Plasma models for the design of the ITER PCS

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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 FMPCFMPFCFMPC project

• Conclusive remarks
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• Conclusive remarks
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

  - 2D finite elements magnetic equilibrium codes
  - Can compute plasma equilibria in the presence of ferromagnetic materials and of eddy currents induced in the passive 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 perform predictive analysis for ITER and JT60-SA
The starting point is the Grad-Shafranov equation (that exploits the axisymmetry assumption)

\[ \Delta^* \psi = -\mu_0 R^2 \frac{dp(\psi)}{d\psi} - \mu_0^2 F(\psi) \frac{dF(\psi)}{d\psi} \]

\[ \Delta^* \psi = -\mu R J_{ext} \]

\[ \Delta^* \psi = 0 \]

- Laplacian operator in the toroidal coordinate system
- Pressure profile
- Function that depends on the toroidal field
- Current density in the active conductors
- The poloidal flux (THE UNKNOWN)

inside the plasma
in the active coils elsewhere
Lumped parameters approximations

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

\[
\frac{d}{dt} \left[ M(y(t), \beta_p(t), l_i(t)) I(t) \right] + RI(t) = U(t),
\]

\[
y(t) = \mathcal{Y}(I(t), \beta_p(t), l_i(t)).
\]

where:

- \(y(t)\) are the output to be controlled
- \(I(t) = [I_{PF}^T(t) \ I_e^T(t) \ I_p(t)]^T\) is the currents vector, which includes the currents in the active coils \(I_{PF}(t)\), the eddy currents in the passive structures \(I_e(t)\), and the plasma current \(I_p(t)\)
- \(U(t) = [U_{PF}^T(t) \ 0^T \ 0]^T\) is the input voltages vector
- \(M(\cdot)\) is the mutual inductance nonlinear function
- \(R\) is the resistance matrix
- \(\mathcal{Y}(\cdot)\) is the output nonlinear function
Starting from the nonlinear lumped parameters model, the following plasma linearized state space model can be easily obtained:

\[
\delta x(t) = A \delta x(t) + B \delta u(t) + E \delta \dot{w}(t), \\
\delta y(t) = C \delta I_{PF}(t) + F \delta w(t),
\]

Typical system order \(\sim 100\)

where:

- \(A, B, E, C\) and \(F\) are the model matrices
- \(\delta x(t) = \begin{bmatrix} \delta I_{PF}^T(t) & \delta I_e^T(t) & \delta I_p(t) \end{bmatrix}^T\) is the state space vector
- \(\delta u(t) = \begin{bmatrix} \delta U_{PF}^T(t) & 0^T & 0 \end{bmatrix}^T\) are the input voltages variations
- \(\delta w(t) = \begin{bmatrix} \delta \beta_p(t) & \delta l_i(t) \end{bmatrix}^T\) are the \(\beta_p\) and \(l_i\) variations
- \(\delta y(t)\) 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
• 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.

<table>
<thead>
<tr>
<th>Computational tool</th>
<th>Plasma description</th>
<th>Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROTEUS, MAXFEA, CREATE_NL</td>
<td>Axisymmetric, Evolutionary equilibrium</td>
<td>Axisymmetric (Finite elements)</td>
</tr>
<tr>
<td>DINA</td>
<td>Axisymmetric, Evolutionary equilibrium</td>
<td>Axisymmetric (Filaments)</td>
</tr>
<tr>
<td>TSC</td>
<td>Axisymmetric, MHD equations</td>
<td>Axisymmetric (Finite Differences)</td>
</tr>
<tr>
<td>CREATE_L, PET</td>
<td>Axisymmetric, Linearized perturbed equilibrium</td>
<td>Axisymmetric (Finite elements)</td>
</tr>
<tr>
<td>CarMa0NL</td>
<td><strong>Axisymmetric, Evolutionary equilibrium</strong></td>
<td><strong>Three dimensional (volumetric)</strong></td>
</tr>
</tbody>
</table>

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!)

![Diagram of EAST tokamak and ITER geometry]
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)
## Model Code

<table>
<thead>
<tr>
<th>Model code</th>
<th>Disturbance</th>
<th>Growth rate (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t80</td>
<td>No disturbance</td>
<td>9.1</td>
</tr>
<tr>
<td>t520</td>
<td>No disturbance</td>
<td>2.9</td>
</tr>
<tr>
<td>t079d50</td>
<td>L-H transition</td>
<td>9.3</td>
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<tr>
<td>t080d50</td>
<td>L-H transition</td>
<td>8.6</td>
</tr>
<tr>
<td>t081d50</td>
<td>L-H transition</td>
<td>7.8</td>
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<tr>
<td>t083d00</td>
<td>L-H transition</td>
<td>5.5</td>
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<tr>
<td>t085d00</td>
<td>No disturbance</td>
<td>5.0</td>
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<tr>
<td>t090d00</td>
<td>No disturbance</td>
<td>3.6</td>
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<tr>
<td>t529d00</td>
<td>H-L transition</td>
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<tr>
<td>t530d50</td>
<td>H-L transition</td>
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• 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
• 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.