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Coupling of Mechanical and Magneto-Thermal Models of Superconducting Magnets by Means of Mesh-Based Interpolation

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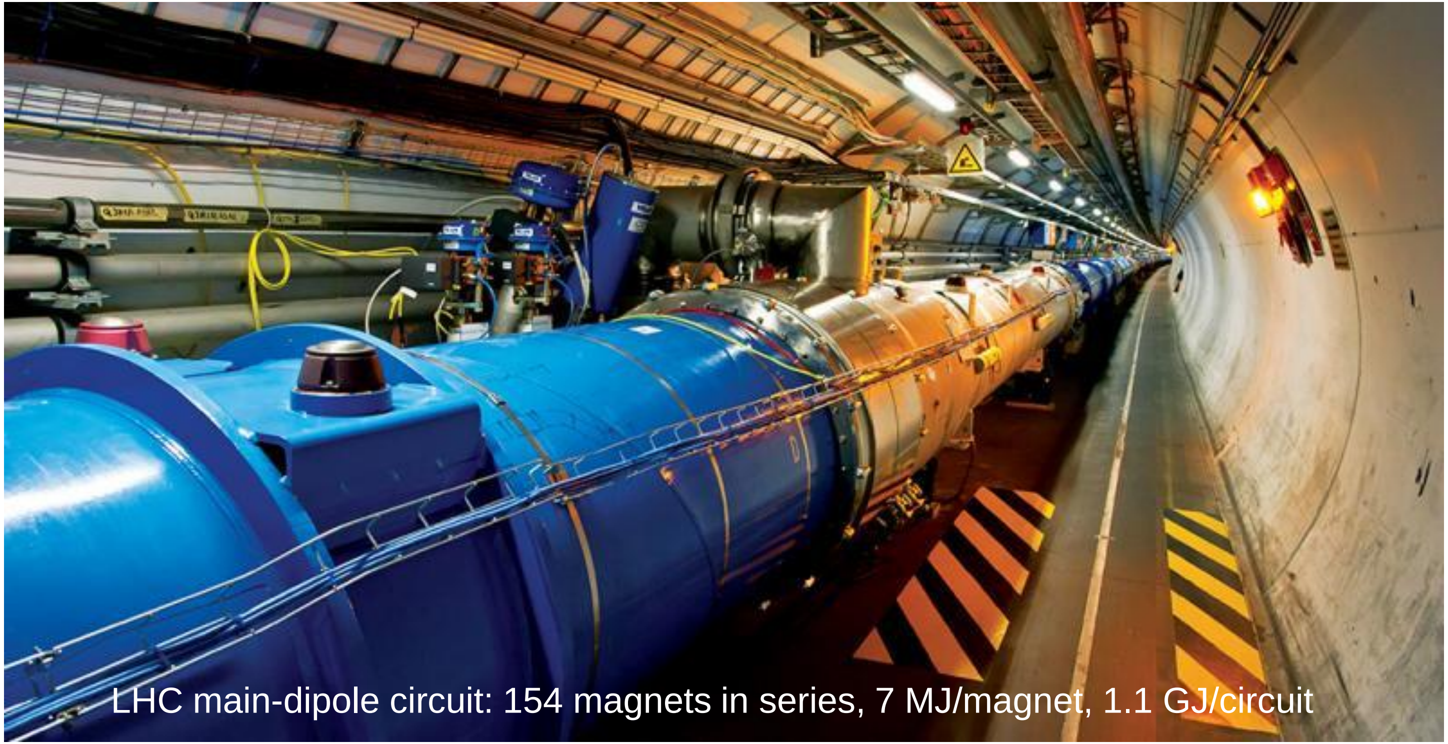
Outline

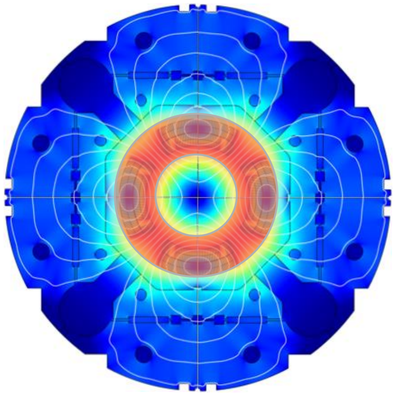
- STEAM: Simulation of Transient Effects in Accelerator Magnets.
- Mesh-based coupling applied to magneto-thermal and mechanical co-simulation.

Protecting Complex SC Magnet Circuits in LHC, HL-LHC and FCC

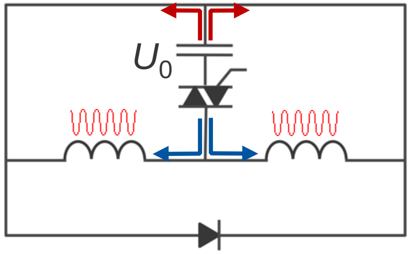


LHC main-dipole circuit: 154 magnets in series, 7 MJ/magnet, 1.1 GJ/circuit

Protecting Complex SC Magnet Circuits in LHC, HL-LHC and FCC

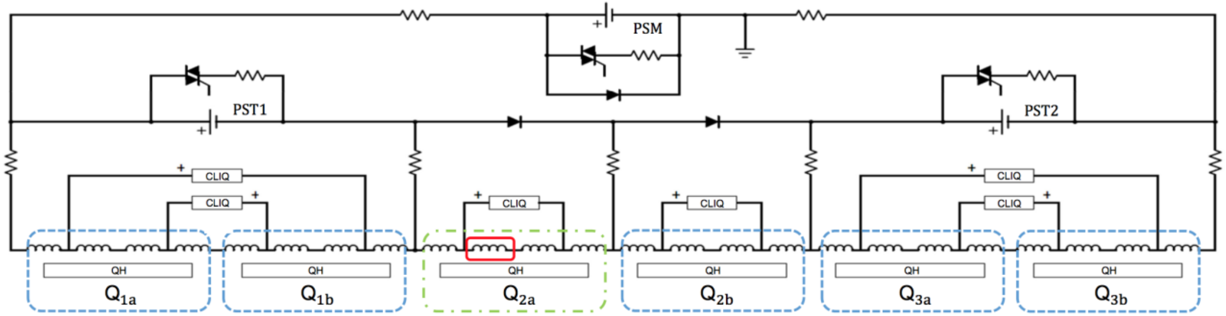


CLIQ



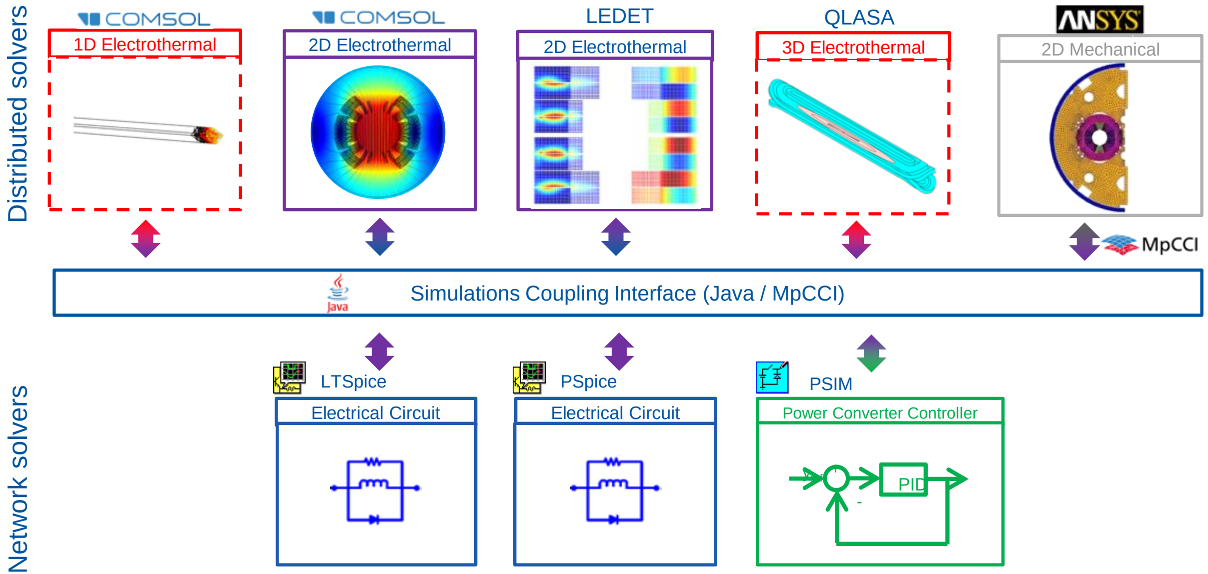
[1] E. Ravaioli, et al. New, coupling loss induced, quench protection system for superconducting accelerator magnets. IEEE Trans. on App. SC., 24, 500905, 2013.

Six CLIQ units in the baseline protection scheme of the HL-LHC inner-triplet circuit with one main and two trim power converters.



Co-Simulation Framework for Accelerator Community

- Provide flexible co-simulation environment to allow users to use software tools according to (1) license availability and tool preference, (2) runtime and accuracy requirements, (3) availability of validated models; and to run multiple instances of a tool.
- Currently available code adapters include: (dashed: experimental)



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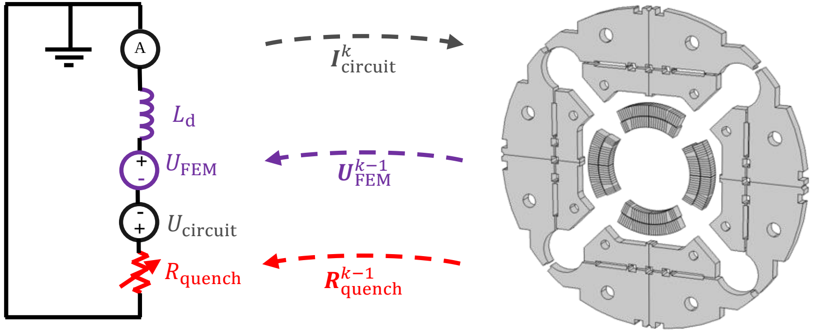
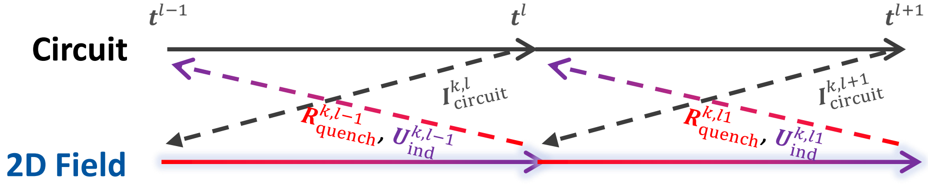
Field/Circuit Coupling, Waveform Relaxation

- We use a current-driven field problem and a circuit representation with an approximated differential inductance and updated resistance.



$$U_{circuit} = L_d\, \partial_t I^k_{circuit}$$



[1] I. Cortes Garcia, et al. Optimized Field/Circuit Coupling for the Simulation of quenches in Superconducting Magnets. IEEE Journal on Multiscale and Multiphysics Computational Techniques, accepted for publication, 2017.

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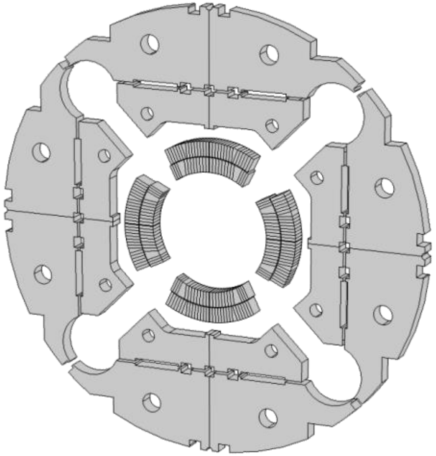
Coupled Field Formulation in COMSOL



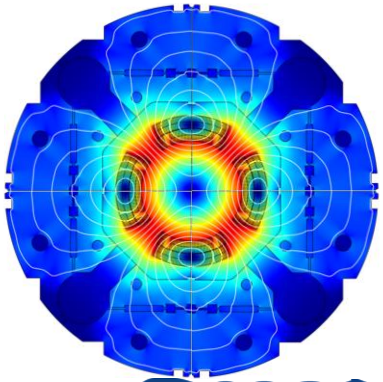
Curl-Curl Equation

$$\nabla \times \left(\mu^{-1} \nabla \times \vec{A} \right) = \vec{J}_s + \sigma(B,T)\partial_t \vec{A} + \nabla \times \vec{M}$$

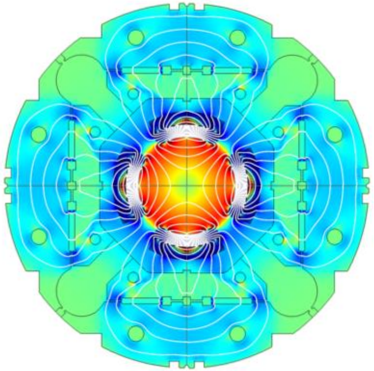
Heat Balance Equation

$$\sigma C_p(B,T)\partial_t T - \nabla \cdot \lambda \nabla T = Q$$

Total field



Field due to $\vec{M}$



[2] L. Bortot, et al., “A 2-D Finite-Element Model for Electro-Thermal Transients in Accelerator Magnets”, IEEE Trans. on Magnetics, accepted for publication, 2017.

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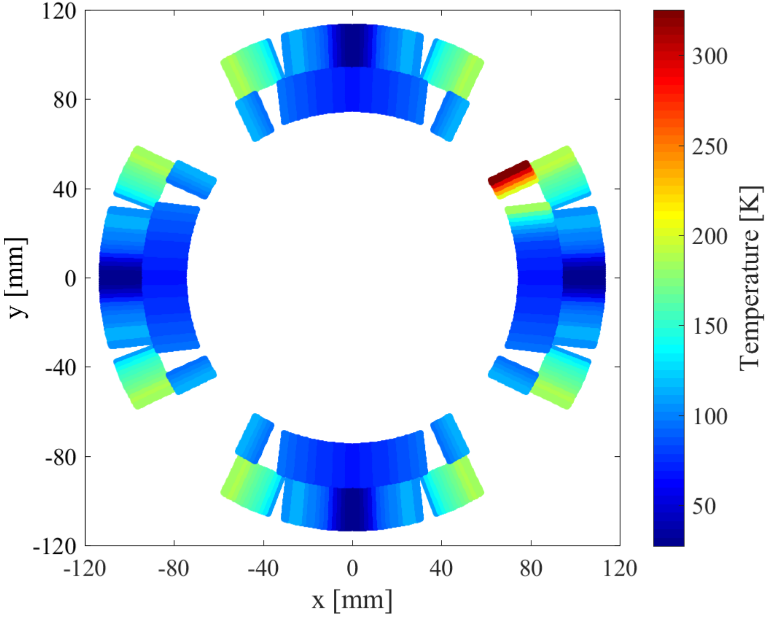
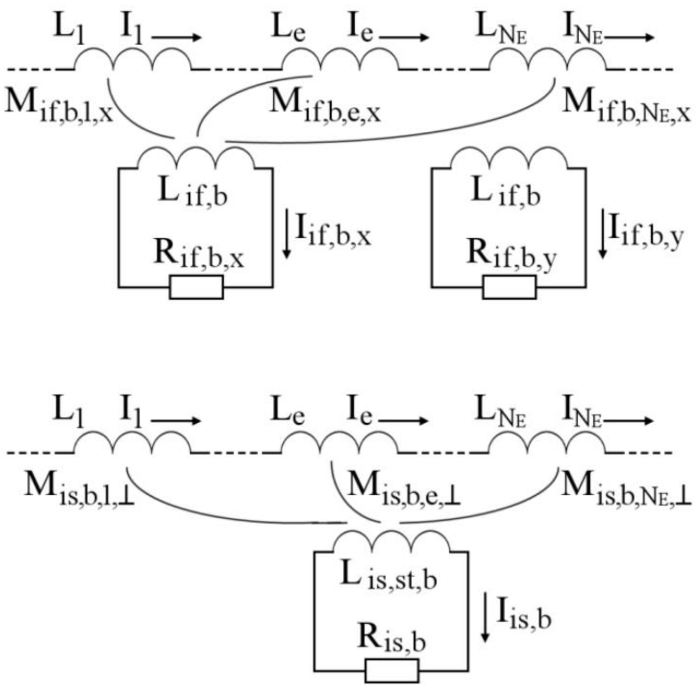
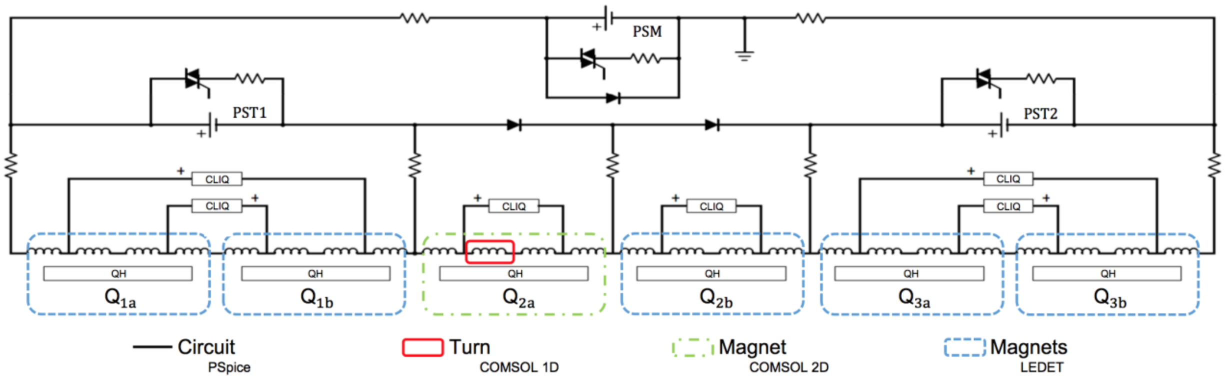
LEDET

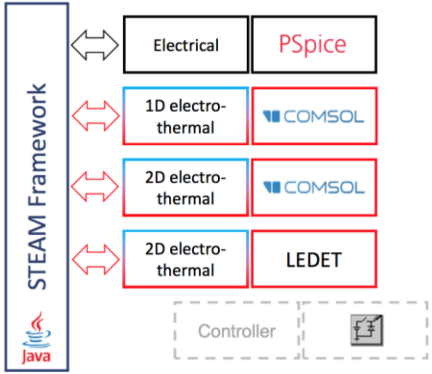


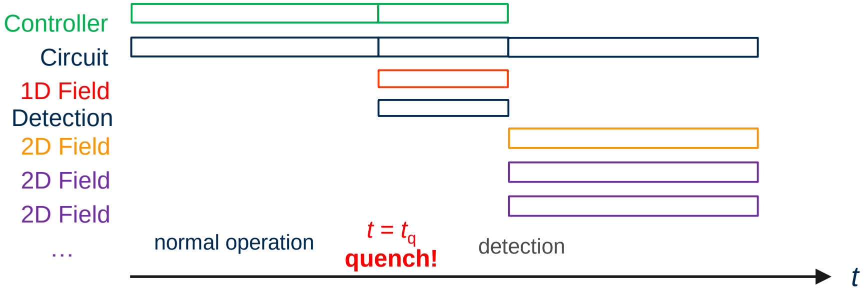


[3] E. Ravaioli, B. Auchmann, M. Maciejewski, H. ten Kate, and A. Verweij, “Lumped-element dynamic electro-thermal model of a superconducting magnet,” *Cryogenics*, vol. 80, pp. 346–356, 2016.

Hierarchical Co-Simulation





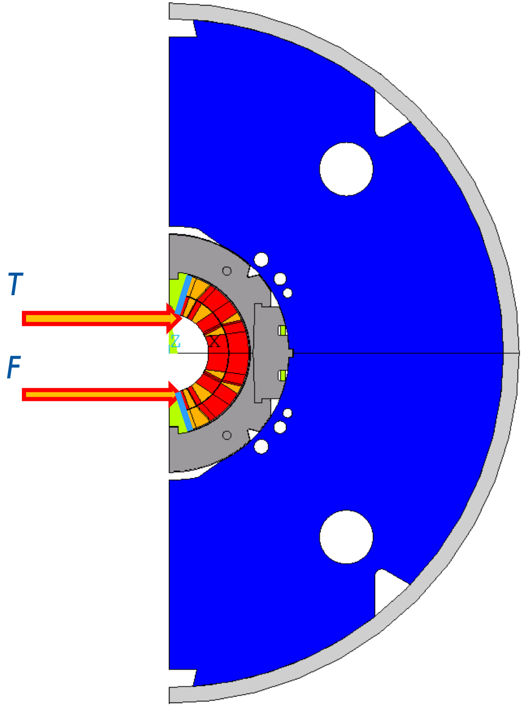


Hierarchical co-simulation controlled by a state machine.

[4] L. Bortot, et al., “STEAM: A Hierarchical Co-Simulation Framework for Superconducting Accelerator Magnet Circuits”, IEEE Trans. on Appl. SC., submitted for publication, 2017.

Mechanical Model in ANSYS APDL

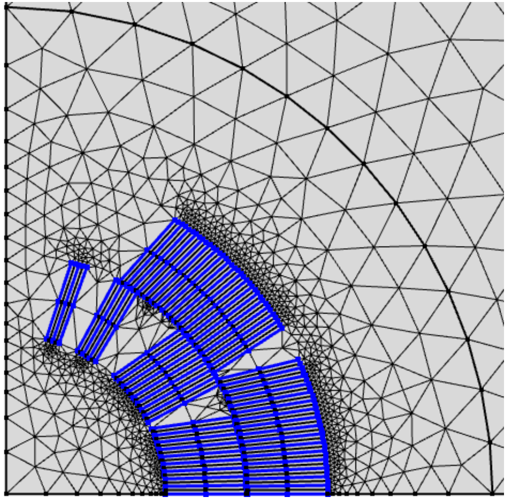
- Reuse a validated mechanical model written in ANSYS APDL.
- Predict the internal stress states during a quench protected with CLIQ.
- Transfer temperature and Lorentz-force from 2-D COMSOL field model.
- Use one of the standard industry tools for generic mesh-based data interpolation.
- MpCCI by Fraunhofer SCAI supports
    - mesh-based interpolation
    - uni-directional coupling
    - bi-directional coupling.



Mesh-Based Interpolation

Magneto-Thermal Model

COMSOL



Coupling Environment

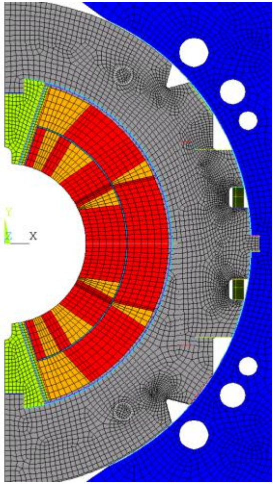
T → $\hat{T}$

$\vec{F}_\mathrm{L}$ → $\widehat{\vec{F}_\mathrm{L}}$

Mesh-based interpolation

Mechanical Model

ANSYS



Implementation of One-way coupling with MpCCI

MpCCI server already supports ANSYS APDL models.
For COMSOL it was necessary to develop a dedicated Java code adapter

COMSOL

```
cml.runTransientStudy();

adapter.init();

for (int j = 0; j < timeIndices.length; j++)
{
    adapter.setCurrentIteration(j);
    adapter.setTimeIndex(timeIndices[j]);
    adapter.exchange();
}

adapter.exit();
```

ANSYS

```
~mpcci,settag,-1,0
~mpcci,init,2D

*DO,j,1,steps
  ~mpcci, receive
  ALLSEL
  SOLVE
  FINISH
  ~mpcci,settag,-1,j
*ENDDO
~mpcci,quit
```

Four MpCCI server commands are required for establishing connection, time-step synchronization, exchange of quantities, and synchronization.

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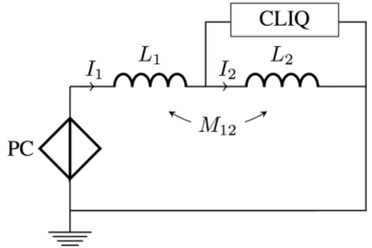
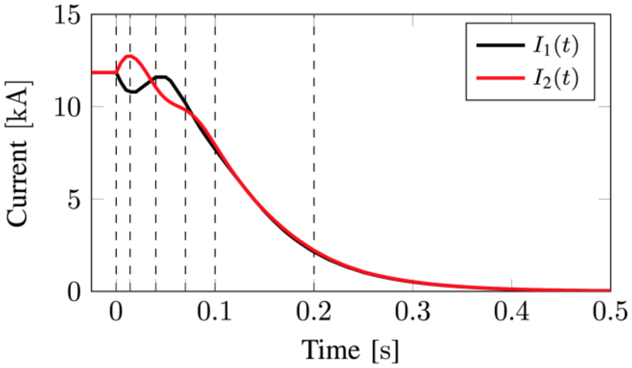
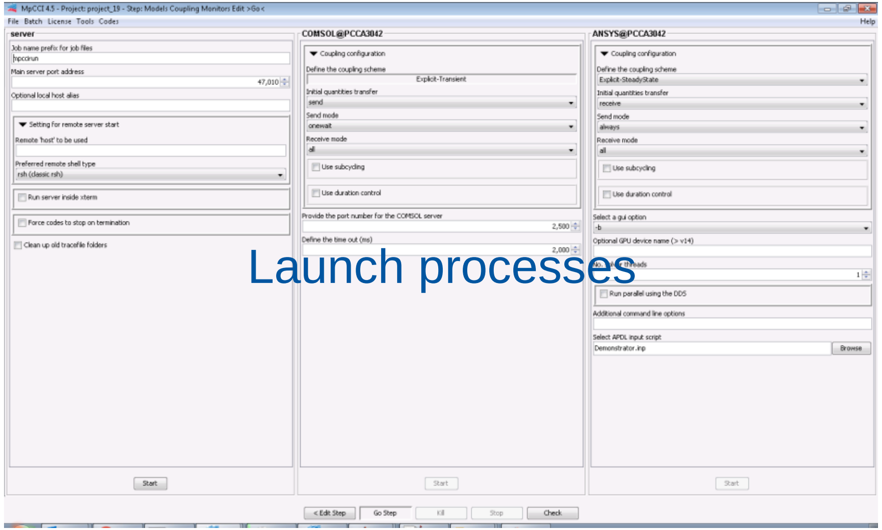
Automated Data Transfer





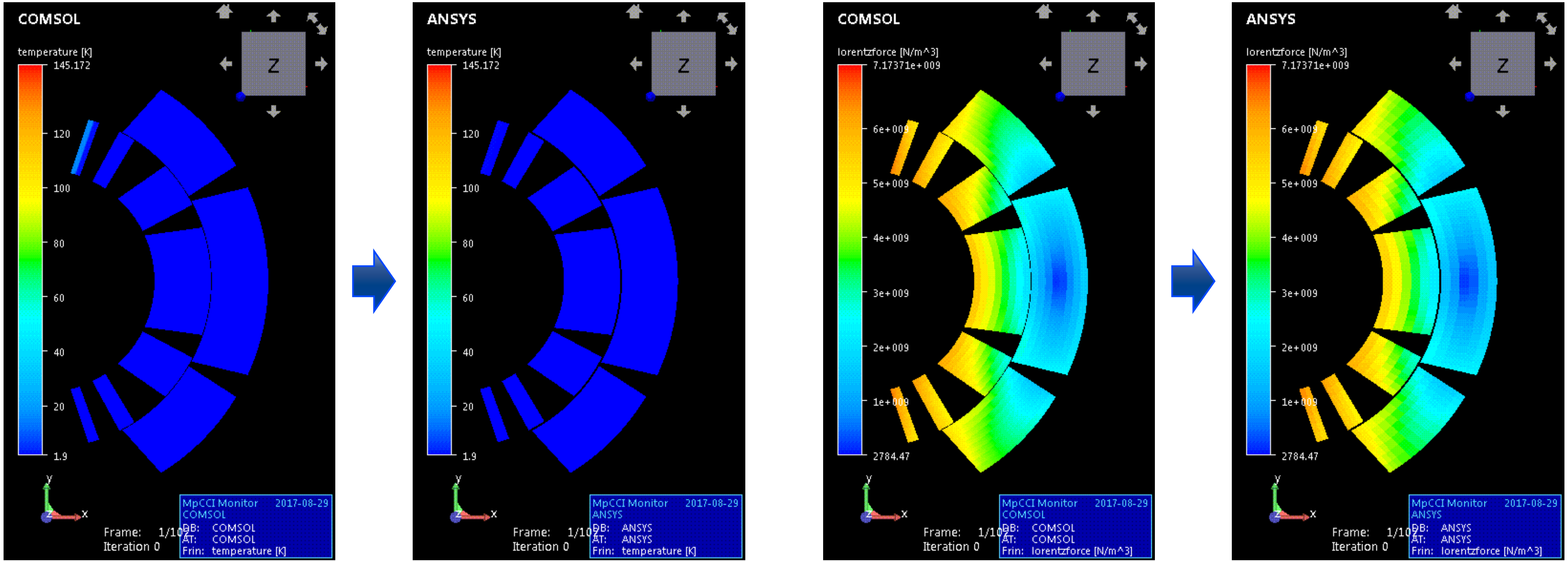


Launch processes

In this proof of concept we simulate a single-aperture 11-T magnet on a test bench during a CLIQ-protected quench.

103 time steps are executed.

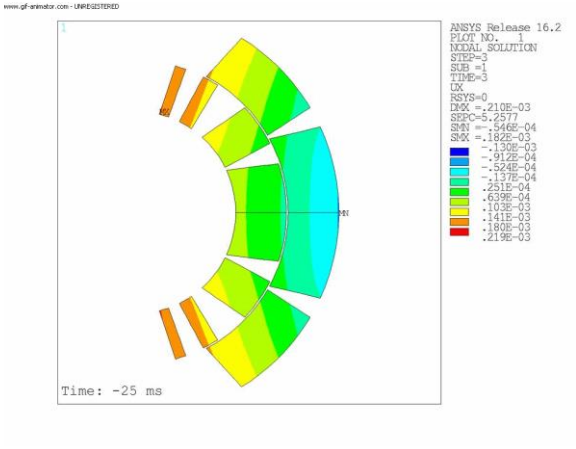
Data Transfer at Sample Times



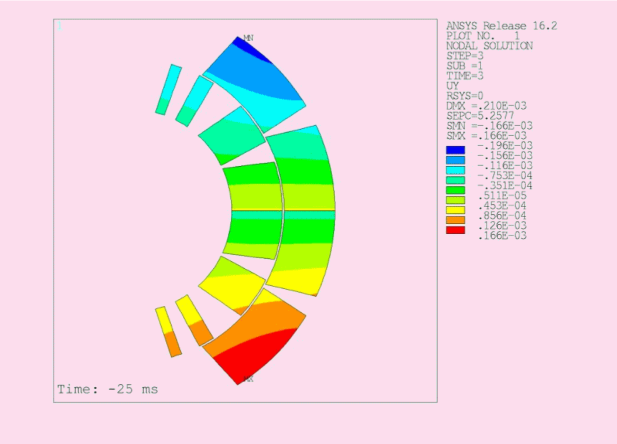
Data transfer preview in MpCCI GUI

ANSYS Results

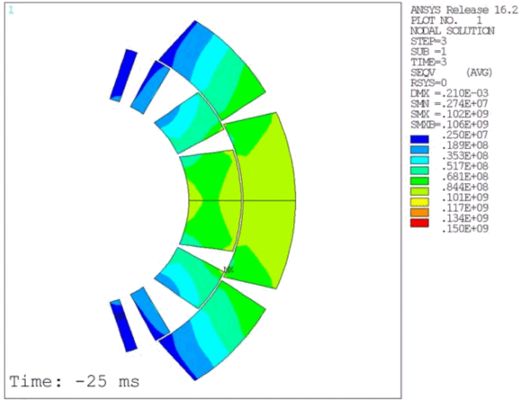
x-displacement



y-displacement



von Mises stress



Asymmetric stress and deformation due to CLIQ discharge and hot-spot evolution.

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Conclusions

- The STEAM project is driven by accelerator-specific needs.
- We harness the power of hierarchical co-simulation with waveform relaxation to provide a new level of flexibility in tackling complex interdependent problems.
- The framework is used in the analysis of LHC, HL-LHC upgrade, and FCC.
- With SCAI, we introduce mesh-based interpolation to our co-simulation (http://mpcci.de).
- Next steps (in the pipeline):
  - extend model-generation modules, simplify model switching,
  - addition of open source FE solvers, HTS-specific models,
  - add model adapters for our 3D models,
  - performance improvements in waveform relaxation.
- On the horizon:
  - extend the availability of mesh-based tool adapters,
  - multi-directional mesh-based coupling with wave-form relaxation,
  - hardware-in-the-loop co-simulation with actual protection electronics,
  - multi-rate (geometrical) domain decomposition.

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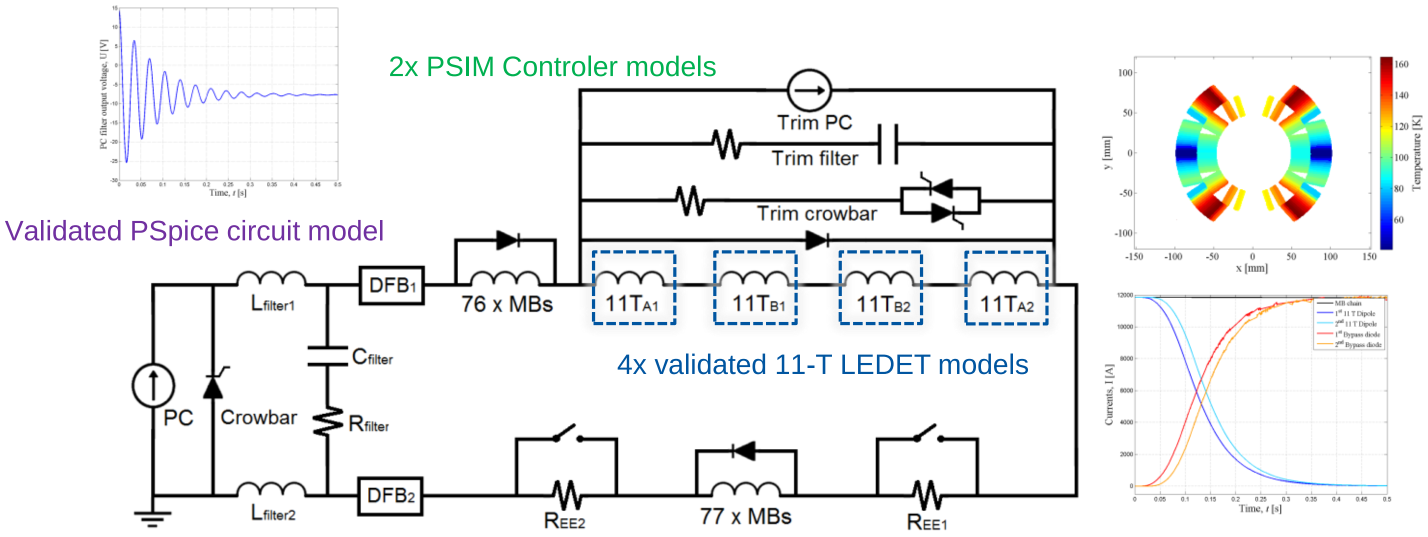
High-Luminosity Upgrade of the LHC Dipole Circuit

- Circuit model, validated to reproduce transmission-line effects.
- Models of quenching upgrade magnets, to be installed in 2020.
- New trim power-supply controllers are tested under realistic conditions.



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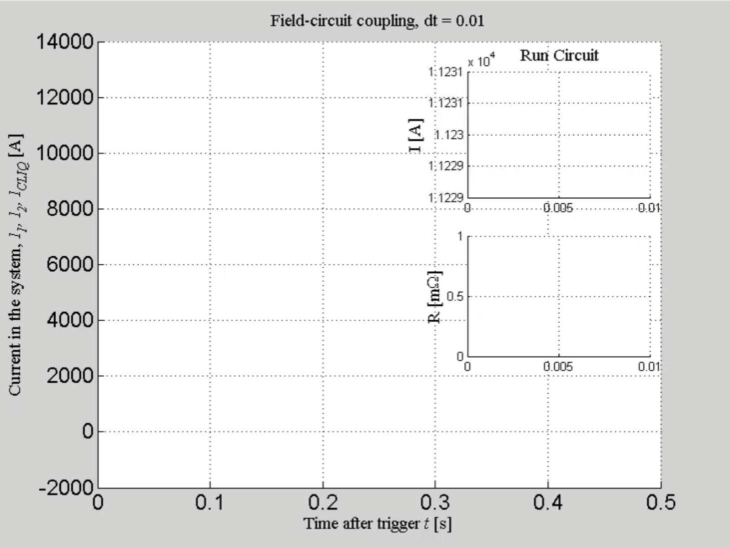
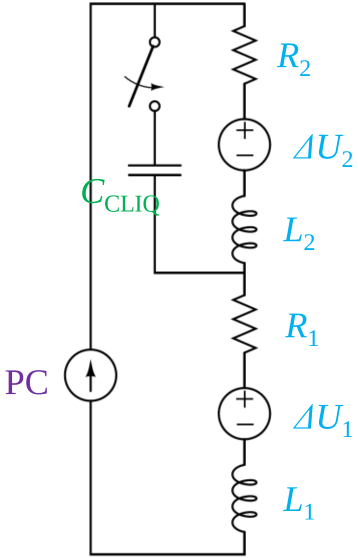
Iterative Solution





C_{CLIQ}=20 mF, U_{CLIQ}=2 kV