MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Control Simulation

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Hi, some words about myself:
Wolfgang Treutterer

PhD as Electric Engineer (Electrical Drives, Control) at TU Munich

ASDEX Upgrade Control System Designer since 1994

- **Plasma Position and Shape control → General plasma control**
- **Real-time control framework and applications → DCS**
- **Head of AUG real-time control group**

ITER engagement since 2010

- **IPT: Integrated Product Team: coordinator for PCS Architecture**
- **Contractual design work (as consortium member)**
  - Plasma Control Simulation Framework (since 2010)
  - Plasma Control System Design (since 2012)
  - Real-Time Framework (since 2013)
- **Member of the ITER Operations Network ION (since 2017)**

DEMO engagement since 2010

- **Work package on diagnostics and control (WPDC): Plasma Control System functional breakdown**

Uses of simulators
(from an ITER perspective)

Domain	Area	Examples
Problem-specific	Power supplies Printed circuits, FPGA Network Logic, state machine Plant	*SPICE, ANSYS, PLECS* *EAGLE, Xilinx* *NS Simulator, OPNET, NetSim* *StateFlow, Enterprise Architect, OMNet++* *custom*
(Fusion) Physics	equilibrium, transport, turbulence, heat deposition, etc.	*ASTRA, CORSICA, DINA, EQUINOX, JINTRAC, Metis, SMITER, SOLPS, etc.* *IMAS: Integrated Modelling and Analysis S*
(Control) System	Plasma control	*PCSSP: Plasma Control System Simulatio Platform*
Operation	Commissioning Pulse design Pulse validation Pulse debugging	*IPSi: Integrated Plant Simulator* *PDS: Pulse Design Simulator* *PCSSP*

A **flight simulator** is a device that artificially **re-creates** aircraft **flight and** the **environment** in which it flies, for pilot **training, design**, or other purposes. It includes **replicating the equations** that govern how aircraft fly, how they **react to applications of flight controls**, the **effects of other aircraft systems**, and how the aircraft **reacts to external factors** such as air density, turbulence, wind shear, cloud, precipitation, …
https://en.wikipedia.org/wiki/Flight_simulator

- refers to the **degree of exactness** achieved
- corresponds to the **believability** of the experience

National Center of Biotechnology Information
https://www.ncbi.nlm.nih.gov/books/NBK559313/

Brainstorming:
Which expectations do you associate with simulations ?

Simulation:
Strengths, Myths and Caveats

Strengths:

- Simulations forecast the transient behaviour of a process under nominal and disturbed conditions
- Simulations help to understand the basic mode of functioning of a process
- Simulations allow to inspect internal, non-observable states of a process

Myth:

- With simulations I can prove, that a system is stable / controllable.
  - **Wrong! This might be true for purely linear systems without noise. For general, non-linear systems, simulations only represent a snapshot behaviour under the simulated operation conditions. A number of simulations can provide confidence but no guarantee of stability.**

Note:

- Simulation models are in general idealized and reduced imitations of reality.
- Simulations cannot be better than their underlying model of the real process.

Brainstorming:
Which features characterize *Control Simulations* ?

Control Simulation

Definition:

Control Simulation is a simulation discipline with a **holistic system view**, where the model comprises a plant and a control system in mutual interaction.

Domain:

- Study, design and validation of control and protection systems
- Study, design and validation of operating scenarios an procedures
- Reconstruction and debugging if compared to measured behaviour
- Training of operators (flight simulator)

Focus:

- investigate the principal and key behaviour
- first order estimation of performance indicators
- often used with reduced models to achieve fast simulation runs
  - quick turn-around ➪ part of Rapid Prototyping for quick iterations
  - quasi real-time ➪ suitable for training of human-machine interaction

HiFi Simulation versus *Control Simulation*

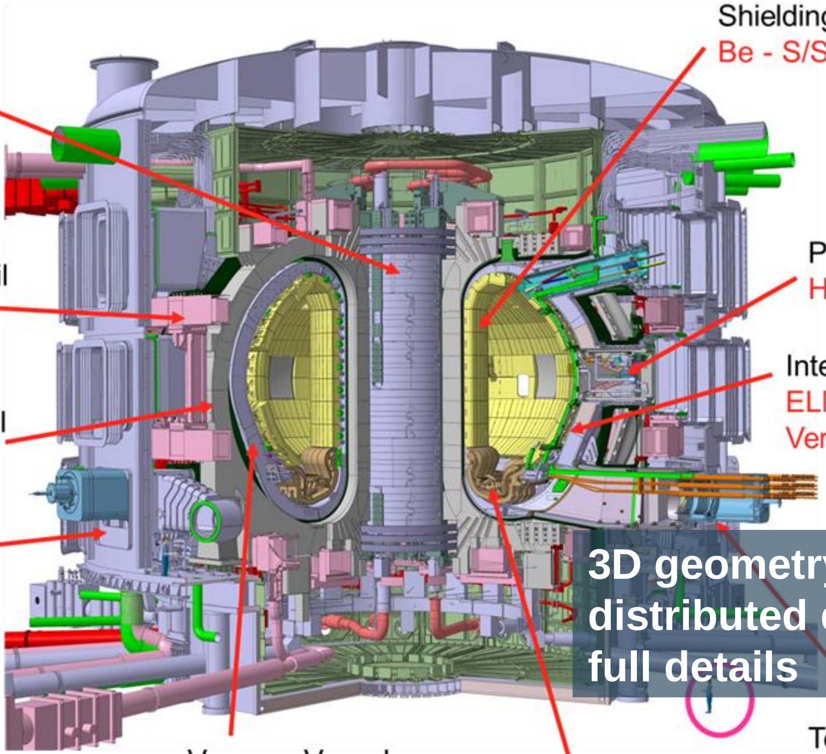
High-Fidelity Simulation

- **Precise and realistic models**
  - high degree of model states
  - accurate reproduction of non-linearities
  - large number of elements
  - Realistic model of disturbances
- **Dedicated codes**
  - tailored to the problem
  - computation intensive (long duration)
  - narrow scope (modelling domain, time , space)

Control Simulation

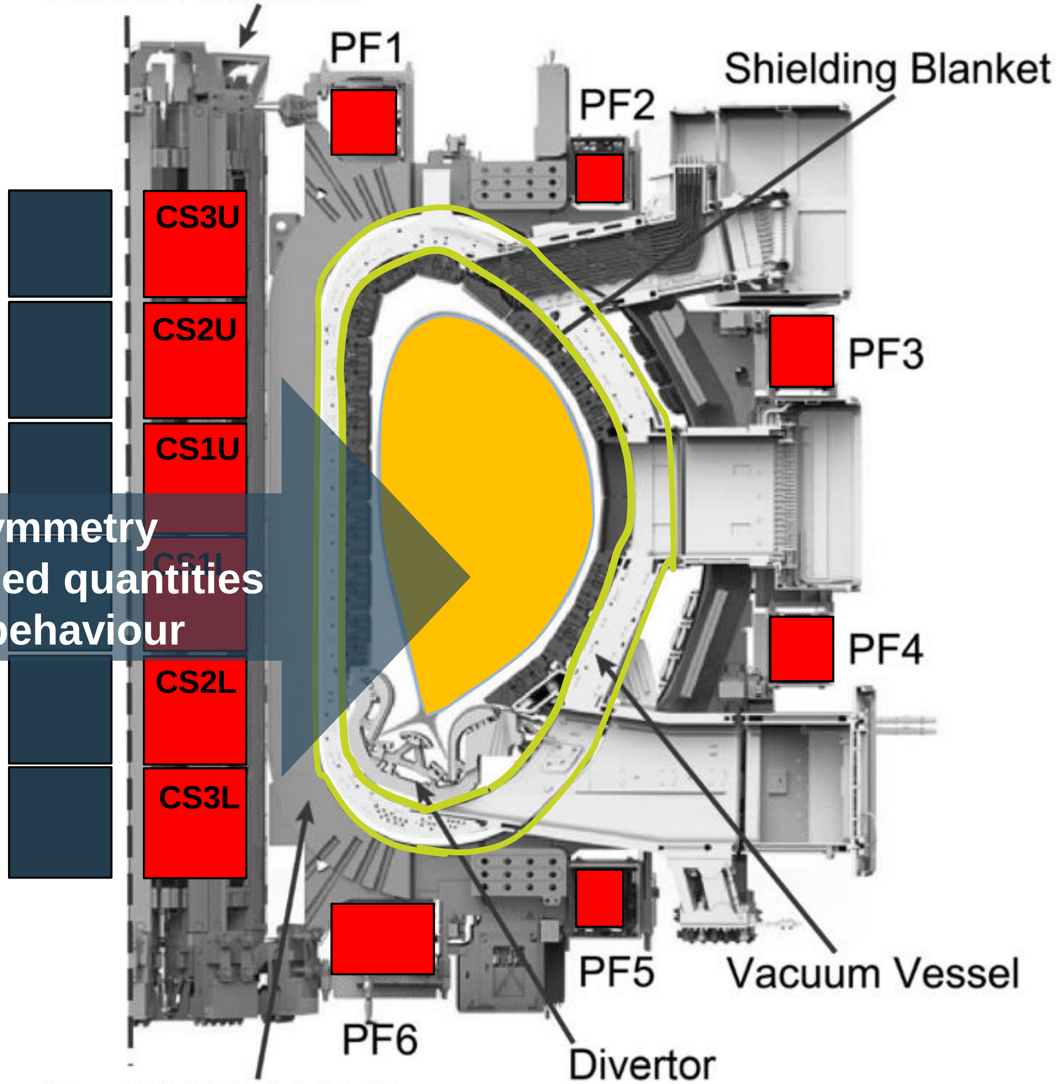
- **Models adequate to the purpose**
  - approximations and generalisations
  - reduced complexity and averaged behaviour
  - standardized perturbations
- **Customized standard components**
  - wide coverage
  - easy modifications, variant studies
  - code generation for real-time use
- **Fast runs**
  - iterative design
  - operation validation
  - (faster-than-) real-time forecasting

Model Reduction Example: Vertical Stabilization

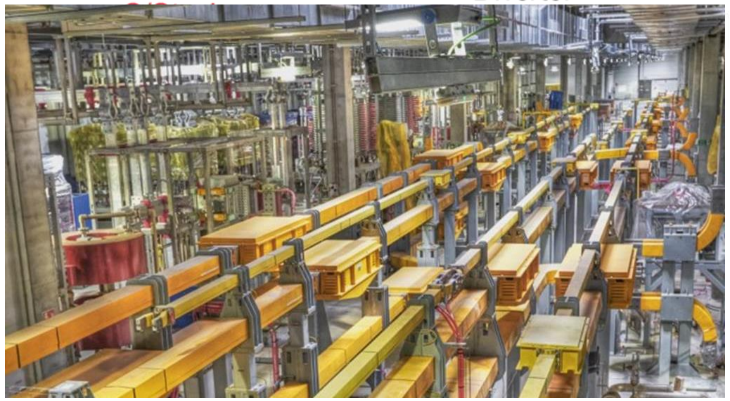


3D geometry
distributed quantities
full details

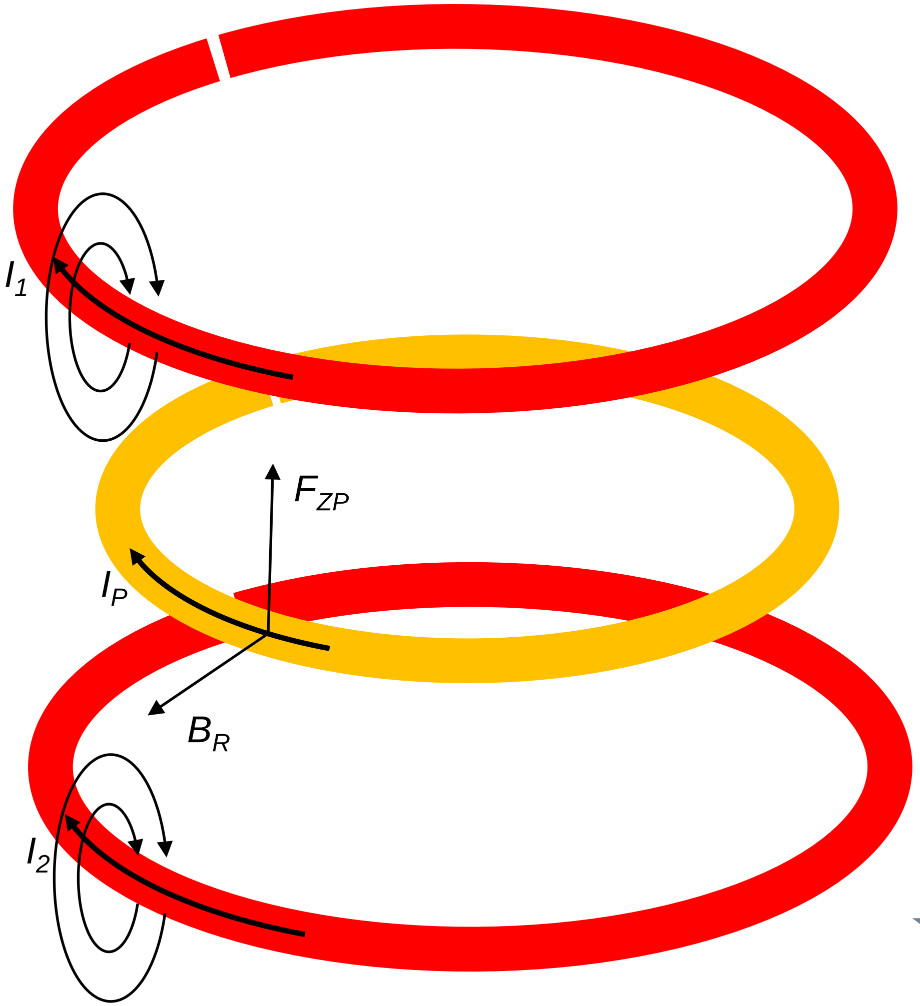
axisymmetry
lumped quantities
key behaviour



Power Supply and Energy Transmission



Model Reduction Example: Vertical Stabilization



Approximation, Reduction, Simulation speed-up

Electrical Circuits (Kirchhoff's law)

$$\begin{bmatrix} V_1 \\ V_2 \\ 0 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_P \end{bmatrix} \cdot \begin{bmatrix} R_1 \\ R_2 \\ R_P \end{bmatrix} + \begin{bmatrix} L_1 & M_{12} & M_{1P} \\ M_{21} & L_2 & M_{2P} \\ M_{P1} & M_{P2} & L_P \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \\ I_P \end{bmatrix}$$

Vertical force balance (Lorentz force)

$m_P \ddot{Z}_P \;=\; F_{ZP} = 2\pi\, R_0 I_P\, B_R,$

where $B_R = f(I_1, I_2, R, Z)$

Simplifying assumption (control oriented model):

m_P very small ➪

$m_P \ddot{Z}_P \;=\; F_{ZP} \approx 0$ ➪ $R, Z = f(I_1, I_2)$

$f_A, f_B \;=\; f(I_1, I_2)$
R, Z : input and output
➪ **algebraic loop simulator challenge !**

State Space Model

$$\frac{d\boldsymbol{I}}{dt} = \boldsymbol{f_A}(\boldsymbol{I}) + \boldsymbol{f_B}(\boldsymbol{V}), \qquad \begin{bmatrix} \boldsymbol{R} \\ \boldsymbol{Z} \end{bmatrix} = \boldsymbol{f_C}(\boldsymbol{I})$$

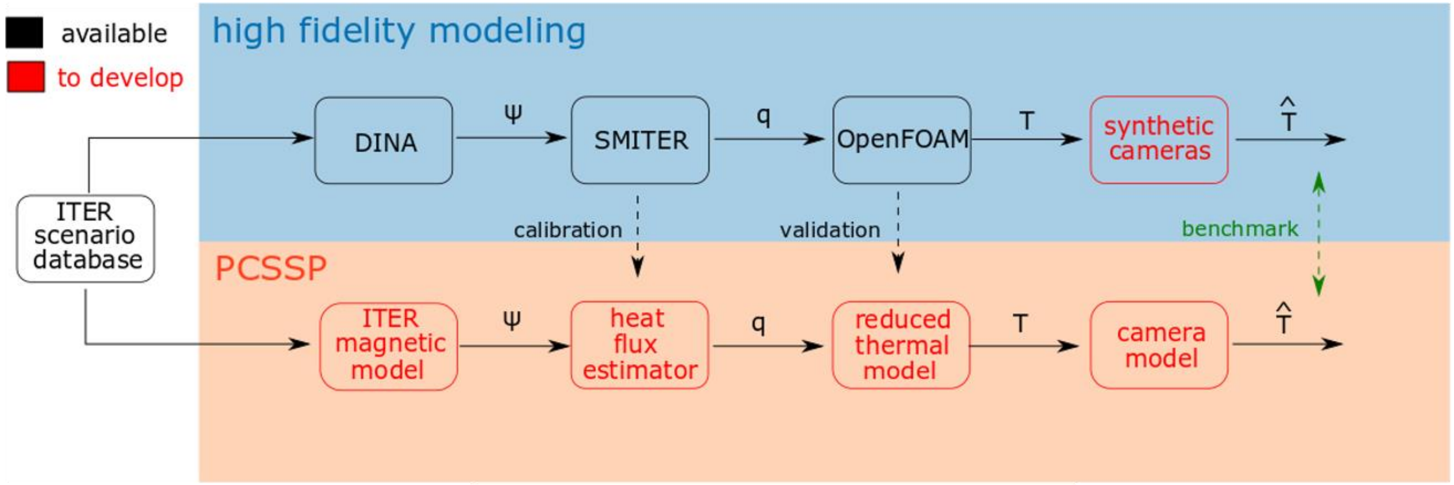
Linearization (often used for controller design)

$$\frac{d\boldsymbol{i}}{dt} = \boldsymbol{A}\,\boldsymbol{i} + \boldsymbol{B}\,\boldsymbol{v}, \qquad \begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{z} \end{bmatrix} = \boldsymbol{C}\,\boldsymbol{i}$$

HiFi Simulation vs Control Modeling Example

Modeling strategy

- Model-based controller design requires simplified but reliable control-oriented models.
- A benchmark is to be performed with a set of high fidelity models.
- Very good results already obtained for JET [4] support this approach.



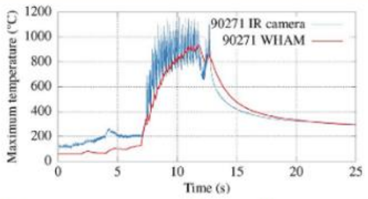
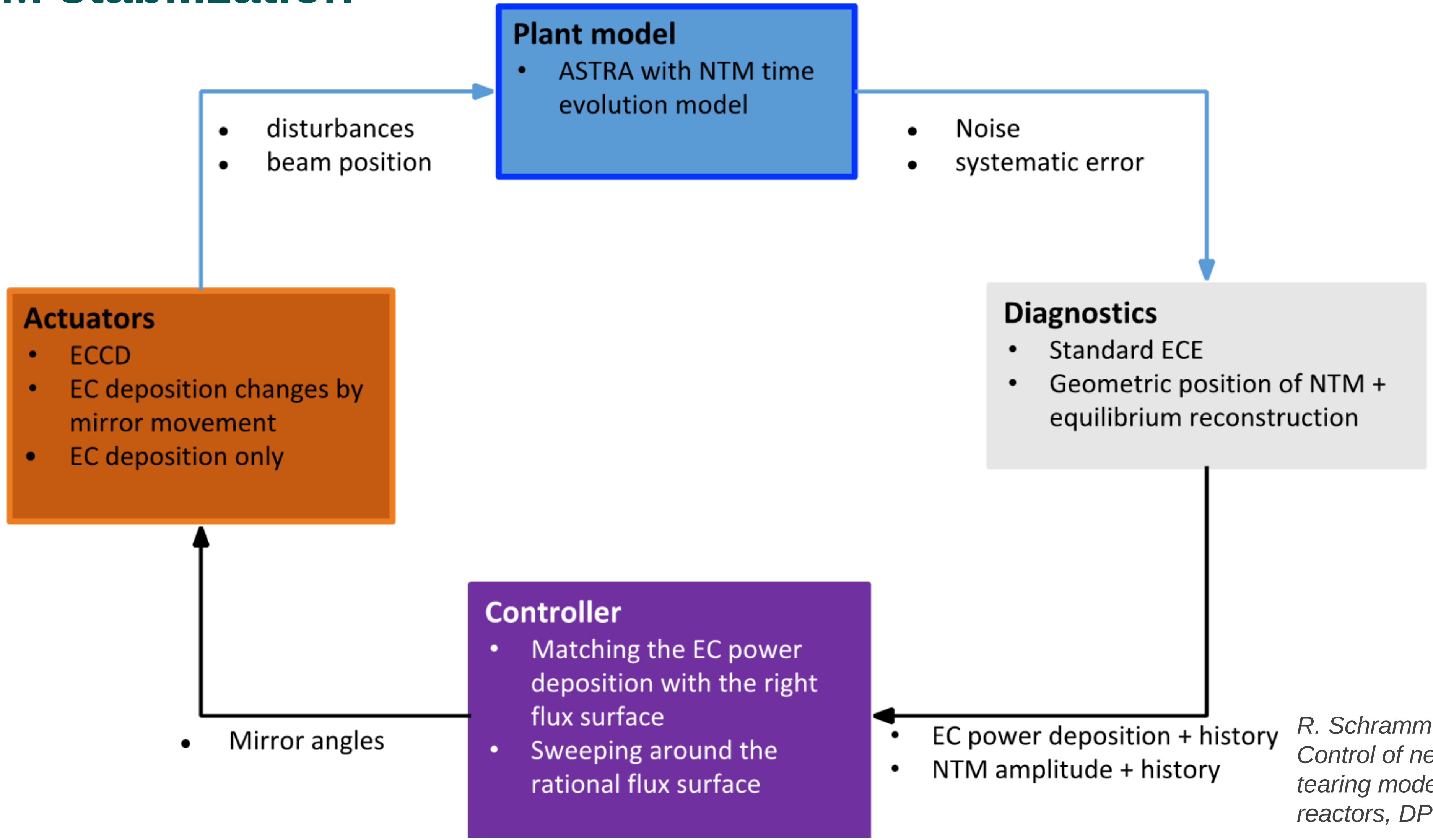


Fig. 10. WHAM maximum temperature real-time simulation compared to IR camera measurement for a high power H-mode pulse (92025).

From ITER PCS Final Design PFPO-1 GMP1 courtesy of F. Pesamosca, T. Ravensbergen

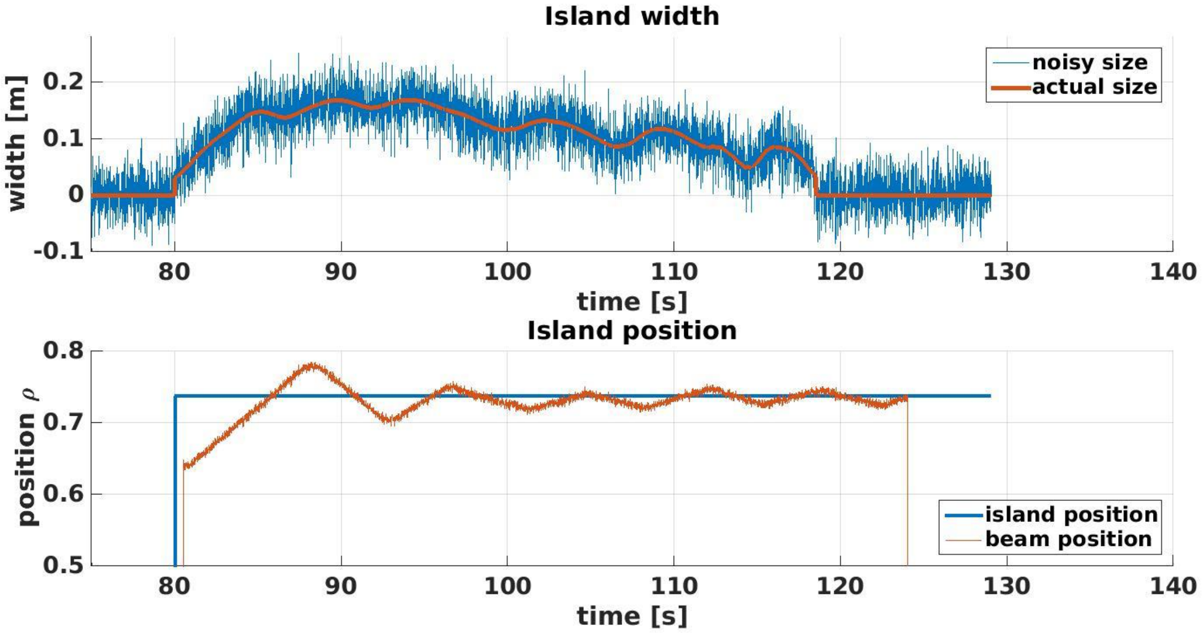
Control Simulation example: NTM stabilization



R. Schramm.et al. Control of neoclassical tearing modes in fusion reactors, DPG 2020

Control Simulation example:
NTM Stabilization

- power: 17 MW
- sweeping speed: 0.02 m/s



- initial guess for EC deposition given by equilibrium reconstruction
- measure island size, detect minima
- sweeping around island to stabilize (adaptive amplitude, speed)
- Improvement options:
  - Higher power
  - Better measurements (position, noise level on size)

R. Schramm.et al. Control of neoclassical tearing modes in fusion reactors, DPG 2020

Brainstorming:
Where can ITER make use of *Control Simulation* ?

ITER use cases and solutions

Flight Simulator

HiFi Simulator

Design

- Scenario
- Plasma control
- Integrated system
- Protection and Safety studies

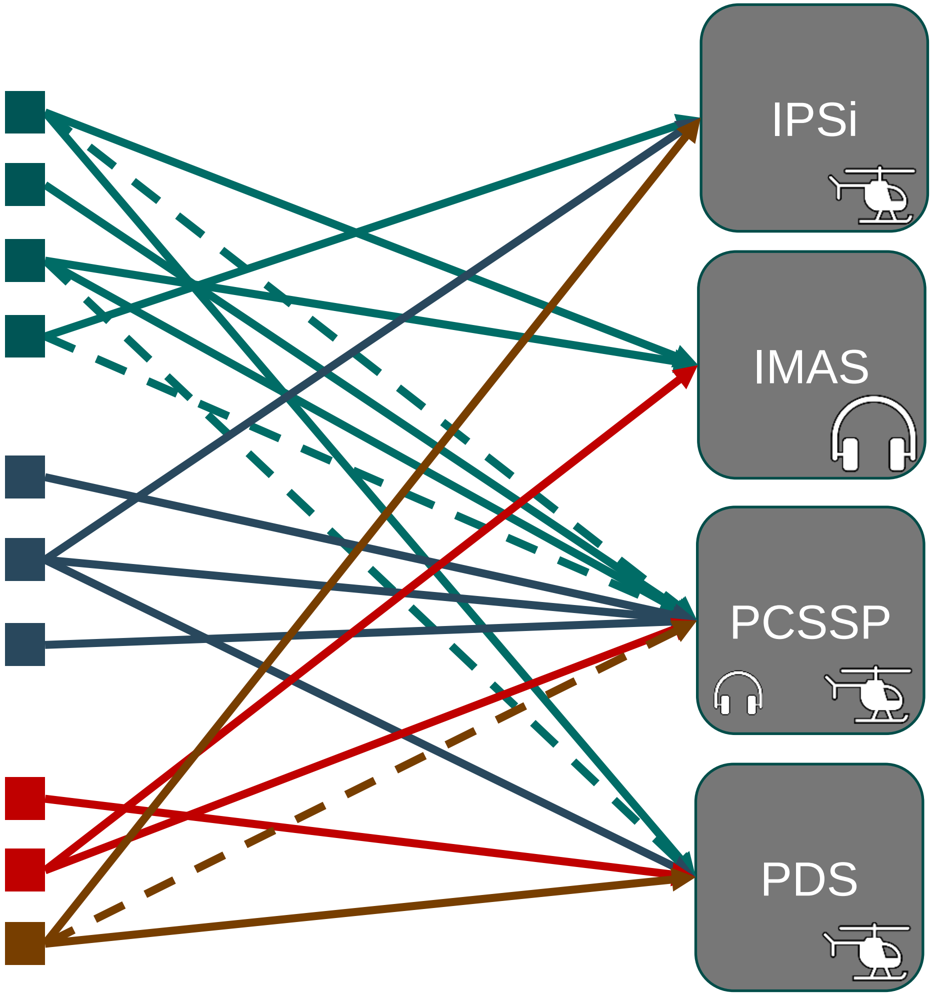
Verification and Validation

- Control properties
- Operational limit compliance
- Control system (continuous and EH)

Operation / Commissioning

- Scenario (final settings) – Validation
- Post-pulse analysis - Debugging

Training



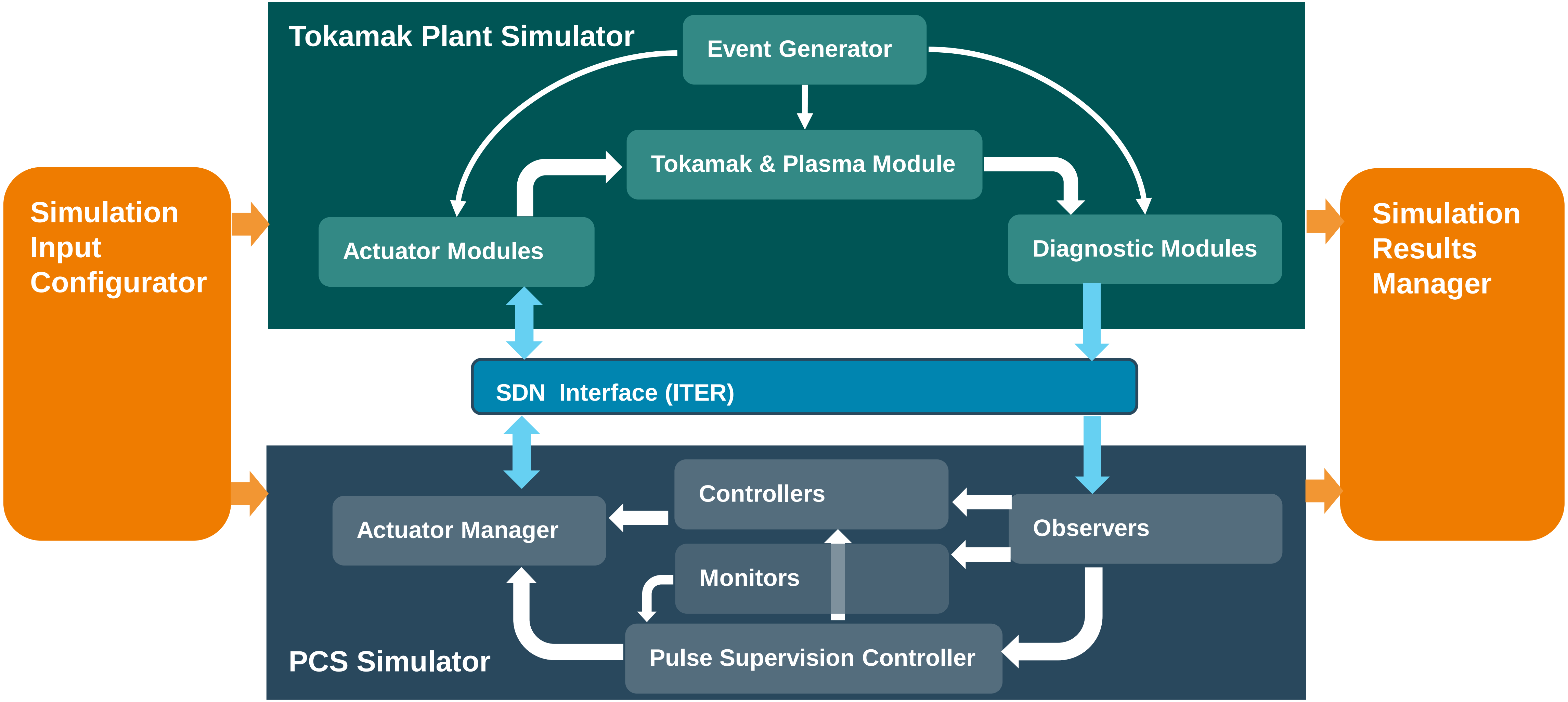
IPSi: Integrated Plant Simulator

IMAS: Integrated Modelling and Analysis Suite

PCSSP: Plasma Control System Simulation Platform

PDS: Pulse Design Simulator

PCSSP:
A tool for Control Simulation



PCSSP:
Highlights

- Built on top of Matlab / Simulink:
  - graphical interface
  - automatic execution flow determination
  - mix of continuous – discrete modules and multiple sampling rates
  - code generation support
- Wealth of ITER plasma, actuator (and diagnostic) modules
- Co-simulation support for external plant simulator
- Event generator(s) for study of abnormal events and PCS reactions
- Re-usable configurable PCS modules (e.g. generic controllers)
- PCS signals with quality tags
- Reference waveform generator with built-in exception handling (Pulse Supervision Controller)
- Publish-subscribe option for large, complex models

PCSSP:
Collaborative approach

Open to all ITER partners

- **Repository: https://git.iter.org/projects/PCSSP**
- **Documentation included**

Development:

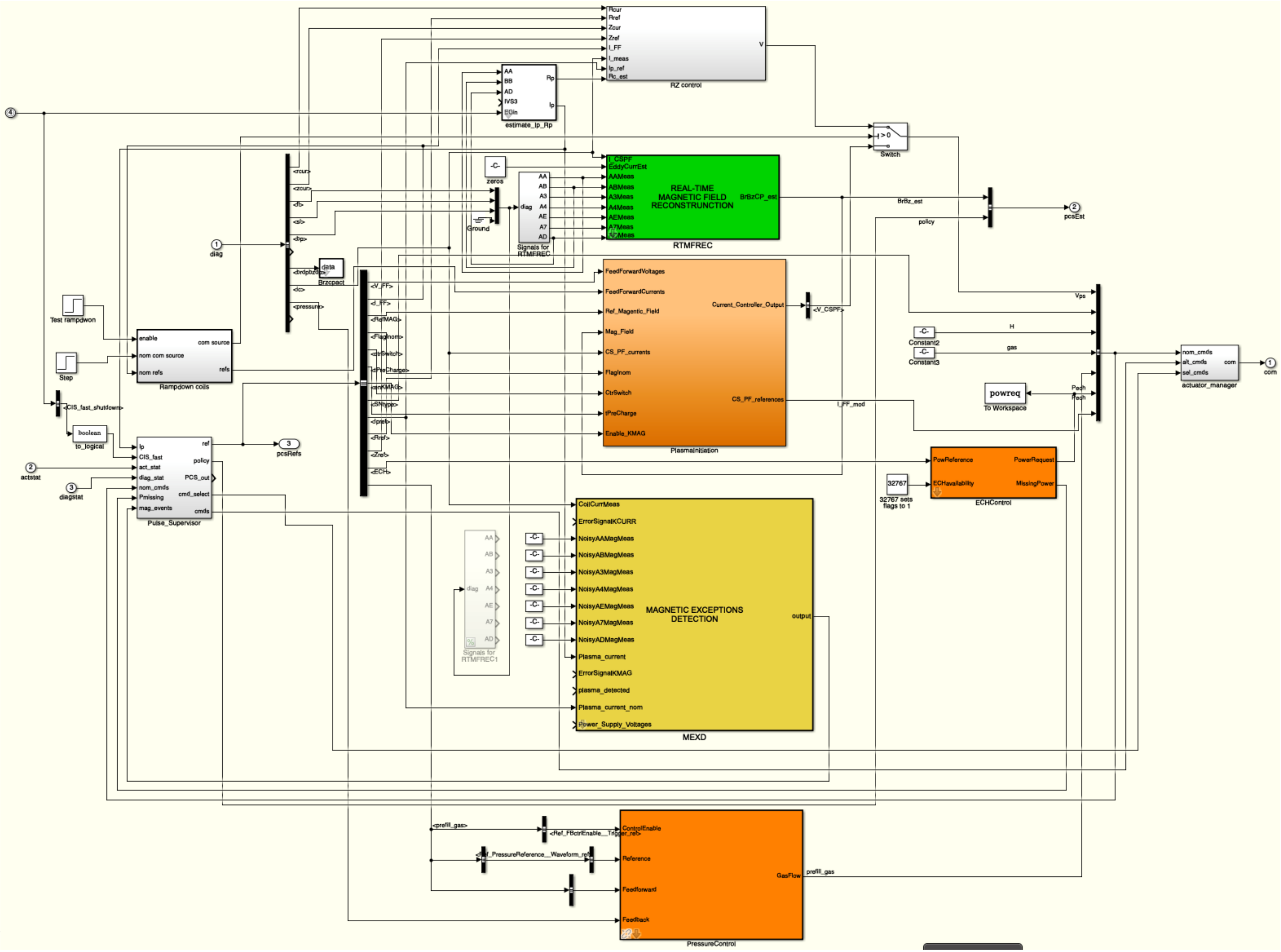
- **Core Team: ITER, General Atomics, CREATE, IPP Garching**
- **Contributions welcome: Review process, Git Workflow**
- **Continuously maintained and extended**

Custom device libraries

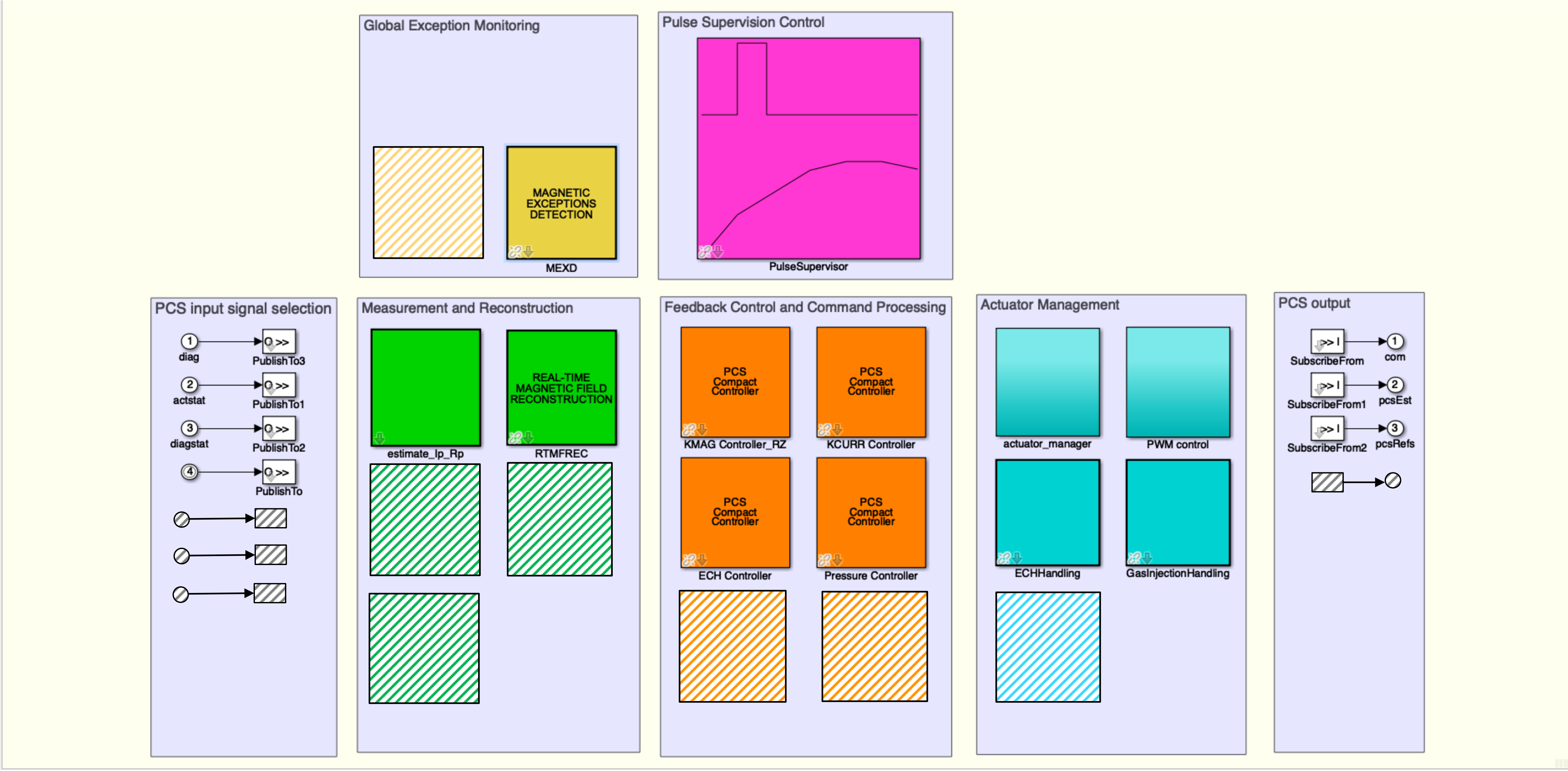
- **ITER**
  Repository: https://git.iter.org/projects/PCSSP-ITER
- DIII-D
- ASDEX Upgrade
- DEMO
- your device ?

} "Private" libraries

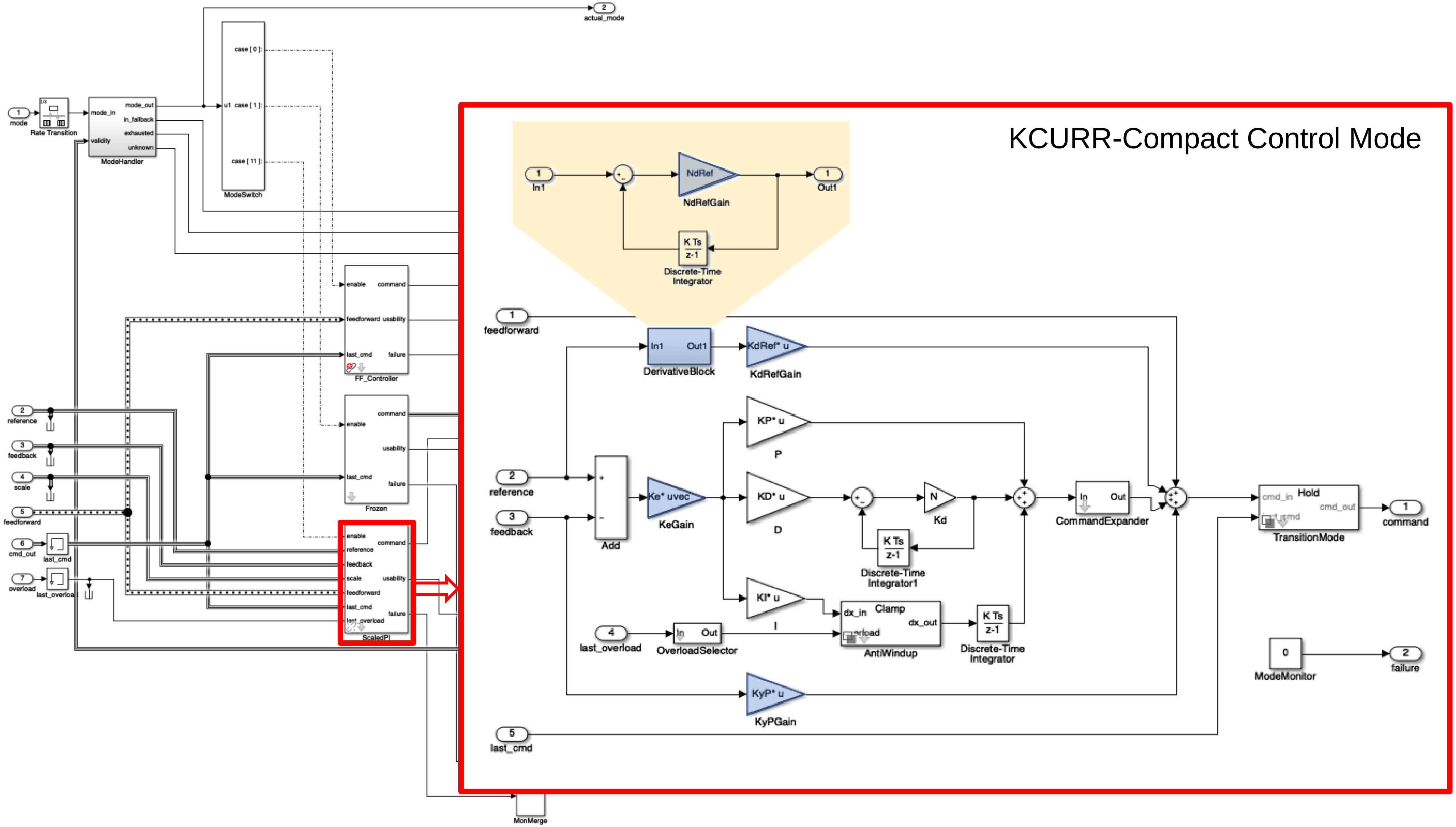
PCSSP Example: PCS Model for First Plasma Operation



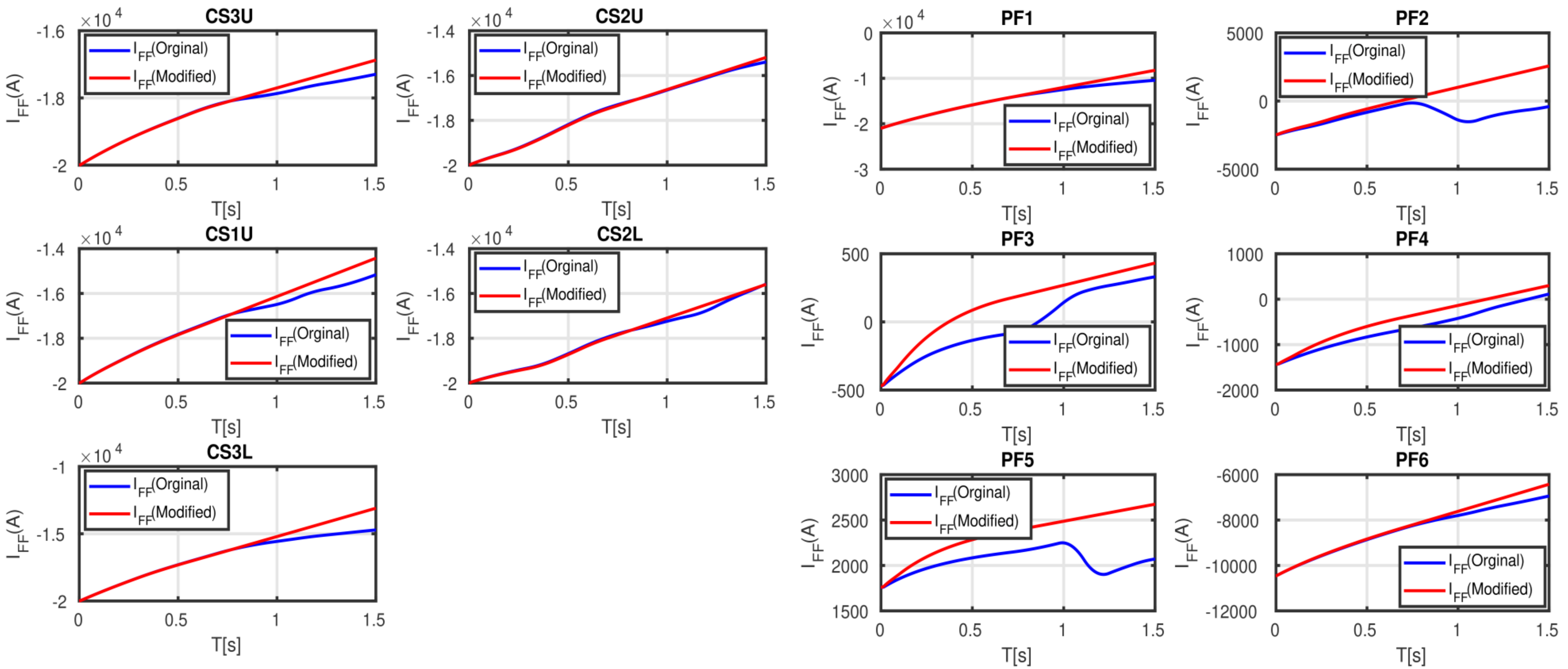
PCSSP Example: PCS Model with Publish/Subscribe



PCSSP Example: Controller detail

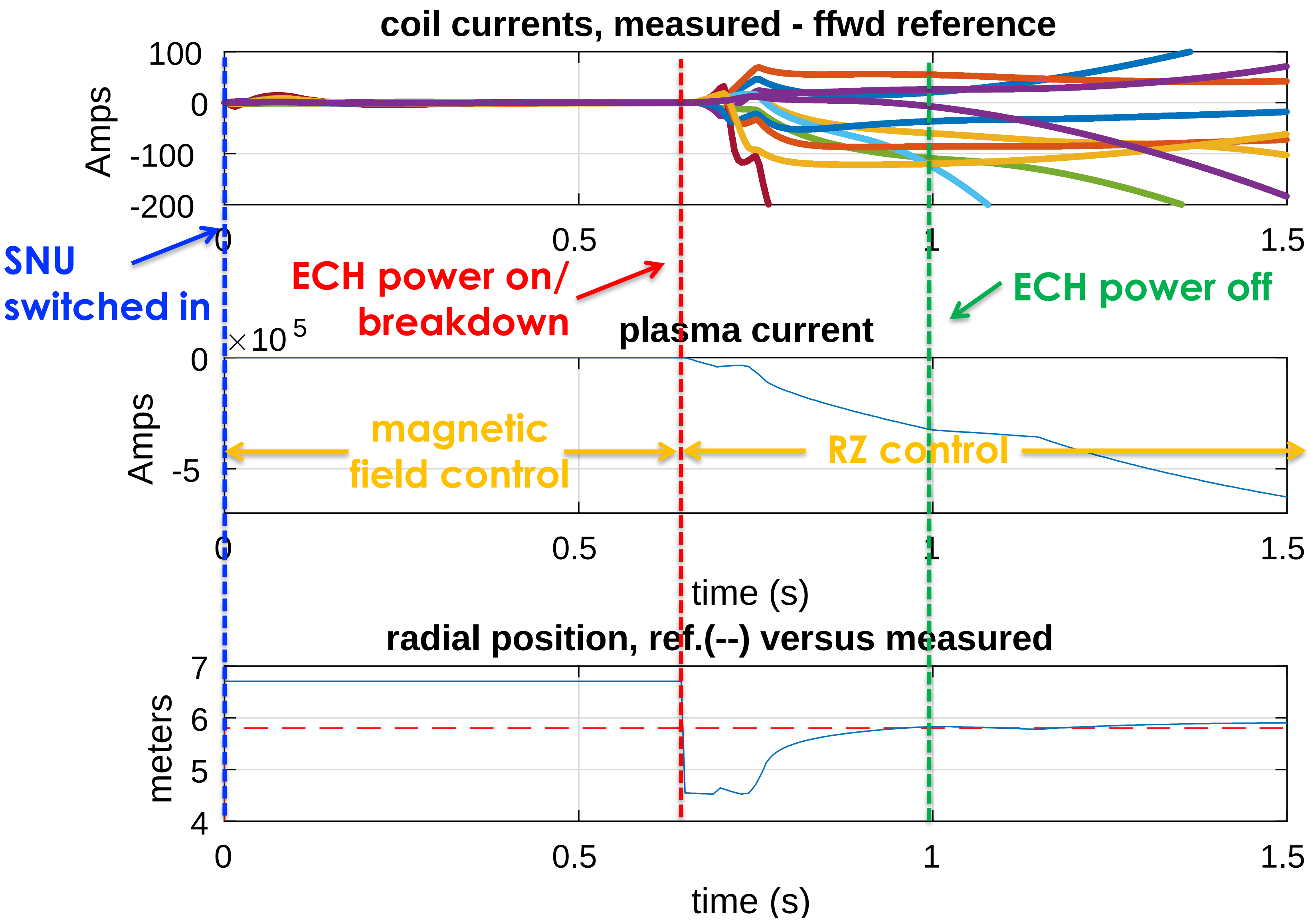


Coil current feedforward references I_{FF} updated to equal those produced by open-loop simulation

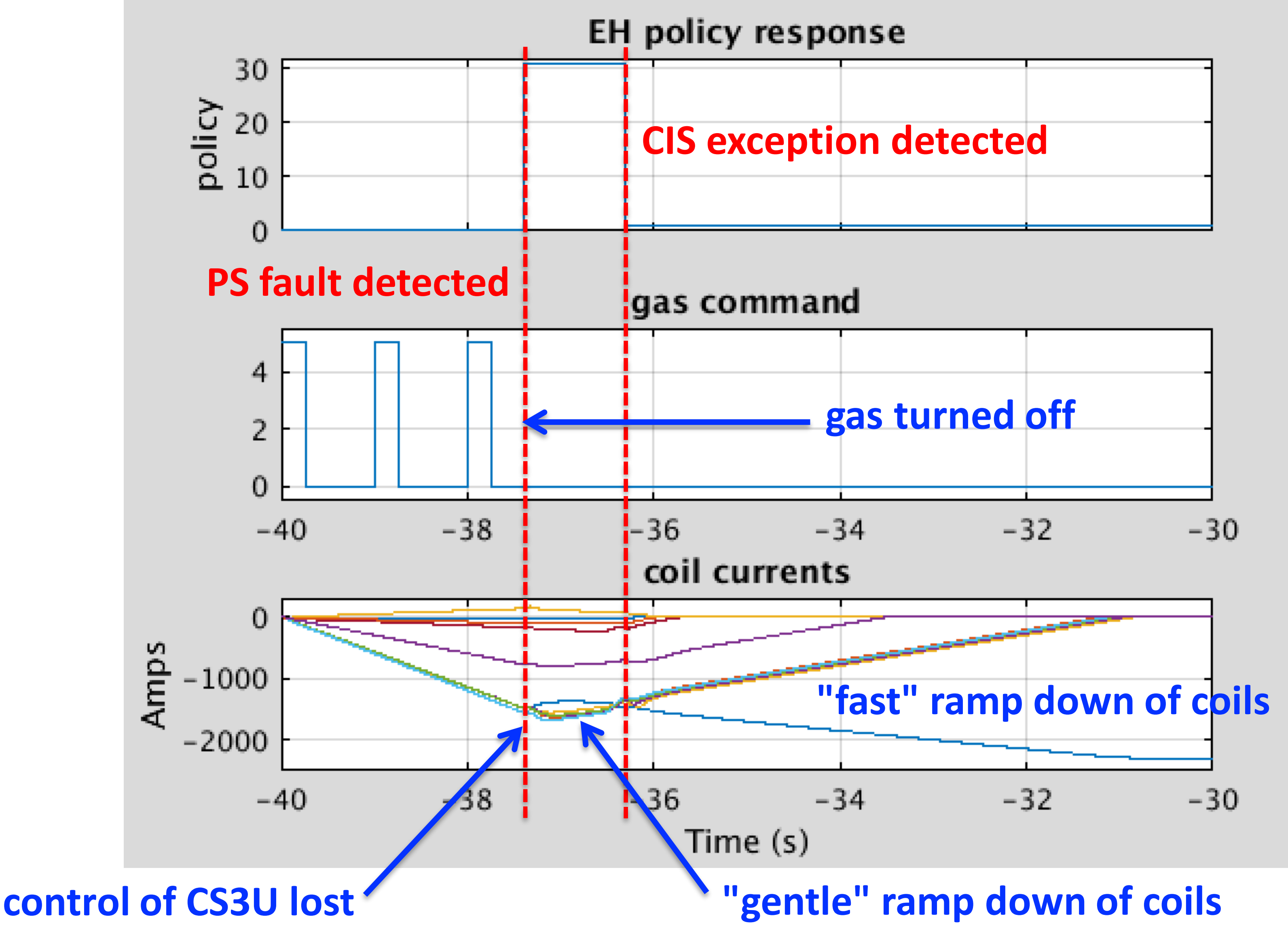


- **Differences in modeled currents mainly due to differing models for SNU effect on system dynamics**

PCS & modified scenario provides good control: plasma initiation



Concurrent exceptions assessment – assessment results: Power supply fault, then CIS exception - VERIFIED



Walker/ITER PCS FDR for First Plasma/July 2020

Conclusion

…

Thank you for your interest !

I am curious for any questions.