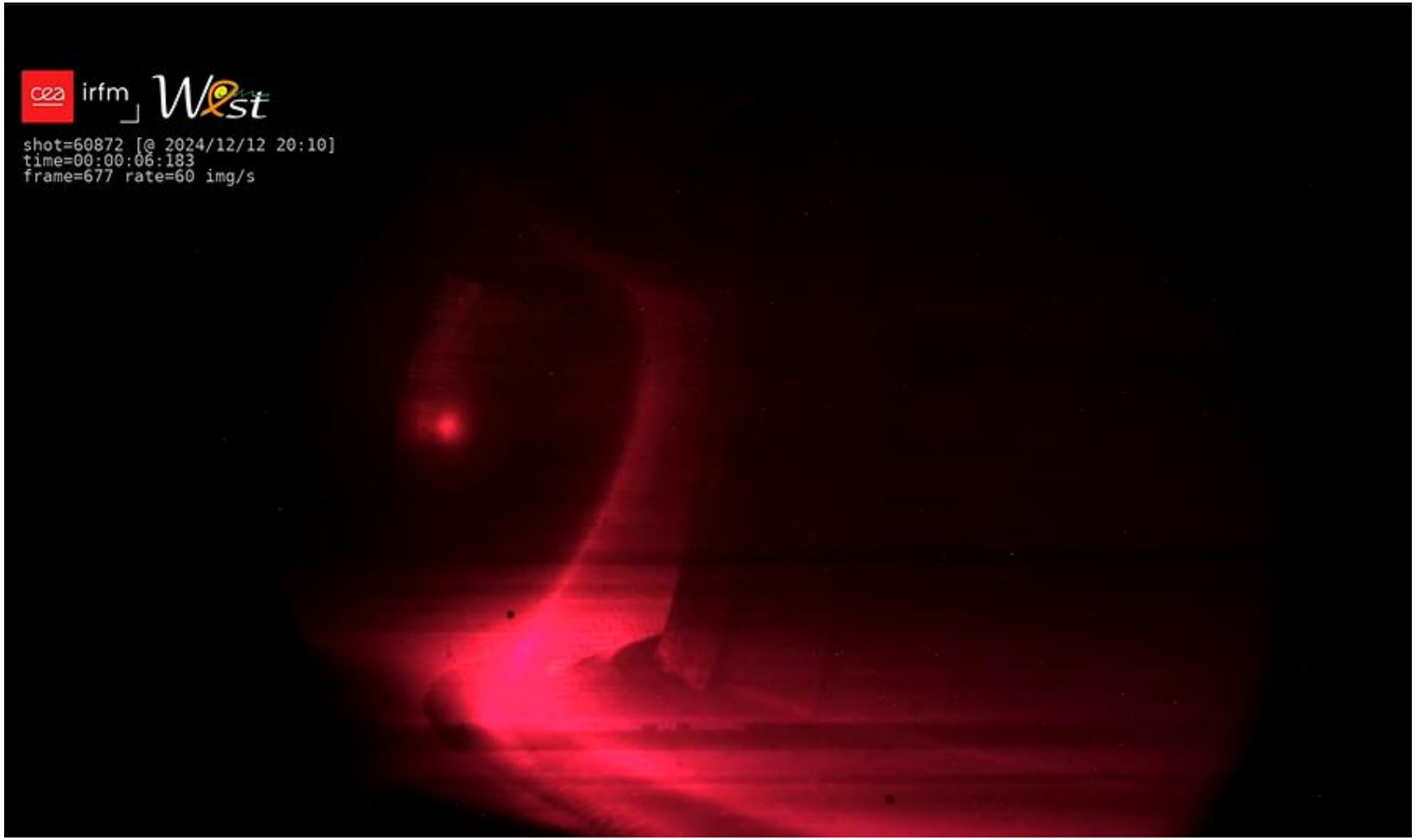


Scenario developed in 4 steps

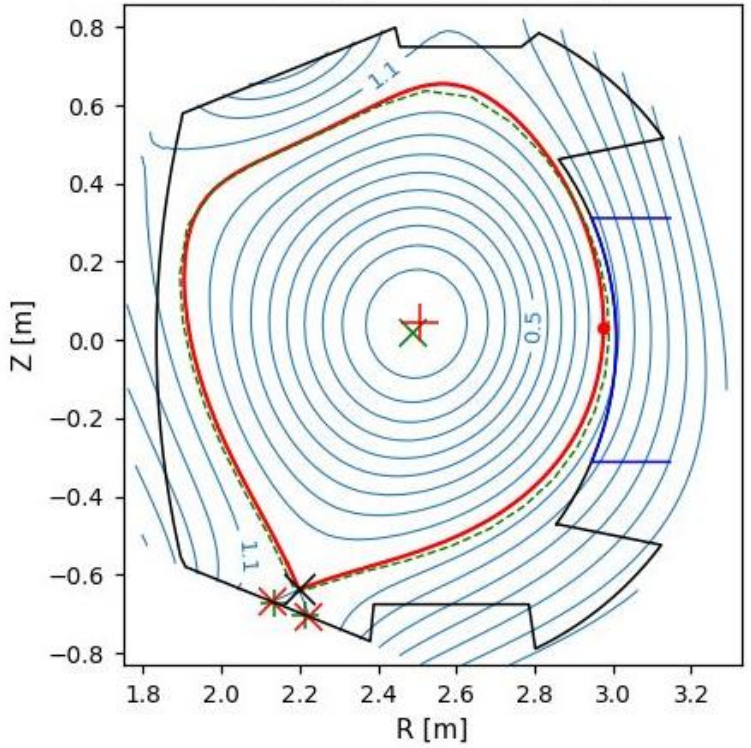
- **Step 1**: Define the sequence of magnetic configuration snapshots to get the final desired shape
- **Step 2**: Set the configuration into the Pulse schedule editor with the corresponding PF current waveforms
- **Step 3**: Run NEST in production mode
- **Step 4**:
  - Simulation OK: Run the scenario on the real plant
  - Simulation not OK: Adjust the waveforms to compensate for eddy currents, plasma drift…



WEST negative triangularity scenario successfully tested and achieved



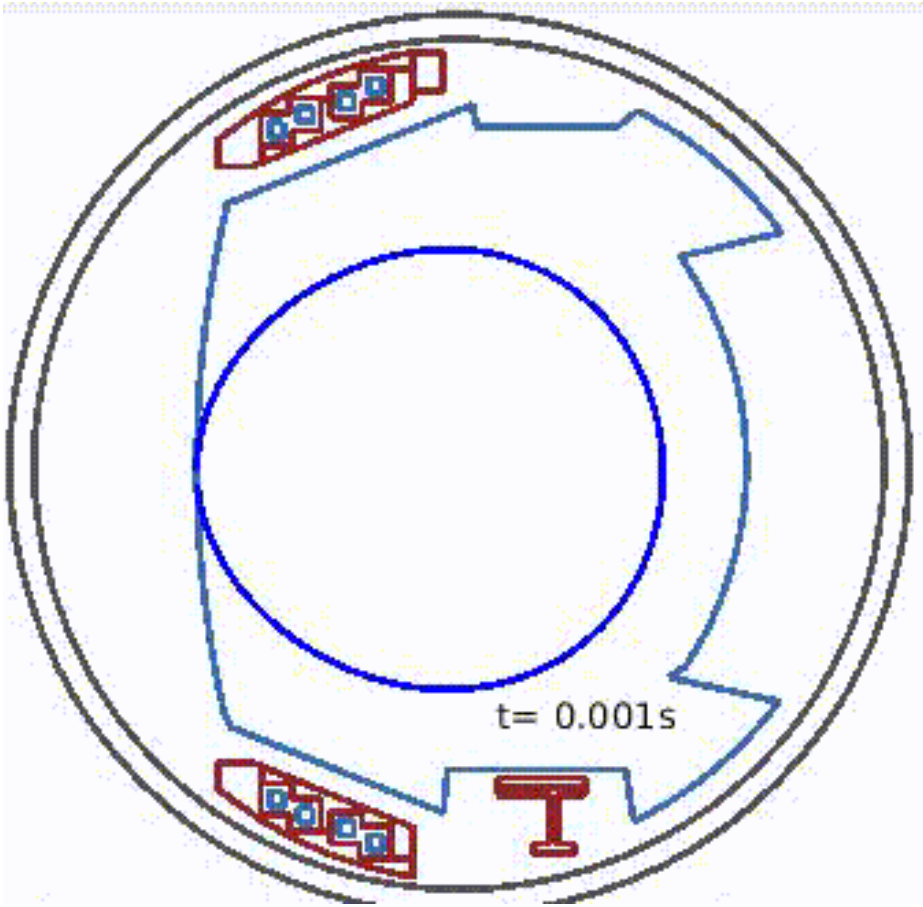
WEST#60872, t=6.859s



- B_T=3.76T
- I_p=400kA
- δ_{up}=-0.18

NT scenario development: Lesson learnt

1. Plasma parameters adjusted to get the realistic flux consumption and eddy currents
2. NEST has validated the modification of the divertor coil current controller
3. This simulation preparation phase (4 weeks, 150 simulations) gave us confidence to start the plasma commissioning
4. Successful first current flat-top in negative triangularity after 6 attempts



NEST NT scenario simulation

3. NEST development mode

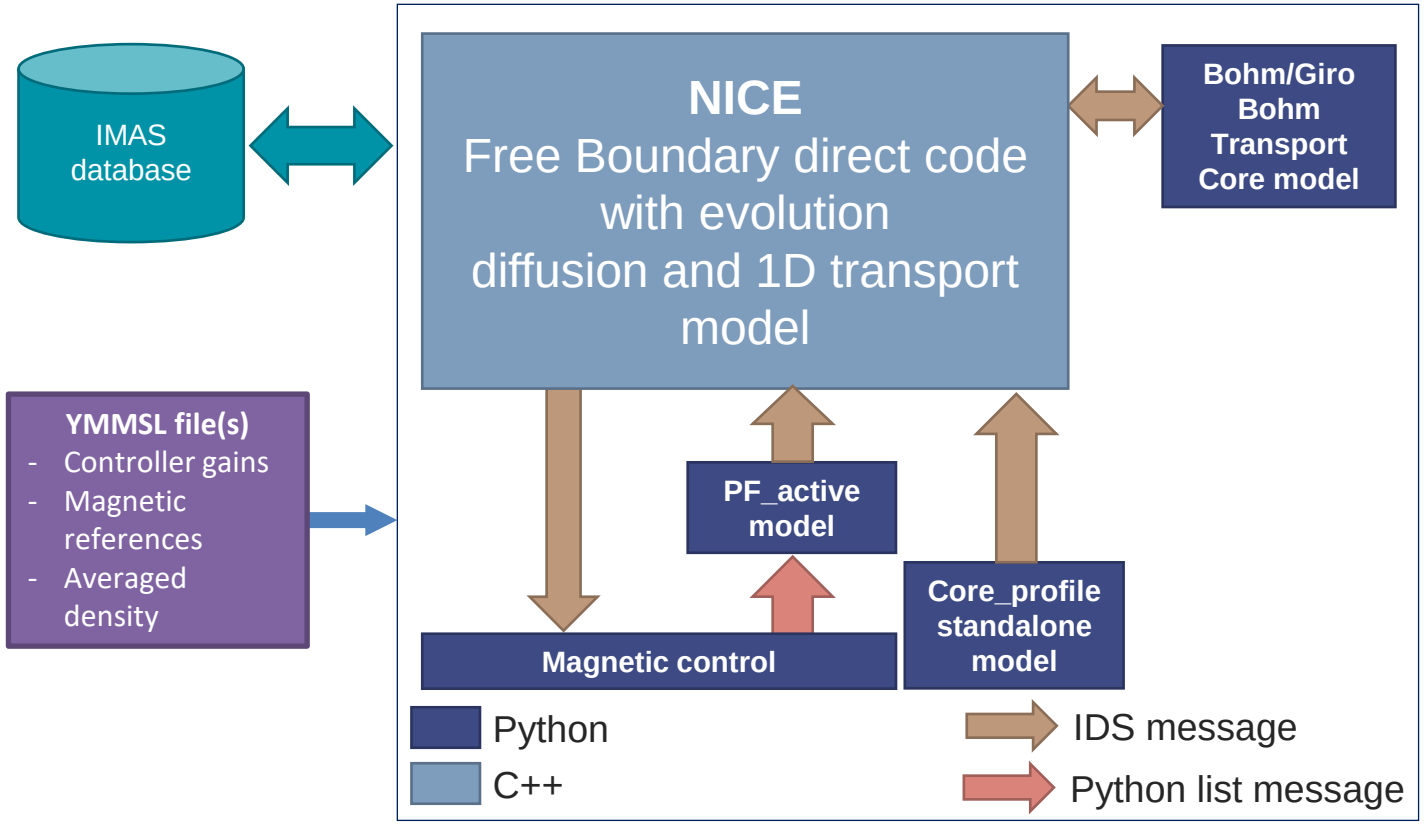
- Double null control development
- Plasma shape reconstruction analysis
- ECRH commissioning preparation
- Stabilization plate design

NEST development mode can be used for multiple purposes

- Tuning/assessment of new magnetic control laws
- Test new modules before integration into the production mode
- Preparation of commissioning of the new WEST EC heating system
- Design of stabilization plates

Configurations

- Function of the use case
- Workflow as simple as possible

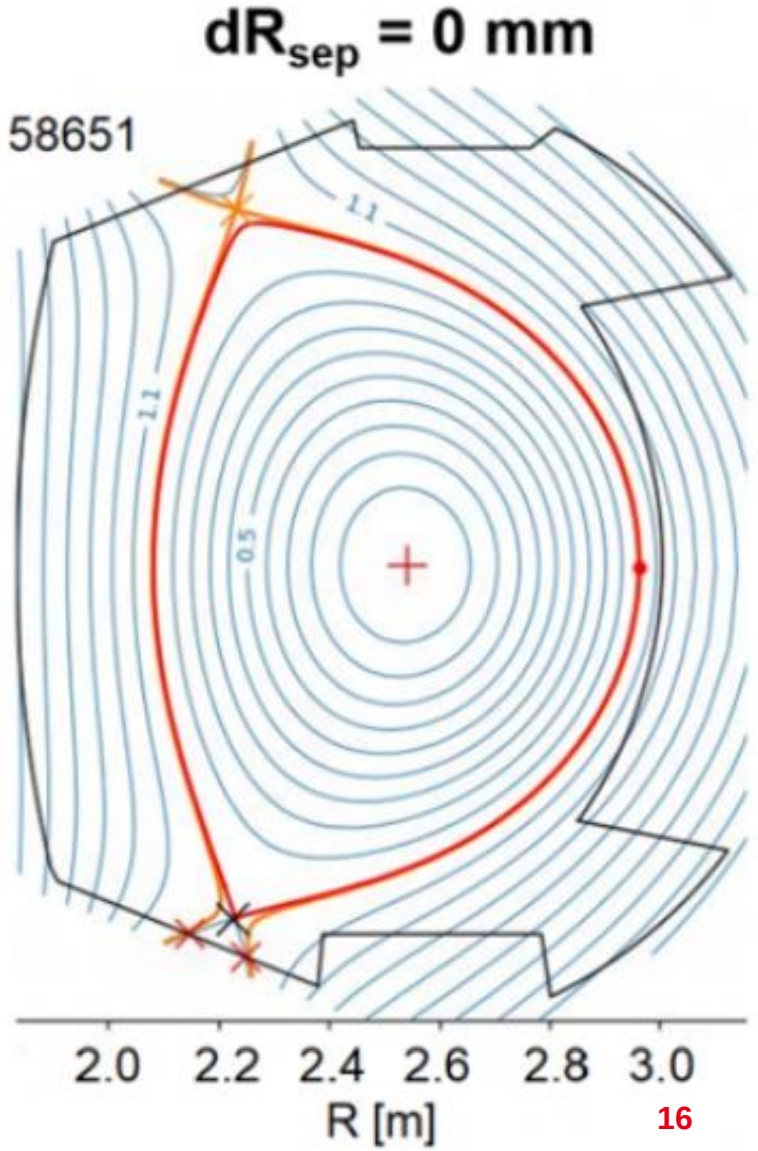


Example of NEST configuration for Magnetic control development

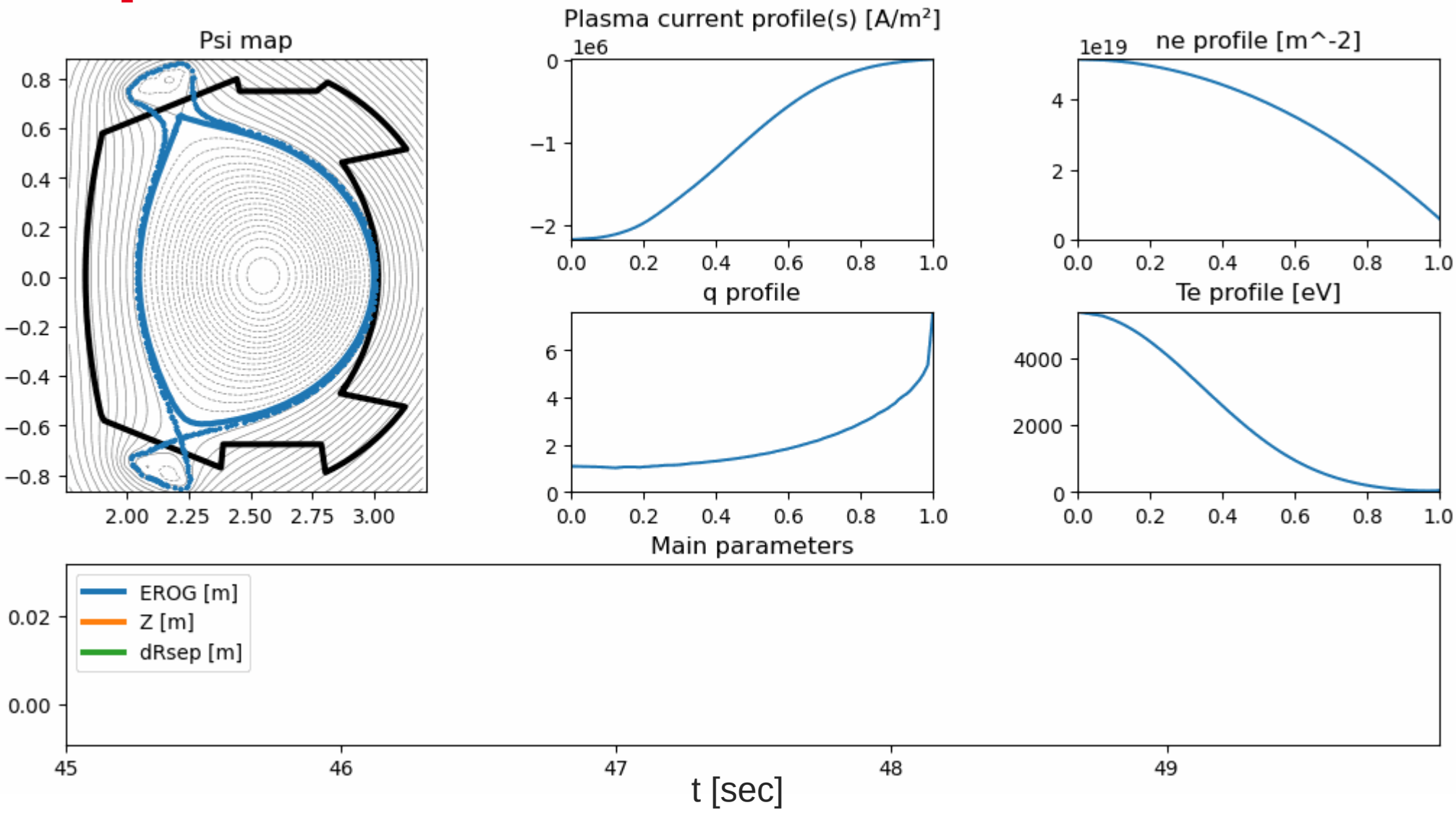
Double null configuration control is designed with NEST development mode

- Double null configuration consists of creating 2 X-points in the vessel
- The gap between the two separatrices (dRSep) controls the power heat load balance between the two divertors
- Shape is controlled using independent SISO controllers

- **Challenges**:
  - dRSep should be feedback controlled
  - Couplings between dRsep and other shape parameters require a new MIMO control design

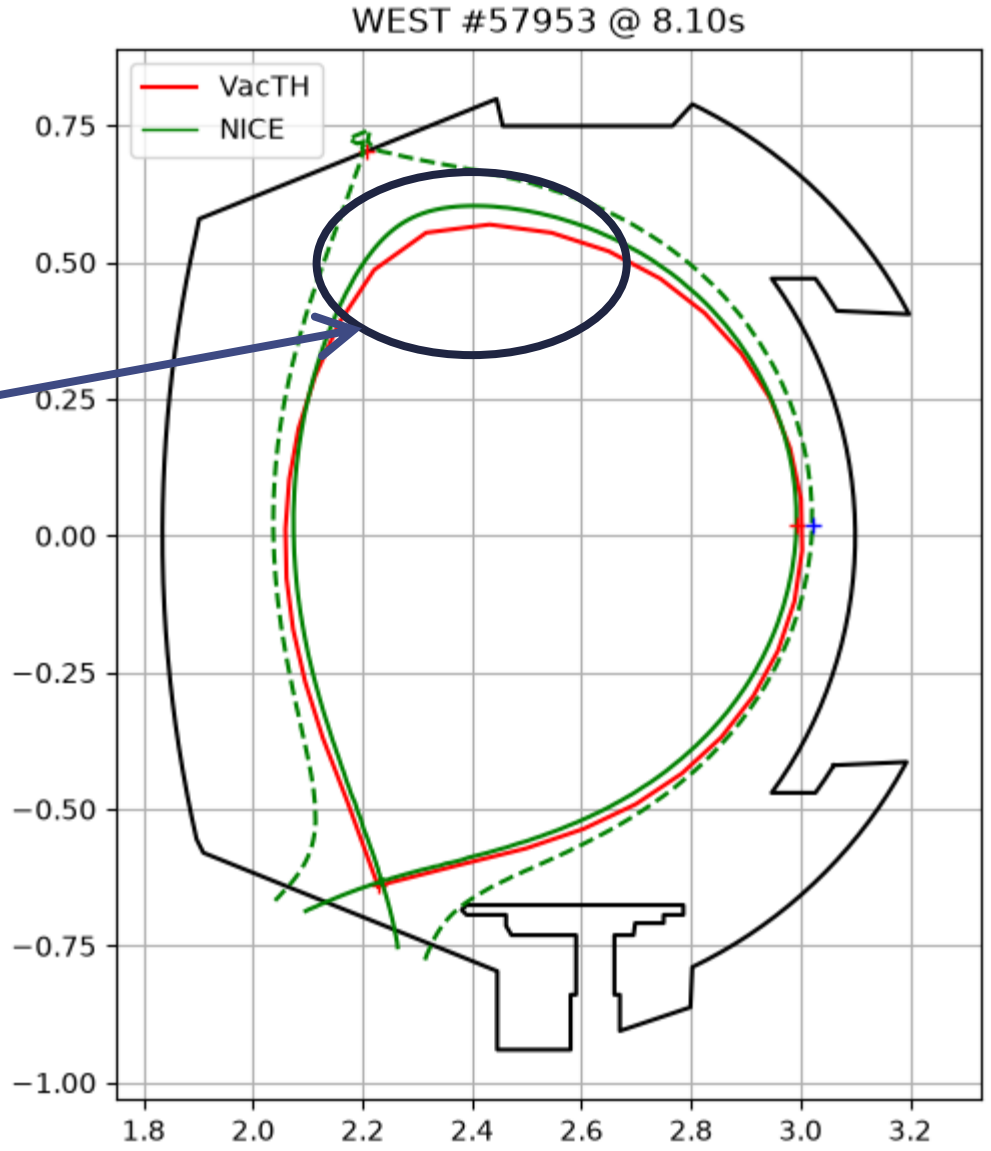


New Double Null MIMO controller successfully developed with NEST



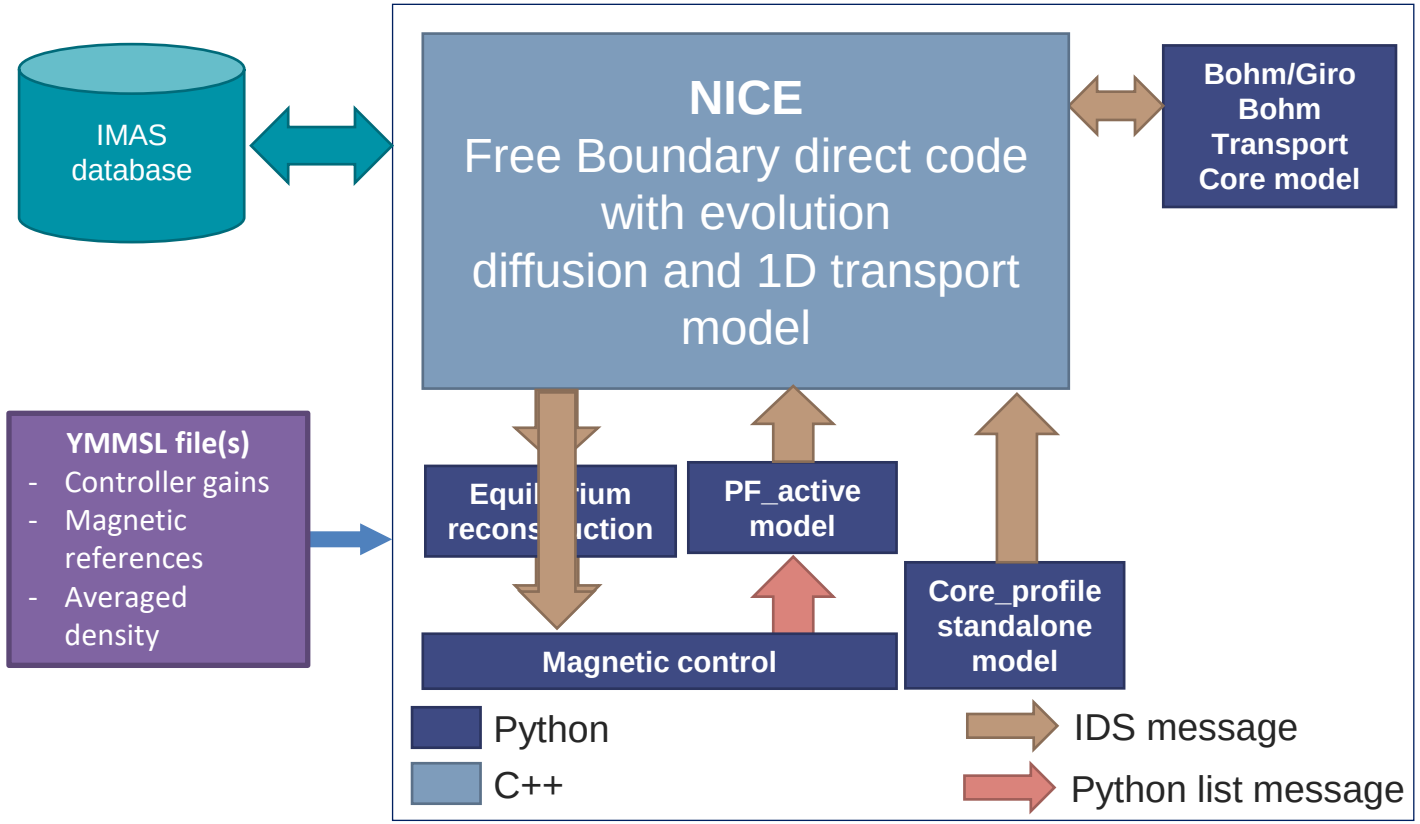
Plasma reconstruction on WEST: where is the plasma?

- On WEST the plasma shape is estimated in real-time using boundary reconstruction code (VacTH)
- It can be compared with the offline full equilibrium reconstruction by NICE
- A significant gap exists



NEST integrates synthetic diagnostics

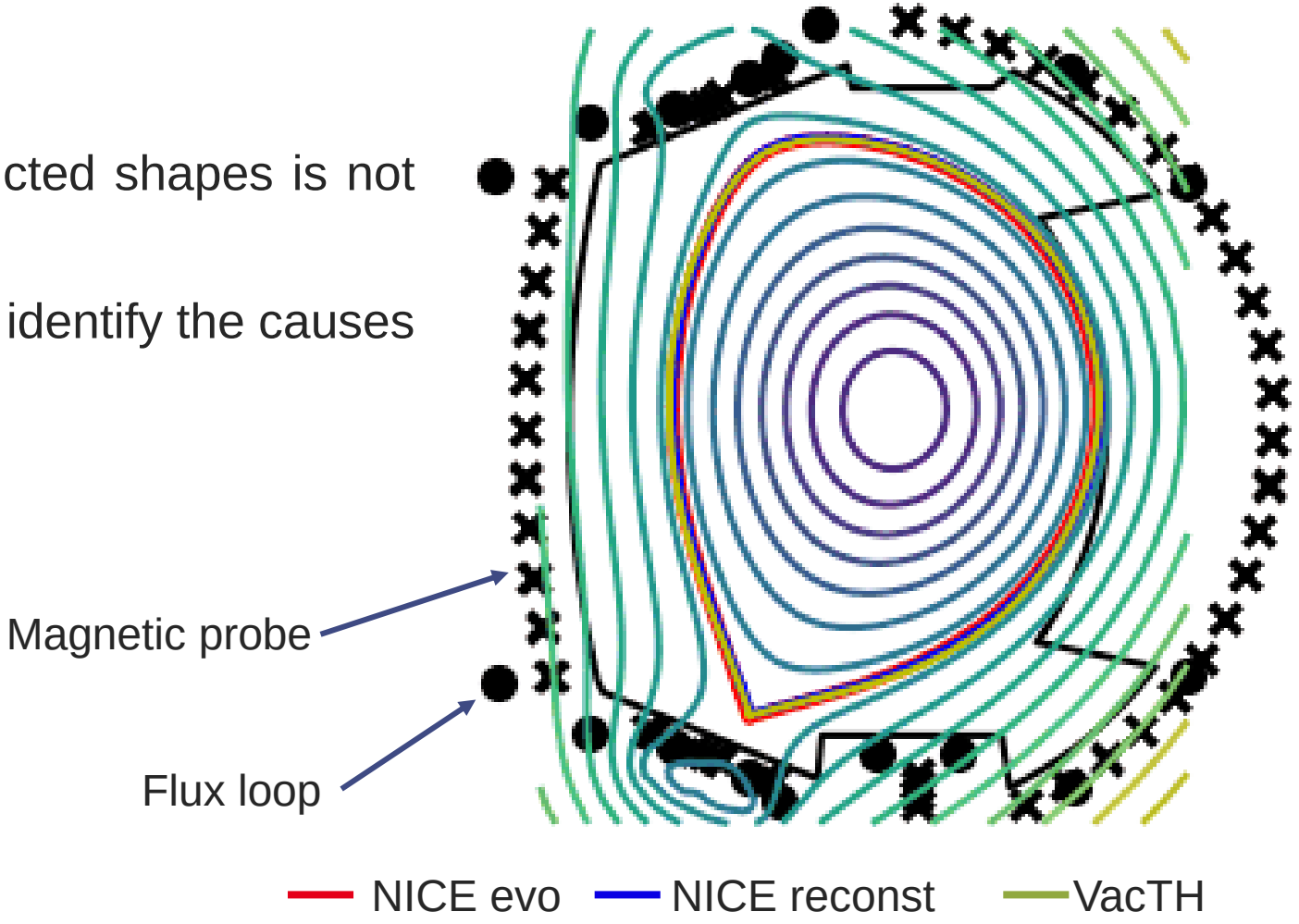
- Recently, a plasma equilibrium reconstruction module has been added to NEST:
  - Synthetic magnetic diagnostic is embedded into NICE evolution mode
  - VacTH and NICE reconstruction mode are both available
  - The reconstructed plasma equilibrium is used to feed the magnetic controller
- It is useful to investigate any shape reconstruction issues



NEST configuration with magnetic equilibrium reconstruction

Reconstructed plasma shapes of VacTH and NICE are very closed to the simulated equilibrium

- The experimental gap between reconstructed shapes is not observed in simulation
- Simulation tests will be now proceeded to identify the causes of the mismatch

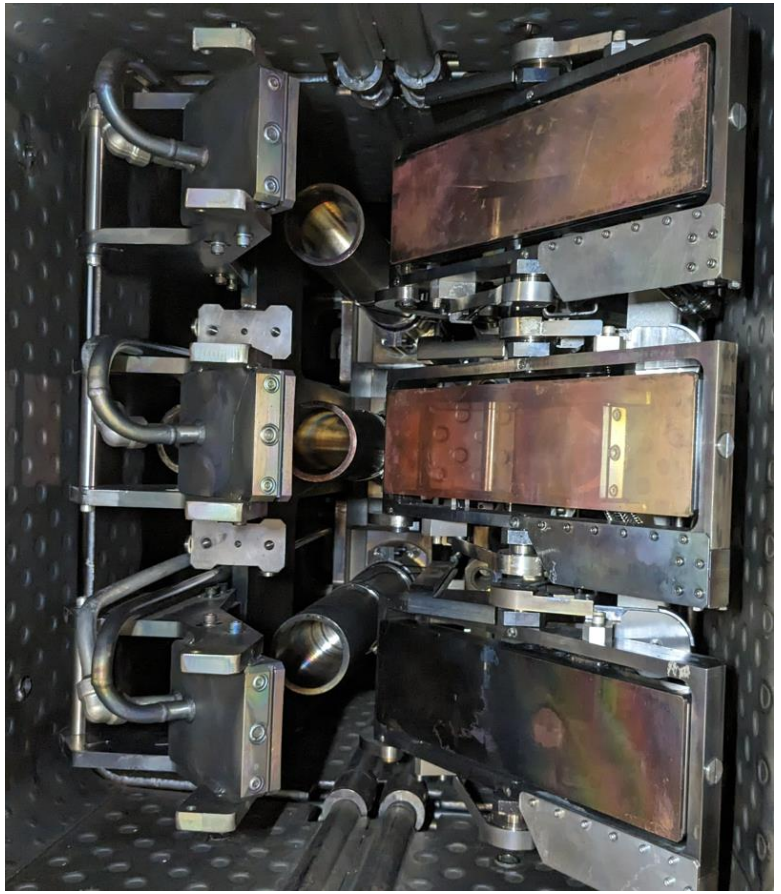


NEST has been setup to prepare ECRH commissioning on WEST

- ECRH system has recently been installed into WEST
- Commissioning phase has been started

Challenges:

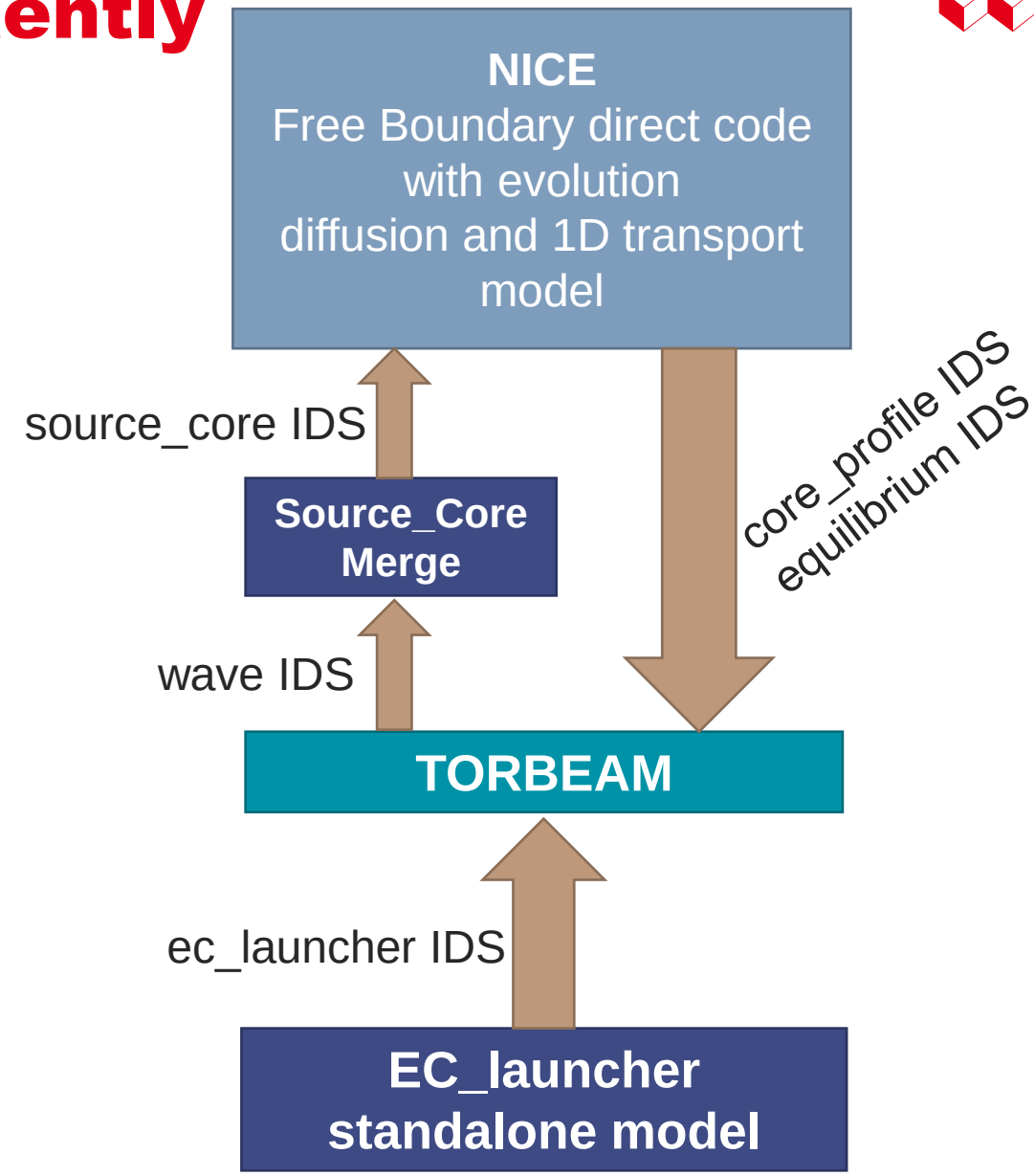
- Power reflections on the wall could damages the wall
- Power/current deposit are related to the mirror angles of the launcher
- To avoid any risks, some diagnostics (ECE, Reflectometry..) are not available during ECRH commissioning



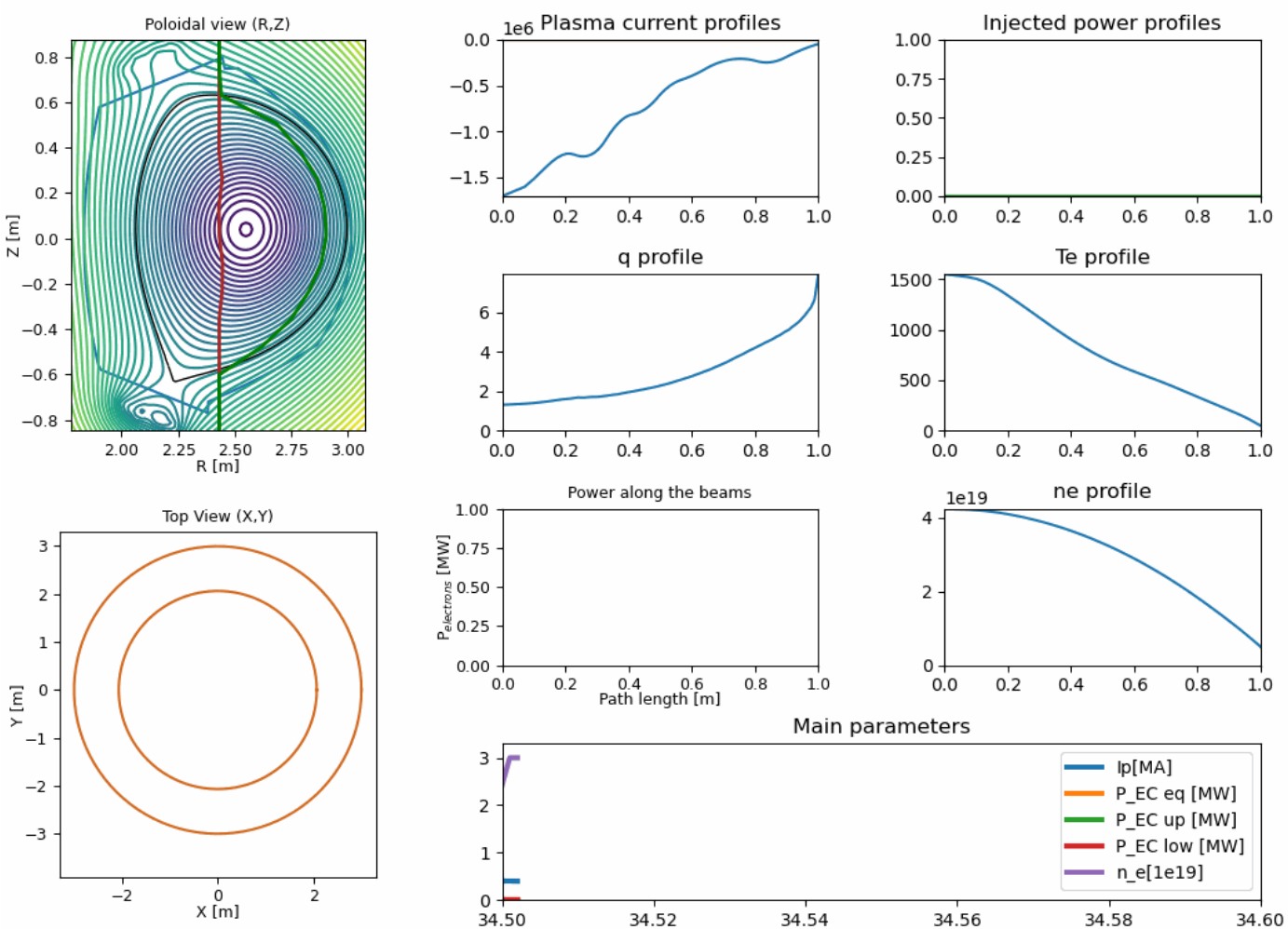
WEST ECRH antennas
[L. Delpech, SOFT 2026, 24/09 11am]

TORBEAM is integrated consistently into NEST

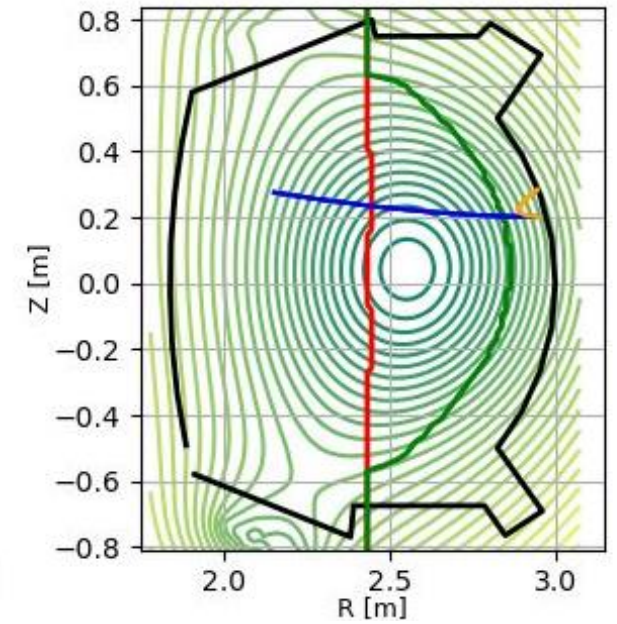
- **TORBEAM:** ECCD and ECRH deposition code [E. Poli, 2018]
- **EcStray** (in TORBEAM) computes the power deposition on the wall



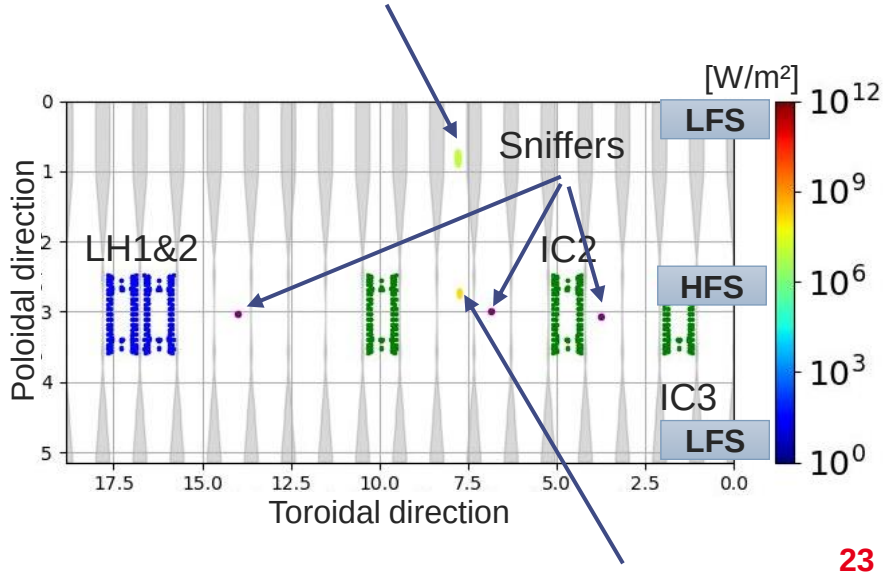
NEST simulation with TORBEAM



WEST ECRH pulse in O mode



Mode O refraction

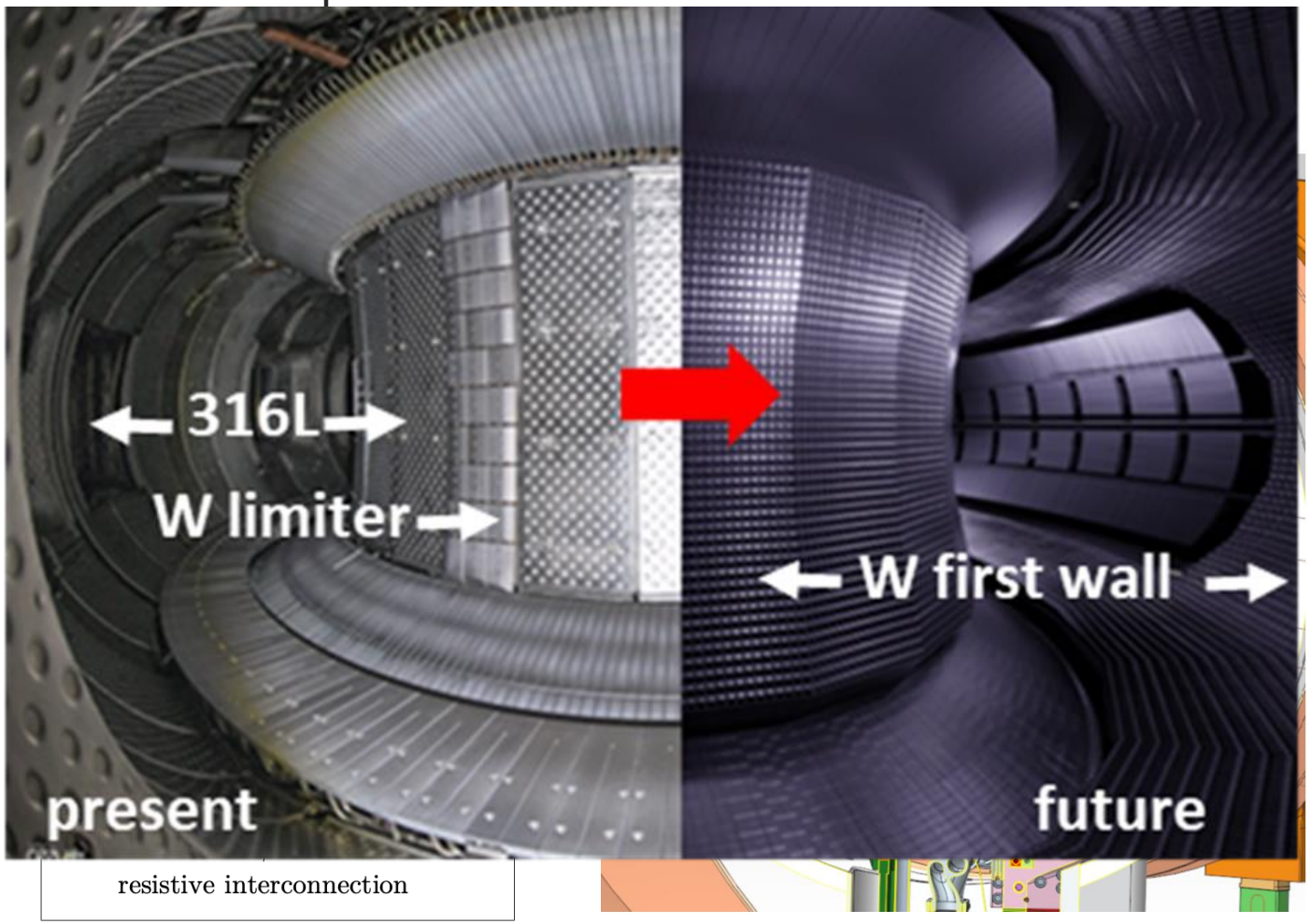


Mode X refraction

New vertical stabilization plates for WEST phase 3

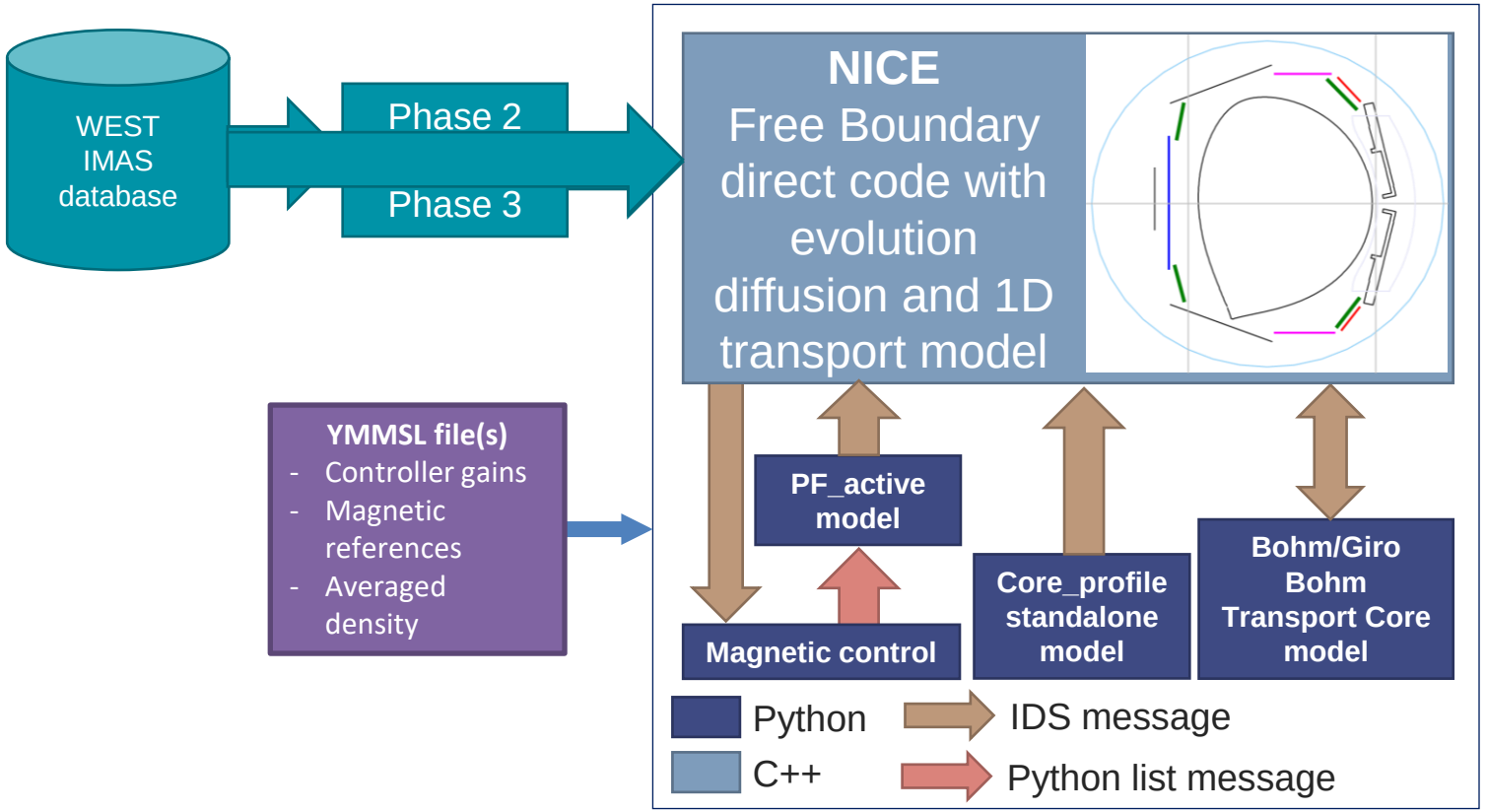
- **WEST phase 3 [J. Bucalossi, SOFT 2026]**
  - 3 hours of plasma by day
  - Water actively cooled wall with tungsten components
  - New passive structures to improve vertical control
- **Questions:**
  - What is the best size, resistance, position?
  - What is the new operation domain?
  - Side effects on the standard plasma scenarios (i.e. X-point formation, eddy currents, breakdown…)? → *Under investigation*

KSTAR passive plates concept



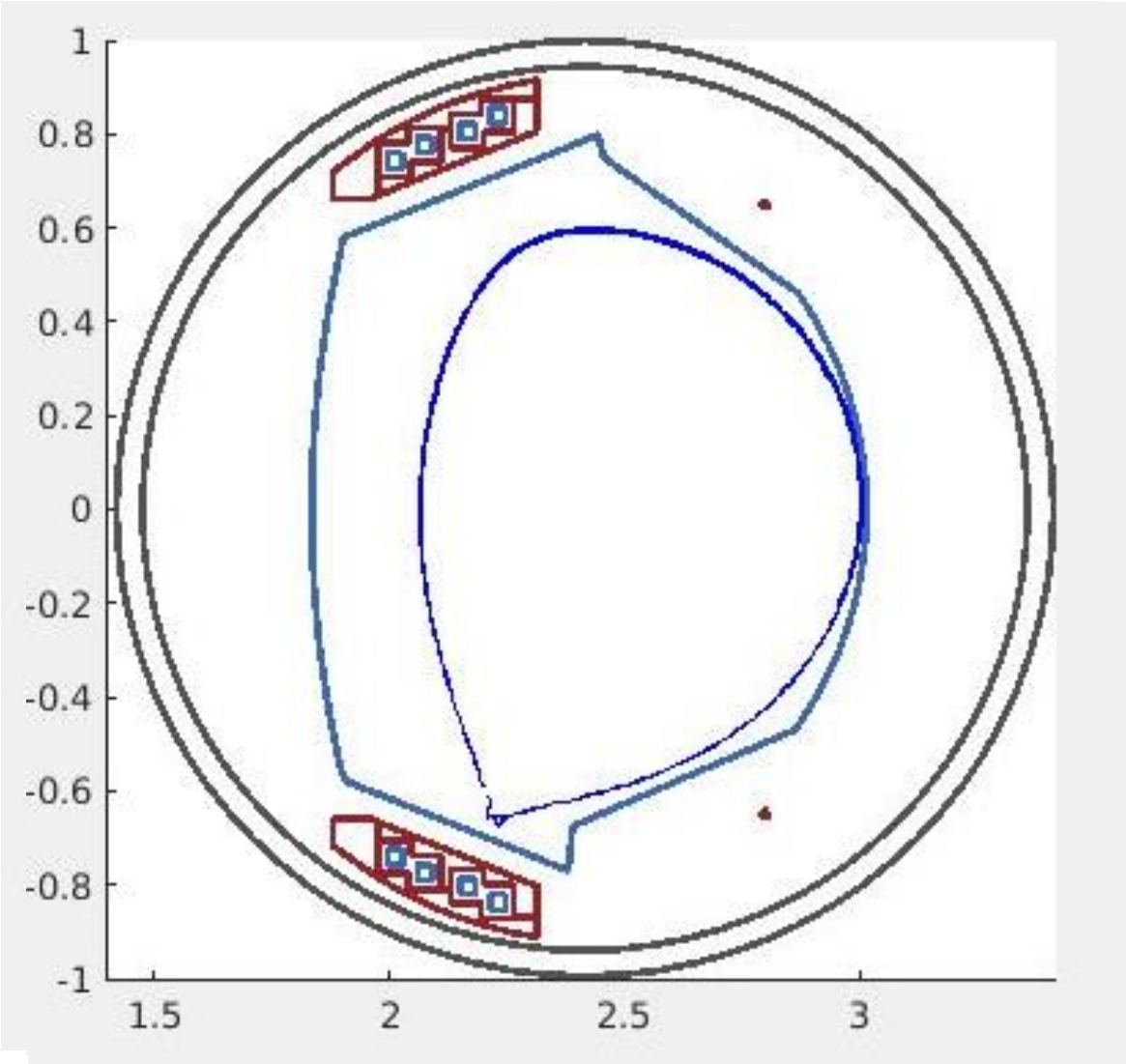
NEST is adapted to design the WEST phase 3

- A dedicated script adapts WEST phase 2 IDS into phase 3 version:
  - New wall shape (preliminary design)
  - Various stabilization plates designs to test
- Stabilization test compares VDE growth rate for different designs

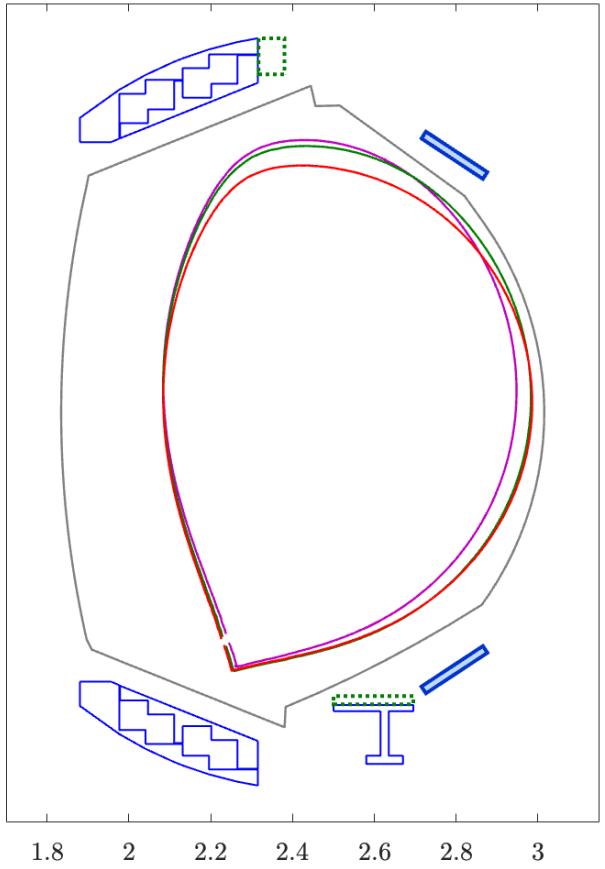


Stabilization plates improve significantly the vertical stability

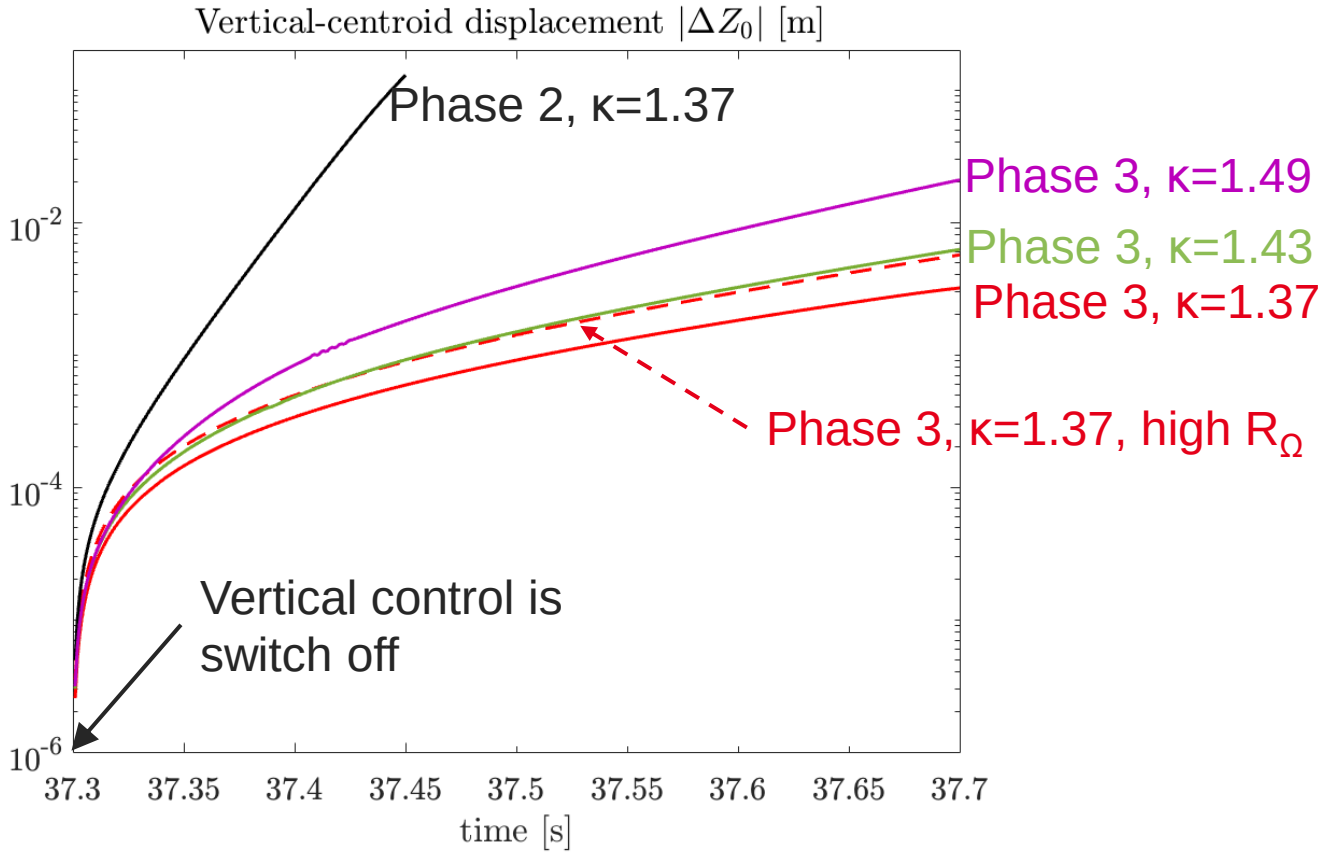
- Standard WEST phase 2 plasma equilibrium is used
- Test different designs
- Comparison of the vertical instability growth for each configuration
- Larger the plates are, more the plasma stable is



The new stabilization plates open significantly WEST operational domain



Removed P2 passive plates (old)
Retained passive structures
Proposed P3 passive plates (new)
baseline equilibrium $\kappa = 1.37$
elongated equilibrium $\kappa = 1.43$
elongated equilibrium $\kappa = 1.49$



- Plasma configuration at higher elongation are tested with NEST
- The maximal elongation could be significatively increased
- Plates' resistance value has significant effects on the stability
  →the value should be checked during assembly

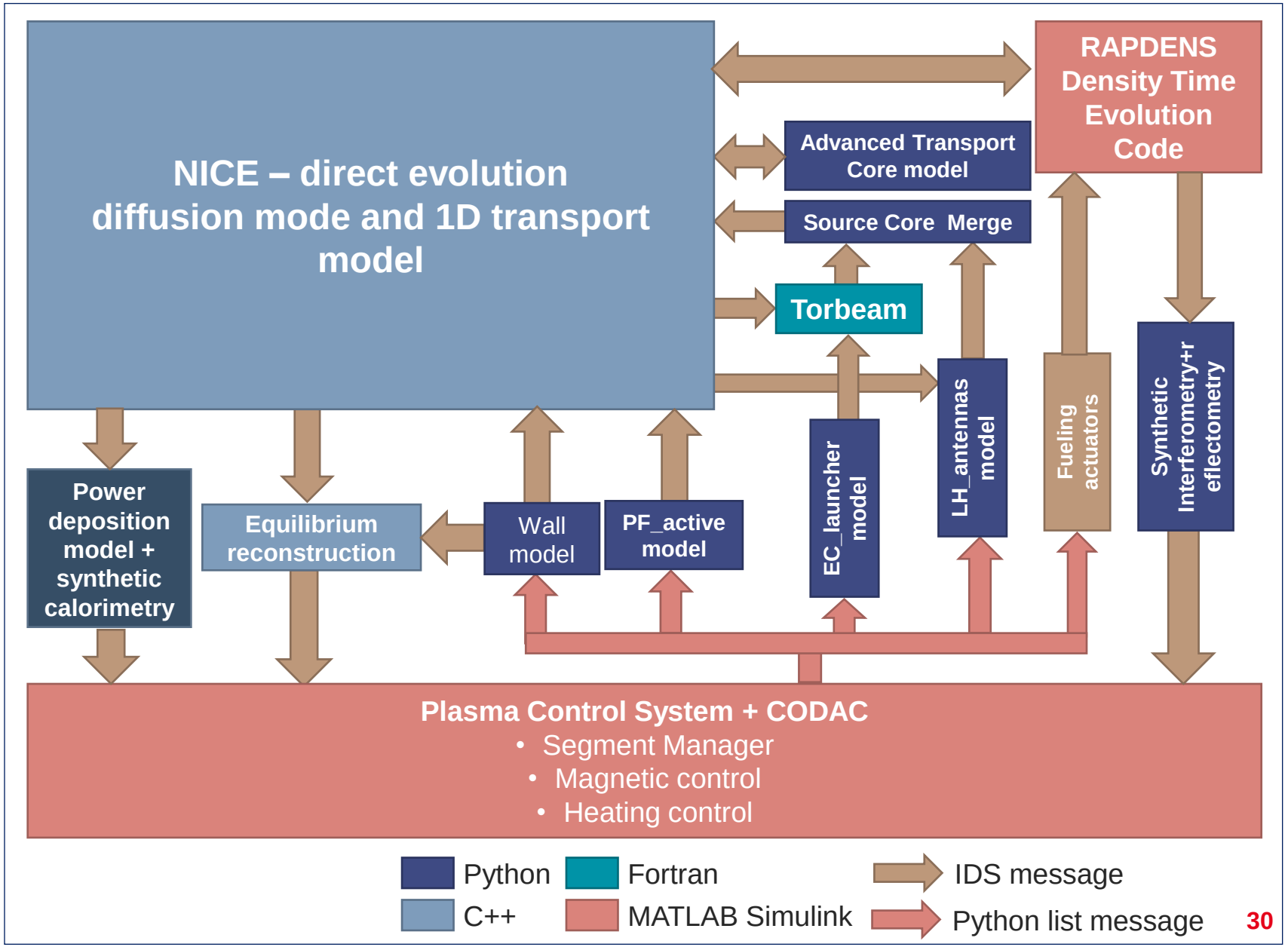
4. Conclusion

Usecases VS NEST features

	Pulse Design Tools	Flight Simulator	Digital Twin
Negative Triangularity scenario preparation	X	X	
Plasma shape reconstruction analysis			X
Double null control development		X	
ECRH commissioning preparation	X	(X)	X
Stabilization plate design for WEST phase 3		(X)	X
I_p/V_{loop} control development (required for WEST plasma duration record)		*X*	
Fast X-point formation scenario	*X*	*X*	

Perspectives

- **4 Tasks**
  1. Make NEST more friendly
  2. Enhance Physics models
  3. Enhance WEST features of NEST
  4. Make NEST a multi-machine simulation platform

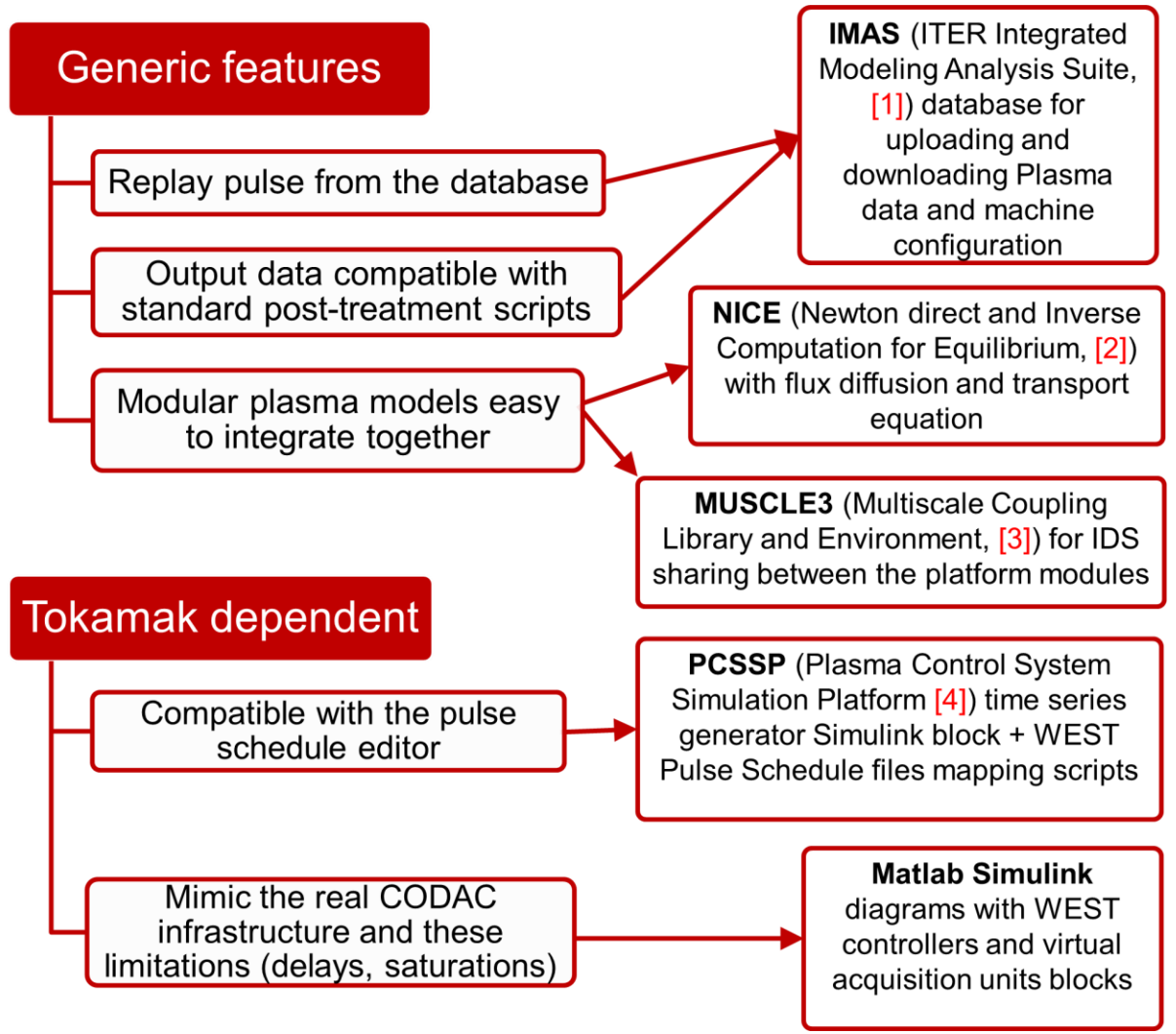




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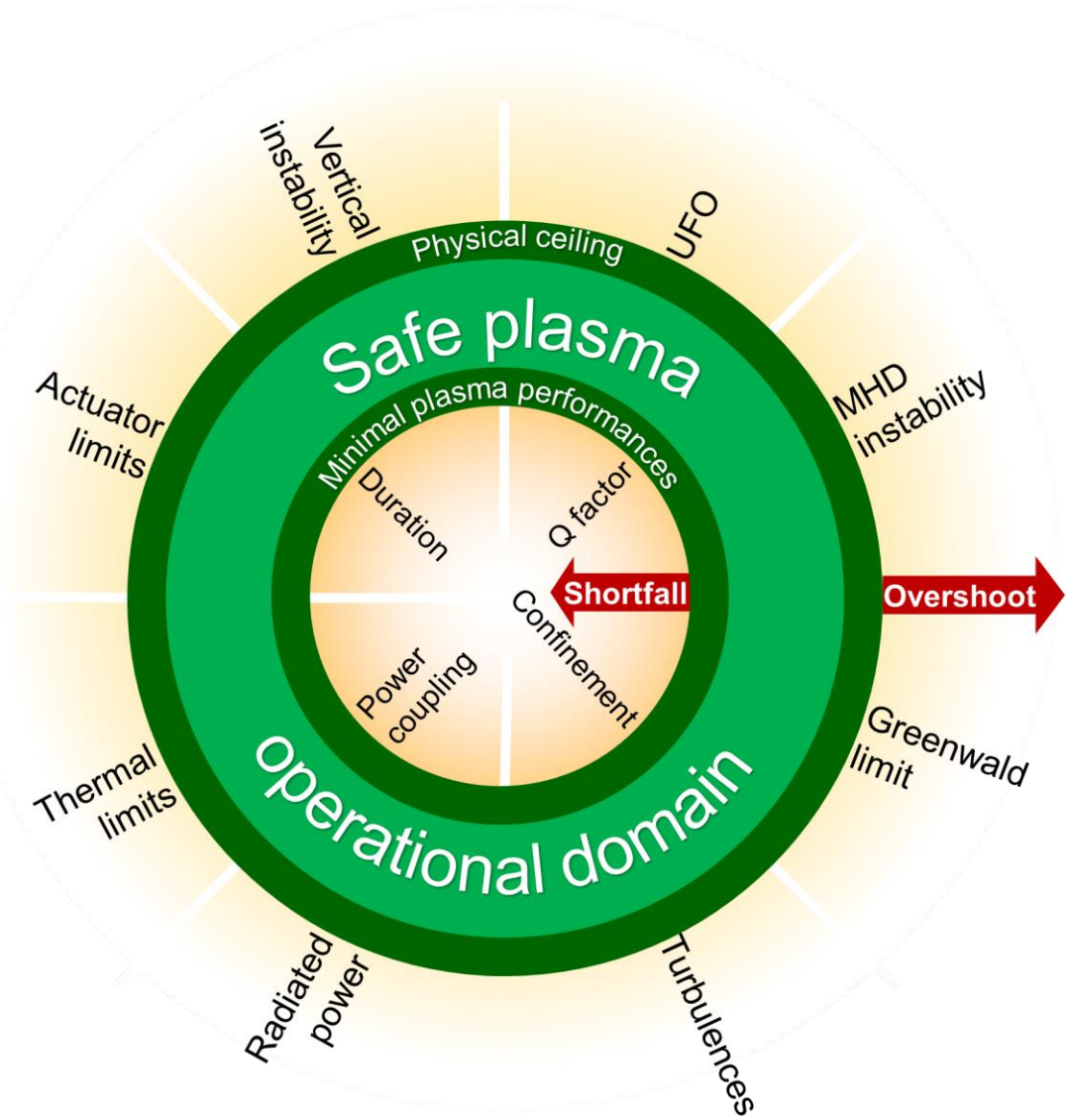
NEST: A generic simulation platform for scenario development, plasma control assessment and tokamak design

- A single, generic, multi-machine tokamak simulator is very difficult to design because of the specificities of each machine.
- However, generic tools (IMAS, PCSSP…) are now available and are used to develop generic plasma component and I/O interfaces while PCS/CODAC/Hardware components still need to be developed for each device
- The simulation time should be compatible with scenario/controller/design development (target: 1 second of plasma computed in 10s of minutes) → A good balance between computing time and accuracy of the results should be found
- Integration of the simulator into the considered tokamak operation environment is very important to ease its use by the operation team



Operation issues of modern tokamak

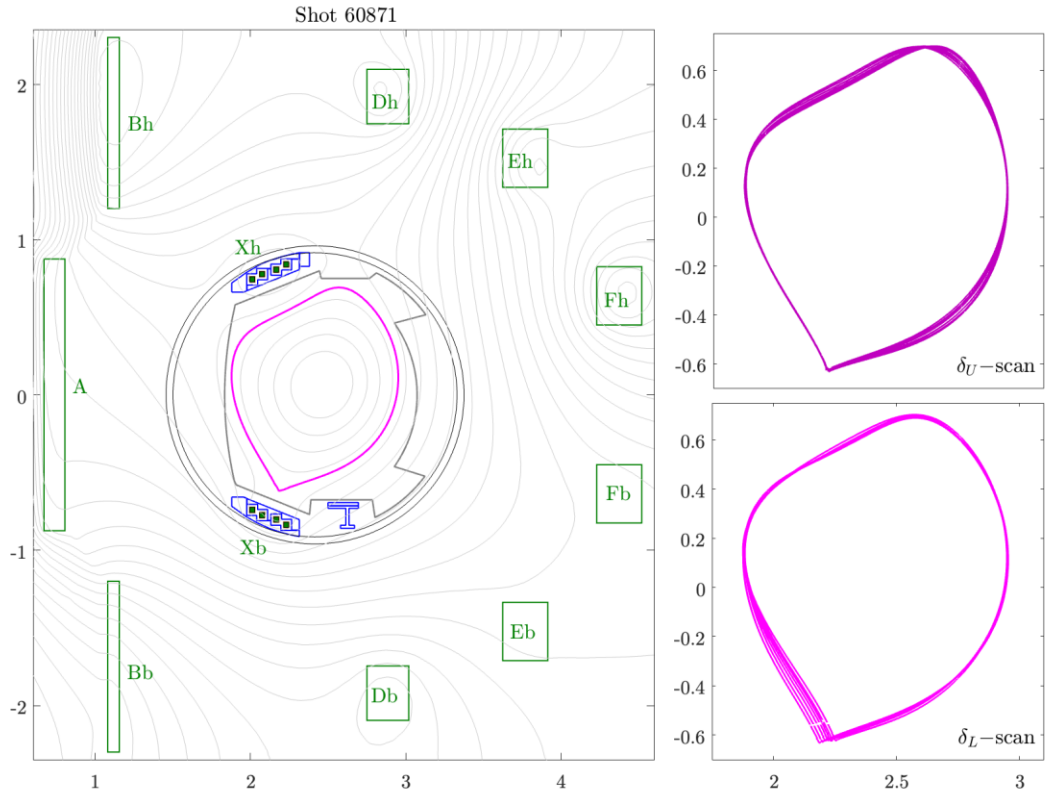
- Tokamak operation is becoming more and more complex within technical limits, machine protection issues, and unexpected plasma events
- Scenario and plasma control development should be assessed in simulation in order to minimize the commissioning time on the real plant and to verify that the operating limits are not exceeded
- For the next generation of tokamaks (ITER), this offline validation will be crucial before attempting a real plasma

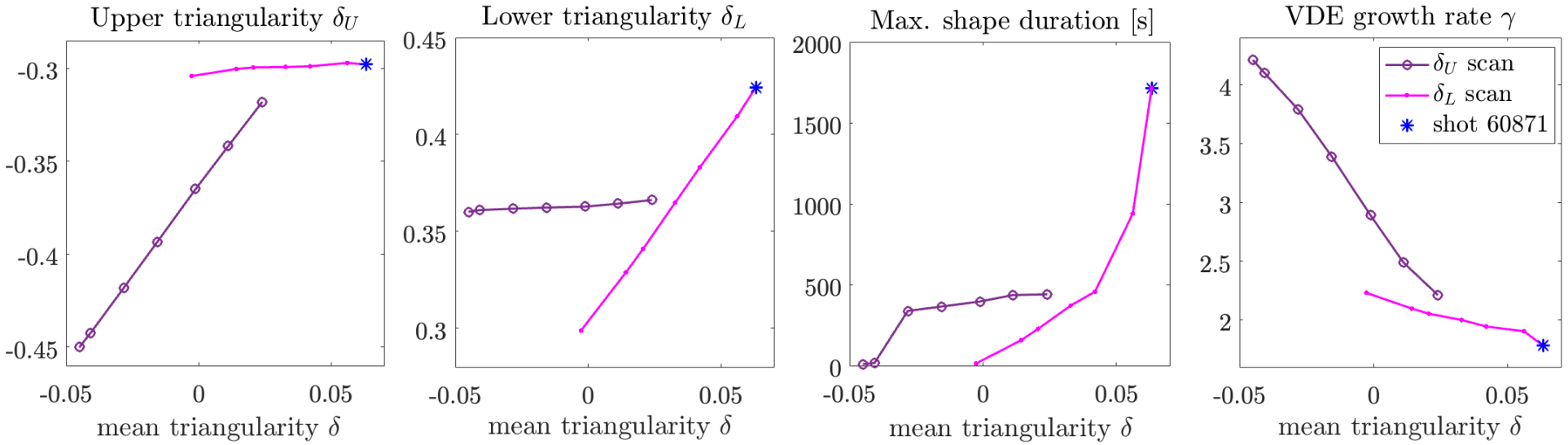


Plasma operation domain doughnut framework

Negative triangularity

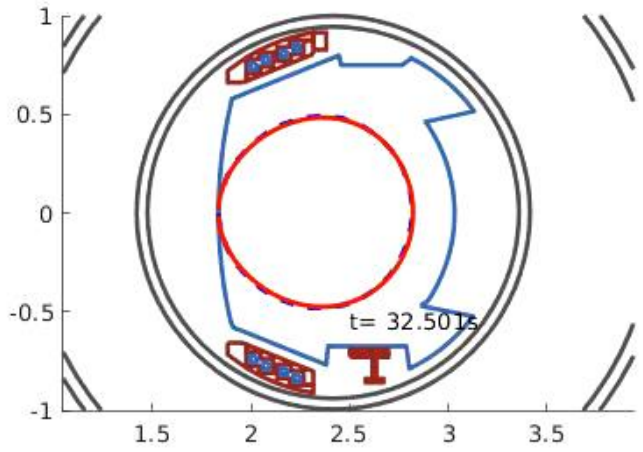
- Scan of the negative triangularity configuration
- The strongly asymmetric upper triangularity branch shows a clear deterioration in vertical stability as the mean triangularity becomes more negative.
- Phase 3 passive plates should ease to reach high upper negative triangularity values

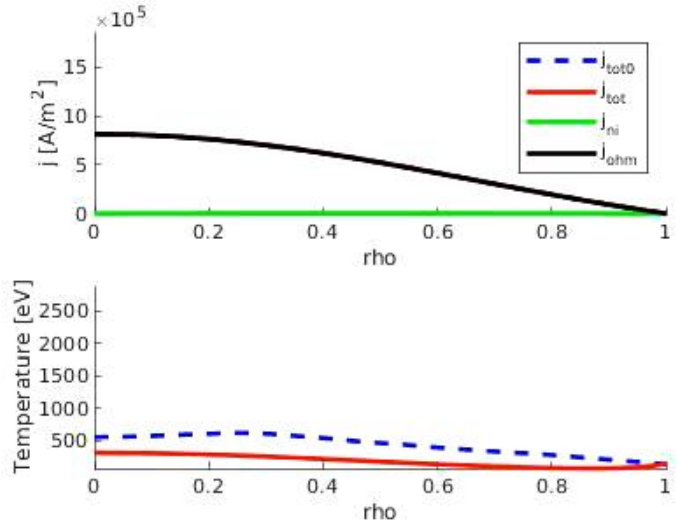


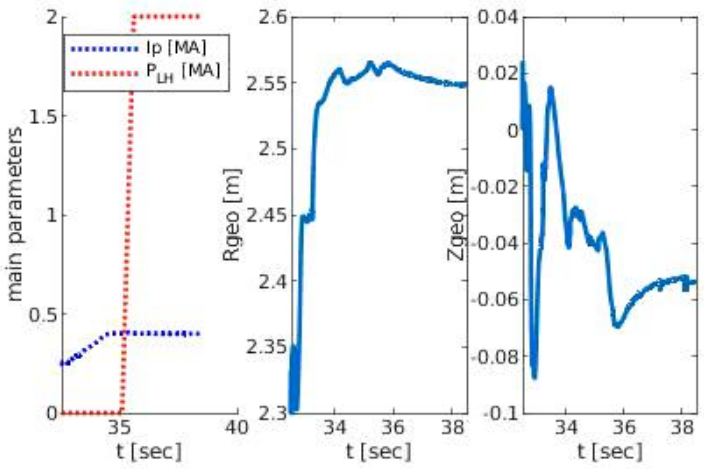


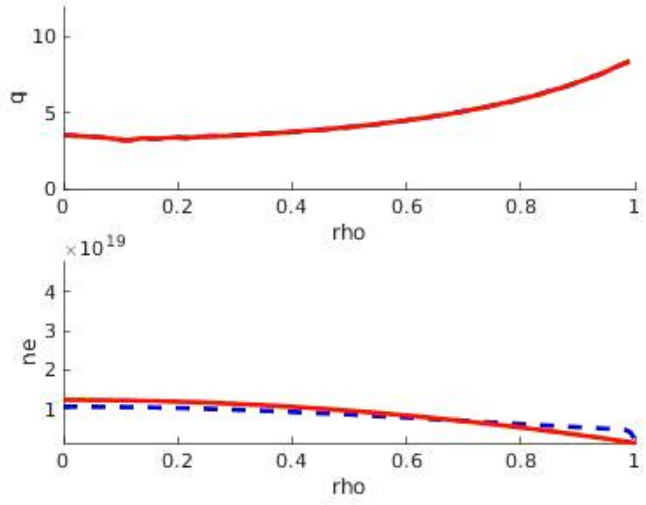
Replay of WEST: X-point formation and LHCD heating ramp-up

- Replay of pulse 61986
- The new fast-X point formation of WEST is used
- A standard LH power ramp-up is simulated
- Ti/Te ratio, Zeff and power deposit scaling factor are tuned in order to fit the experimental data
- Overestimation of Ti/Te ratio to avoid plasma collapse → Need to implement a profile
- Error on the simulated VS reconstructed shapes come from X-point definition on a point of the mesh
- Good match of the internal profiles, reconstructed profiles are smoother than simulated one because of regulation parameter tuning of NICE reconstruction



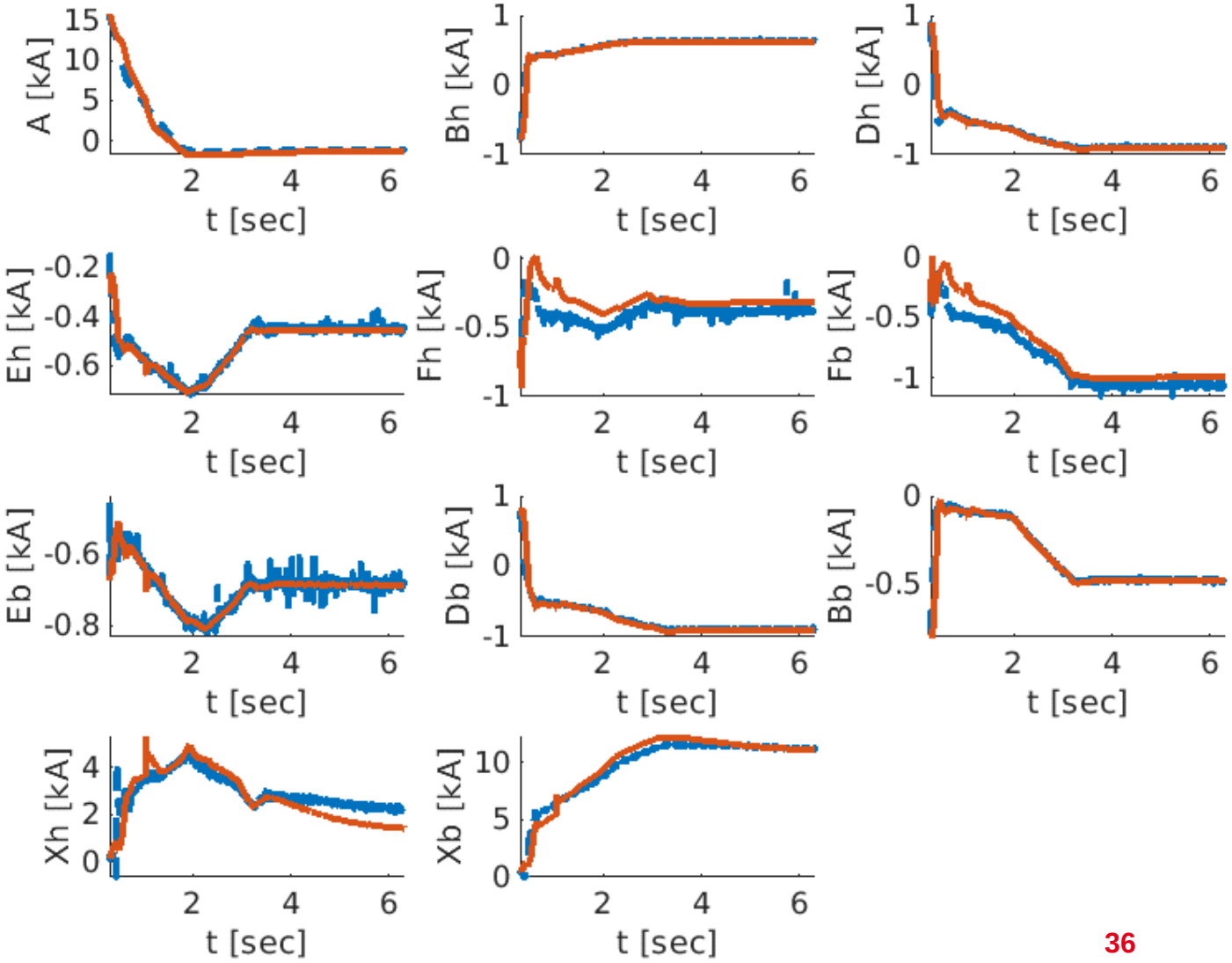






Replay of WEST: X-point formation and LHCD heating ramp-up

- Good match on the PF coils current → The simulation is accurate enough to validate a pulse schedule
- 3h39 to run 6 seconds of plasma (sample time=1ms)
- 5.4Go of IDS files: equilibrium, core_profiles, core_sources, core_transport, lh_antennas, pf_active, pf_passive, iron_core, wall



Control development process in 7 steps

- **Step 1**: Generate a linear model from double null configuration snapshot (generated by NICE inverse mode)
- **Step 2**: Synthetize a MIMO control law based on the linear model
- **Step 3**: Test the control law using the linear model (i.e. Simulink workflow) → check stability and performance against several linear models
- **Step 4**: Test the control law using NEST development mode → check robustness against non-linearity and adjust gains if required
- **Step 5**: Implement the new control mode in the WEST magnetic controller workflow
- **Step 6**: Test the modifications running a double null scenario with NEST flight simulator mode
- **Step 7**: Deploy the new release of the controller on the WEST PCS and test it on plasma (commissioning session)

ECRH target angles analysis tool

- Based on NEST-TORBEAM simulation database
- Visualization of the rho gaussian center ECRH/ECCD deposition function of the mirror angles
- Define the optimal mirror angles for a desired power/current deposition position (maximization)
- Check the wall deposit using EcStray in mode X and mode O
- **Limitations:**
  - Limited to the dataset
  - ECRH pulse only (no LH or ICRH coupling)

