EUROfusion

Plasma models for the design of the ITER PCS

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create

DIETI. UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
DIPARTIMENTO DI INGEGNERIA ELETTRICA E TECNOLOGIE DELL'INFORMAZIONE

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Contents

- (brief) Overview of the CREATE modeling tools
- A recent (further) experimental validation of the CREATE models → the EAST tokamak
- Models provided for the FMPCFMPC project
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The CREATE modeling tools

The **plasma modeling tools** are part of the set of **CREATE Matlab/Simulink applications**

They can be used:

- to allow to perform analysis with 2D nonlinear magnetic equilibrium codes
  - to support the design and validation of scenarios
  - to support the design and commissioning of plasma magnetic diagnostic
- to automate the generation of linearized models for plasma/circuits behavior
- to automate the design/validation/deployment workflow of model-based plasma magnetic control systems
  - to support the design plasma current, position and shape control algorithms
  - to ease the optimization of the control gains between the experiment

CREATE-L and CREATE-NL

- CREATE-L (Albanese et al., Nucl. Fus. 1998)
  & CREATE-NL (Albanese et al, Fus. Eng. Des. 2015)
  - 2D finite elements magnetic equilibrium codes
  - can compute plasma equilibria in the presence of ferromagnetic materials and of eddy currents induced in thepassive structures
  - can produce linearized models

  CREATE-NL can also be used
  - to compute both direct and inverse equilibrium
  - to perform coupled simulations with transport codes
  - to perform nonlinear simulations with Simulink

The availability of (at least) two independent modelling tools is essential during experimental activities for cross-validation of the predictive simulations (e.g., inter-shot simulation aimed at optimizing the control gains)

CREATE-L and CREATE-NL have been validated experimentally on an extensive set of devices (JET, TCV, MAST, EAST, FTU, RFX)

They are successfully used to perfrom predictive anlysis for ITER and JT60-SA

Plasma modeling – The foundations

The starting point is the Grad-Shafranov equation (that exploits the axisymmetry assumption)

$$\Delta^* \psi = -\mu_0 R^2 \frac{\mathrm{d}p(\psi)}{\mathrm{d}\psi} - \mu_0^2 F(\psi) \frac{\mathrm{d}F(\psi)}{\mathrm{d}\psi} \quad \text{inside the plasma}$$

$$\Delta^* \psi = -\mu R J_{ext} \quad \text{in the active coils}$$

$$\Delta^* \psi = 0 \quad \text{elsewhere}$$

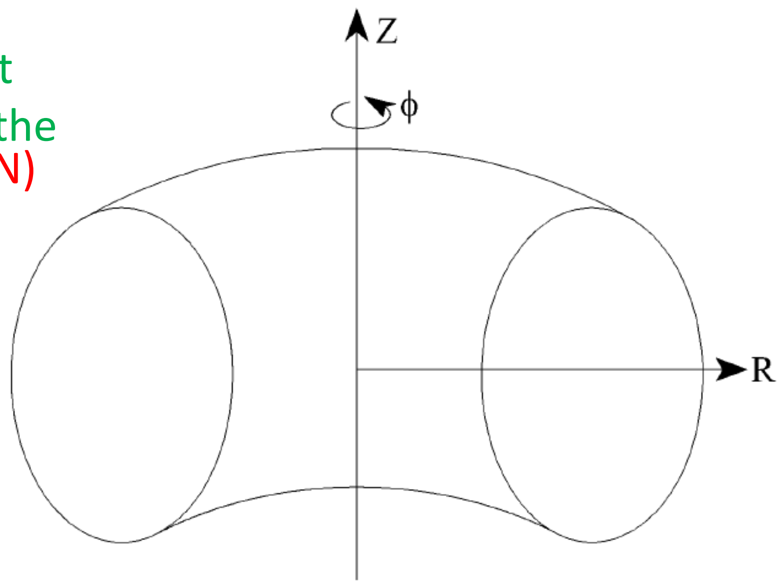
Function that depends on the toroidal field

The poloidal flux (THE UNKNOWN)

current density in the active conductors

Pressure profile

Laplacian operator in the toroidal coordinate system



Lumped parameters approximations

By using finite-elements methods, nonlinear lumped parameters approximation of the PDEs model is obtained

$$\frac{\mathrm{d}}{\mathrm{dt}}\Big[\mathcal{M}\big(\mathbf{y}(t), \beta_p(t), l_i(t)\big)\mathbf{I}(t)\Big] + \mathbf{R}\mathbf{I}(t) = \mathbf{U}(t)\,,$$

$$\mathbf{y}(t) = \mathcal{Y}\big(\mathbf{I}(t), \beta_p(t), l_i(t)\big)\,.$$

where:

- $\mathbf{y}(t)$ are the output to be controlled
- $\mathbf{I}(t) = \left[\mathbf{I}_{PF}^T(t)\ \mathbf{I}_e^T(t)\ I_p(t)\right]^T$ is the currents vector, which includes the currents in the active coils $\mathbf{I}_{PF}(t)$, the eddy currents in the passive structures $\mathbf{I}_e(t)$, and the plasma current $I_p(t)$
- $\mathbf{U}(t) = \left[\mathbf{U}_{PF}^T(t)\ \mathbf{0}^T\ 0\right]^T$ is the input voltages vector
- $\mathcal{M}(\cdot)$ is the mutual inductance nonlinear function
- $\mathbf{R}$ is the resistance matrix
- $\mathcal{Y}(\cdot)$ is the output nonlinear function

Plasma linearized model

Starting from the nonlinear lumped parameters model, the following plasma linearized state space model can be easily obtained:

Typical system order ~100

$$\delta\dot{\mathbf{x}}(t) = \mathbf{A}\delta\mathbf{x}(t) + \mathbf{B}\delta\mathbf{u}(t) + \mathbf{E}\delta\dot{\mathbf{w}}(t), \quad (1)$$

$$\delta\mathbf{y}(t) = \mathbf{C}\ \delta\mathbf{I}_{PF}(t) + \mathbf{F}\delta\mathbf{w}(t), \quad (2)$$

Linear models with the same structure are generated by both CREATE-L and CREATE-NL

where:

- **A**, **B**, **E**, **C** and **F** are the model matrices
- $\delta\mathbf{x}(t) = \left[\delta\mathbf{I}_{PF}^T(t)\ \delta\mathbf{I}_e^T(t)\ \delta I_p(t)\right]^T$ is the state space vector
- $\delta\mathbf{u}(t) = \left[\delta\mathbf{U}_{PF}^T(t)\ \mathbf{0}^T\ 0\right]^T$ are the input voltages variations
- $\delta\mathbf{w}(t) = \left[\delta\beta_p(t)\ \delta l_i(t)\right]^T$ are the β_p and l_i variations
- $\delta\mathbf{y}(t)$ are the output variations

The model (1)–(2) relates the variations of the PF currents to the variations of the outputs around a given equilibrium

3D modeling of the passive structures (thanks to F. Villone)

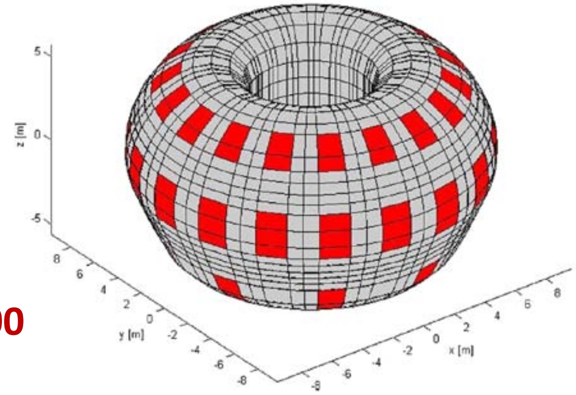
- Besides CREATE-L and CREATE-NL, other modelling tools are available for the electromagnetic interaction of plasma with conductors under the axisymmetric assumption

- The **CarMa0NL** tool is able to describe the nonlinear evolution of axisymmetric plasmas, in presence of three-dimensional volumetric conducting structures.

Computational tool	***Plasma description***	***Structures***
PROTEUS, MAXFEA, **CREATE_NL**	Axisymmetric, Evolutionary equilibrium	Axisymmetric (Finite elements)
DINA	Axisymmetric, Evolutionary equilibrium	Axisymmetric (Filaments)
TSC	Axisymmetric, MHD equations	Axisymmetric (Finite Differences)
CREATE_L, PET	Axisymmetric, Linearized perturbed equilibrium	Axisymmetric (Finite elements)
CarMa0NL	*Axisymmetric, Evolutionary equilibrium*	*Three dimensional (volumetric)*

The CarMa code can generate **(very high order!)** linearized plasma models that include the non-axisymmetric kink instability (aka Resistive Wall Mode)

Typical system order (for ITER) ~4000



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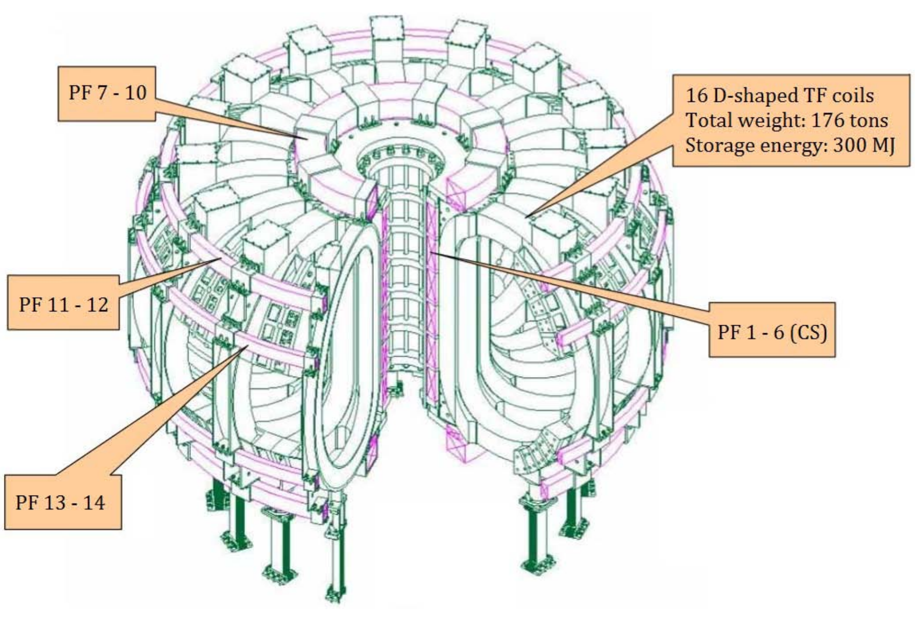
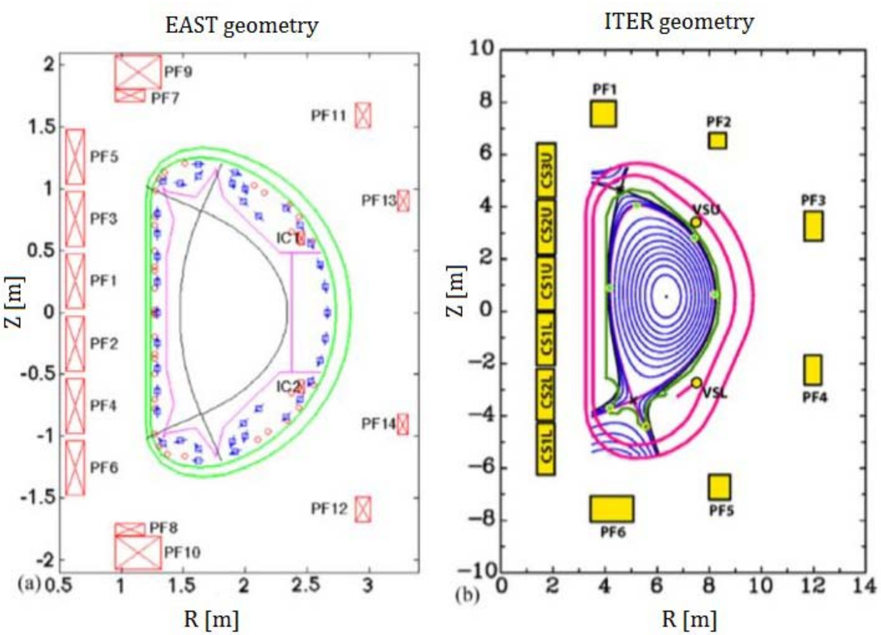
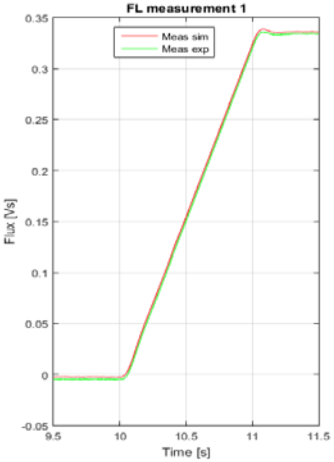
A recent (further) experimental validation of the CREATE models – The EAST tokamak

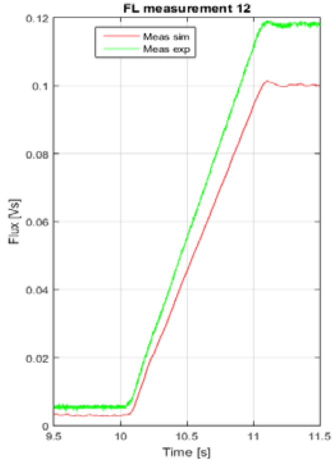
- The EAST tokamak
  - is a superconductive tokamak (previous validations on non superconductive devices)
  - has an ITER-like PF coils layout (of course downscaled!)

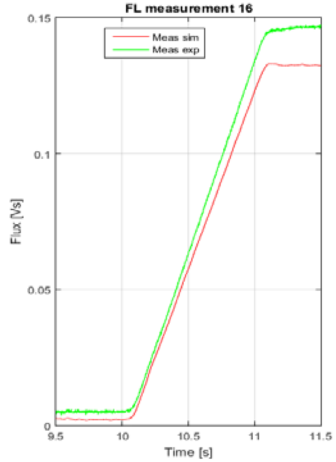


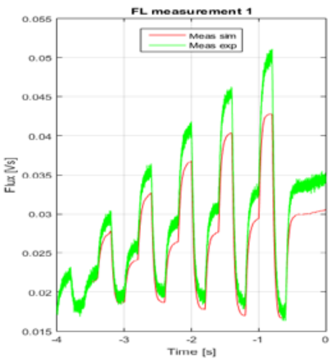


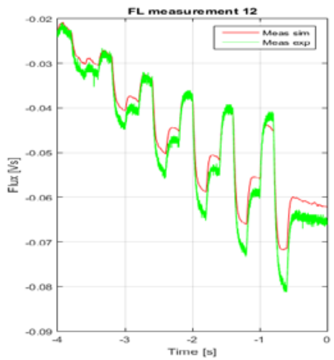
Open loop validations (thanks to A. Castaldo)

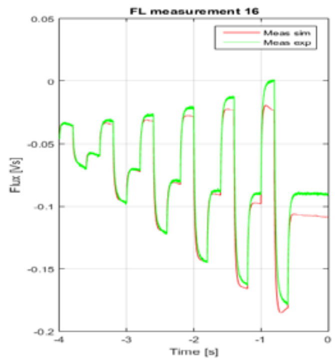


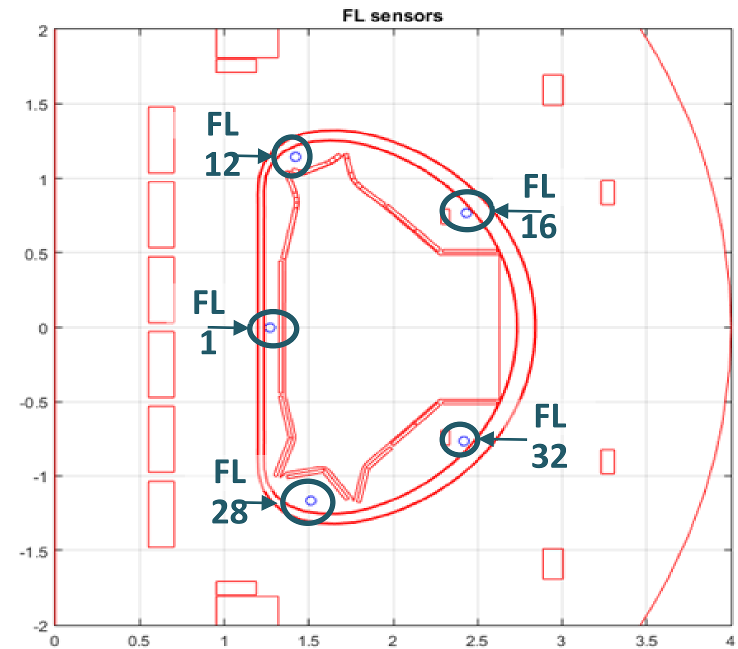




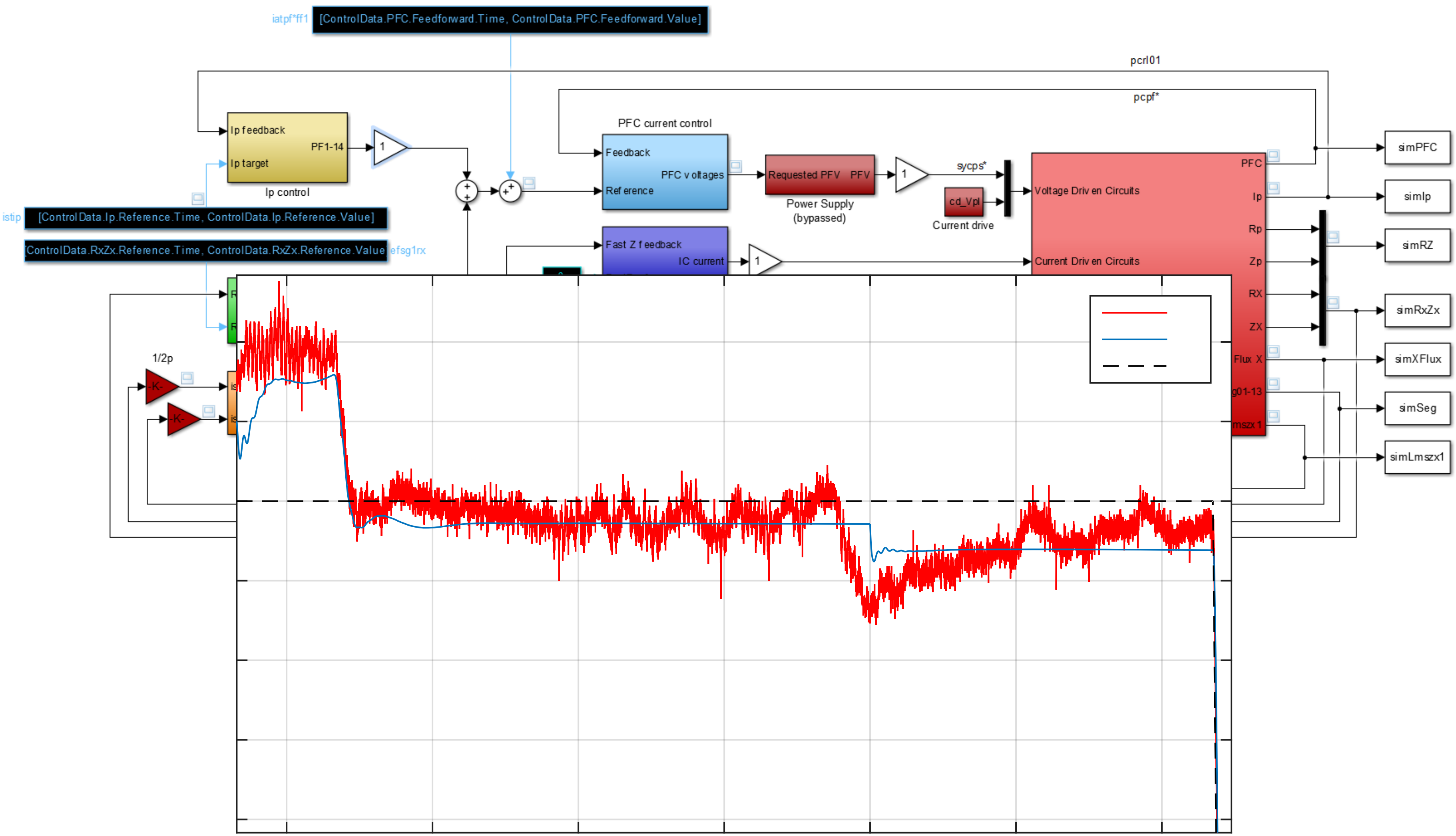








Closed loop validations (thanks to A. Mele)



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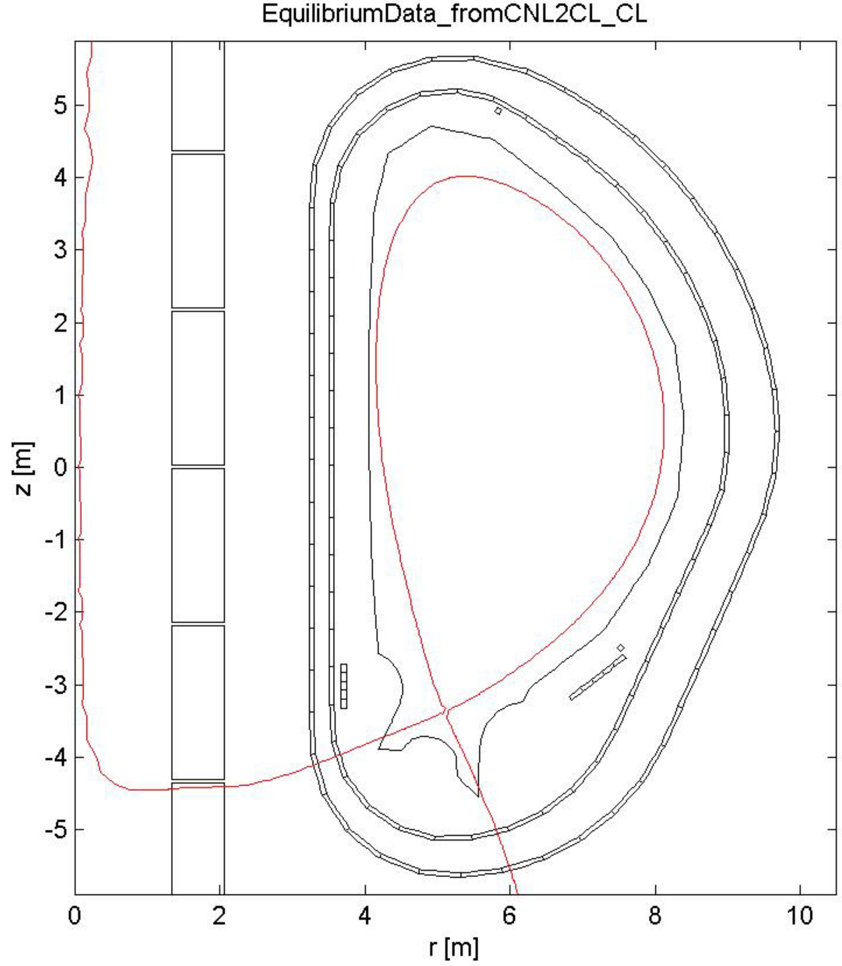
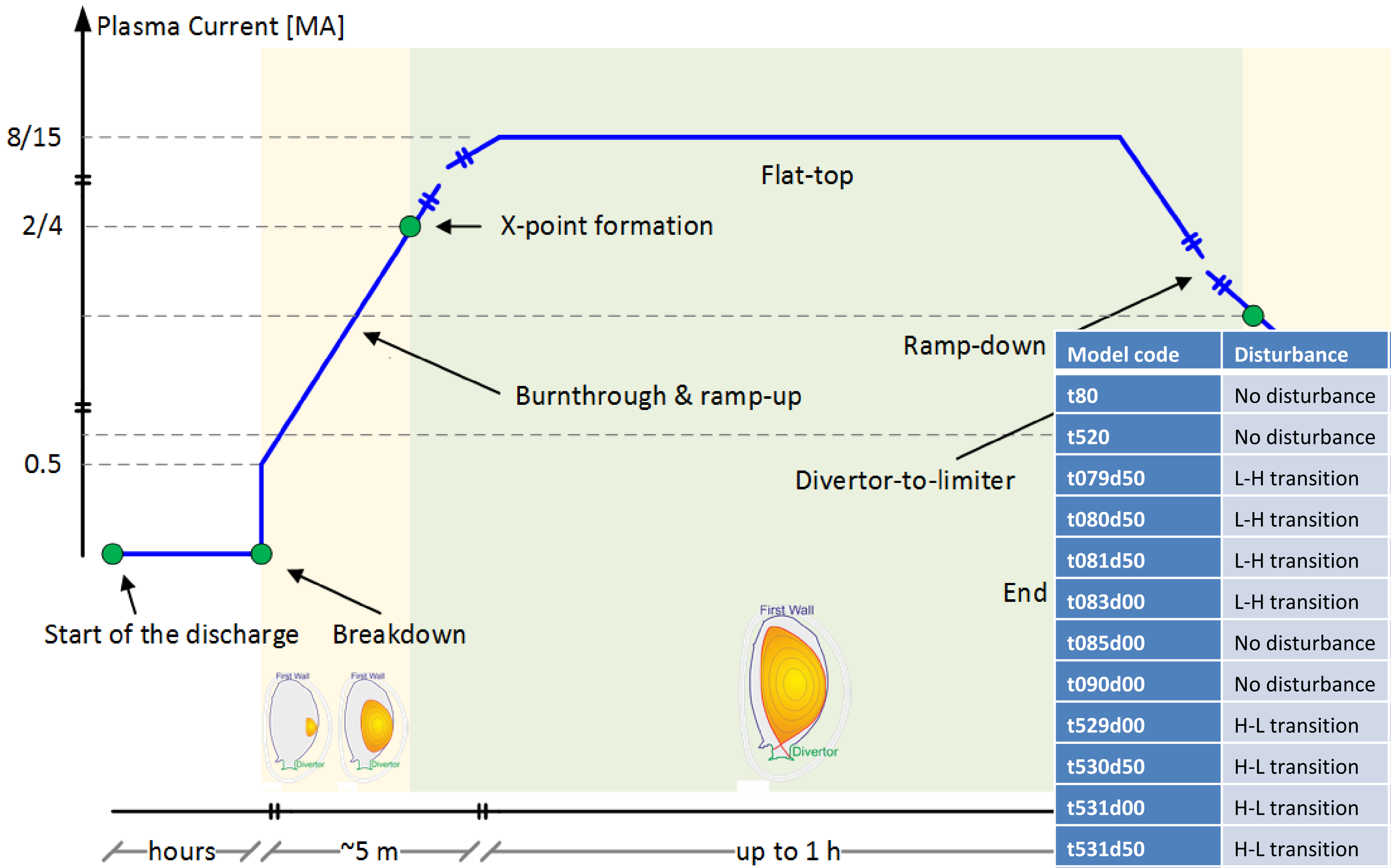
ITER Scenario 1

- ITER Reference Scenario 1
- 15 MA scenario
- L-H transition just after the end of the ramp rump
- H-L transition before the ramp down
- (almost) fully inductive during the flat top (when in H mode)



A tokamak discharge



Model code	Disturbance	Growth rate (s^{-1})
t80	No disturbance	9.1
t520	No disturbance	2.9
t079d50	L-H transition	9.3
t080d50	L-H transition	8.6
t081d50	L-H transition	7.8
t083d00	L-H transition	5.5
t085d00	No disturbance	5.0
t090d00	No disturbance	3.6
t529d00	H-L transition	3.5
t530d50	H-L transition	6.5
t531d00	H-L transition	10.1
t531d50	H-L transition	10.1
t532d00	H-L transition	6.8
t532d50	H-L transition	6.5

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Linear models and simulations VS nonlinear models and simulations

- Linear models are OK for
  - controller design
  - controller validation (robustness analysis under different operating scenarios)

- If detailed performance analysis are needed then it is worth to resort to nonlinear simulations
  - to check the behavior of the system close to the limits (e.g., small plasma-wall clearance, small control margin, etc.)

- Within the CREATE modeling tools, nonlinear simulations can be carried out using the Simulink version of the CREATE-NL code

The nonlinear CREATE-NL Simulink block

- In order to reduce the computational burden, the overall plasma model is obtained by combining a nonlinear dynamic free boundary equilibrium solver with a linear model of the dynamics induced by eddy currents, including the n = 0 unstable mode modeling plasma vertical instability

- The combination of the two models allows simulation with both plasma shape and vertical stabilization control

- The nonlinear free boundary equilibrium solver simulates the plasma shape and current evolution on the time scale of seconds.

  This dynamic is time-integrated with a suggested fixed time step of 100 ms (good trade-off suggested for ITER), and is implemented by wrapping into an S-function a light version of the CREATE-NL solver.

- In order to perform closed-loop nonlinear simulations, a strong iteration between the CREATE and IJS team will be necessary