
CERN

# Experience in Co-Simulations with STEAM

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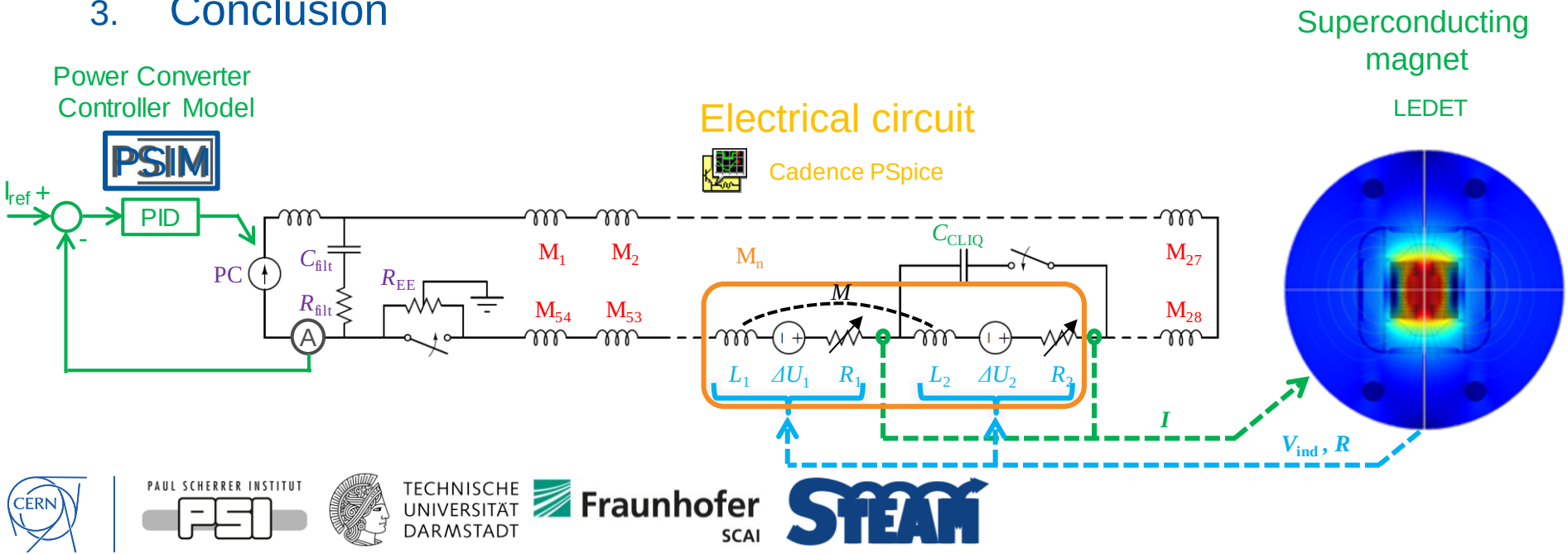
# Outline

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

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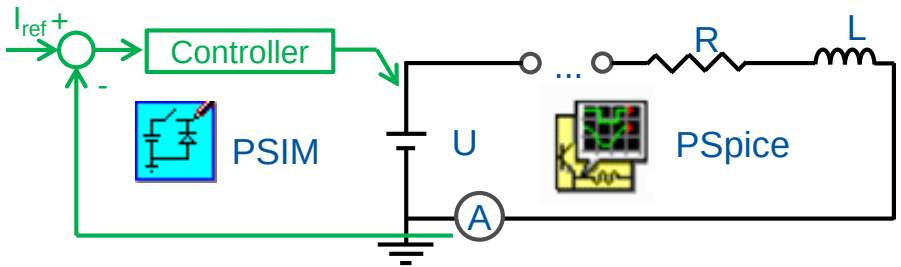
# Simulation of Accelerator Magnets – *Nominal Operation*



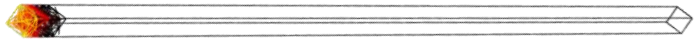

~metres - kilometres
~milliseconds - minutes

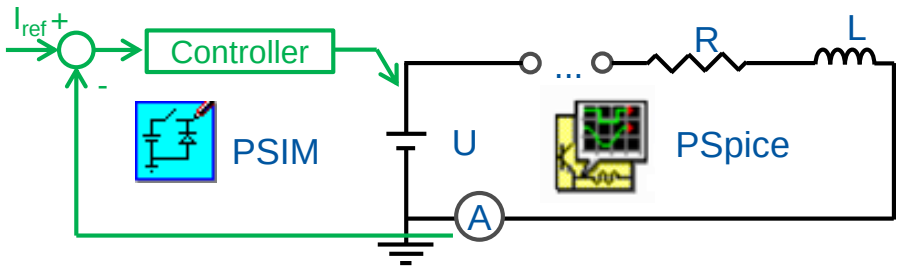
# Simulation of Accelerator Magnets – *Quench*

COMSOL

**Quench** → **1D Quench Propagation**

~micrometres
~microseconds






~metres - kilometres
~milliseconds - minutes

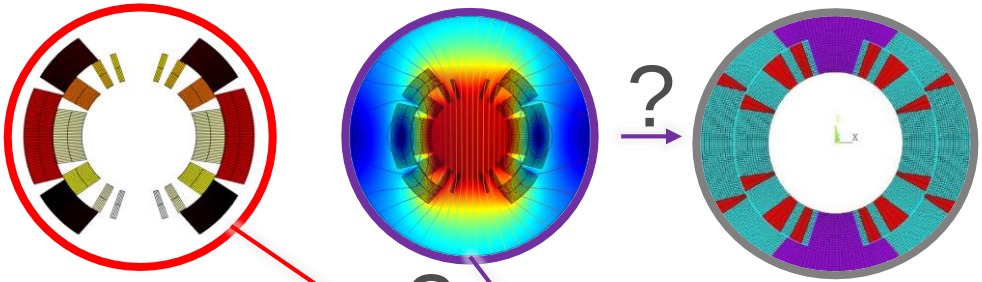
# Simulation of Accelerator Magnets – *Protection*

COMSOL COMSOL COMSOL ANSYS

Quench → 1D Quench Propagation → 2D Quench Propagation → 2D Magnetic Model → 2D Mechanical Model

~micrometres
~microseconds

~millimetres-centimetres
~milliseconds




**Multi-domain**
**Multi-physics**
**Multi-rate**
**Multi-scale**

~metres - kilometres
~milliseconds - minutes

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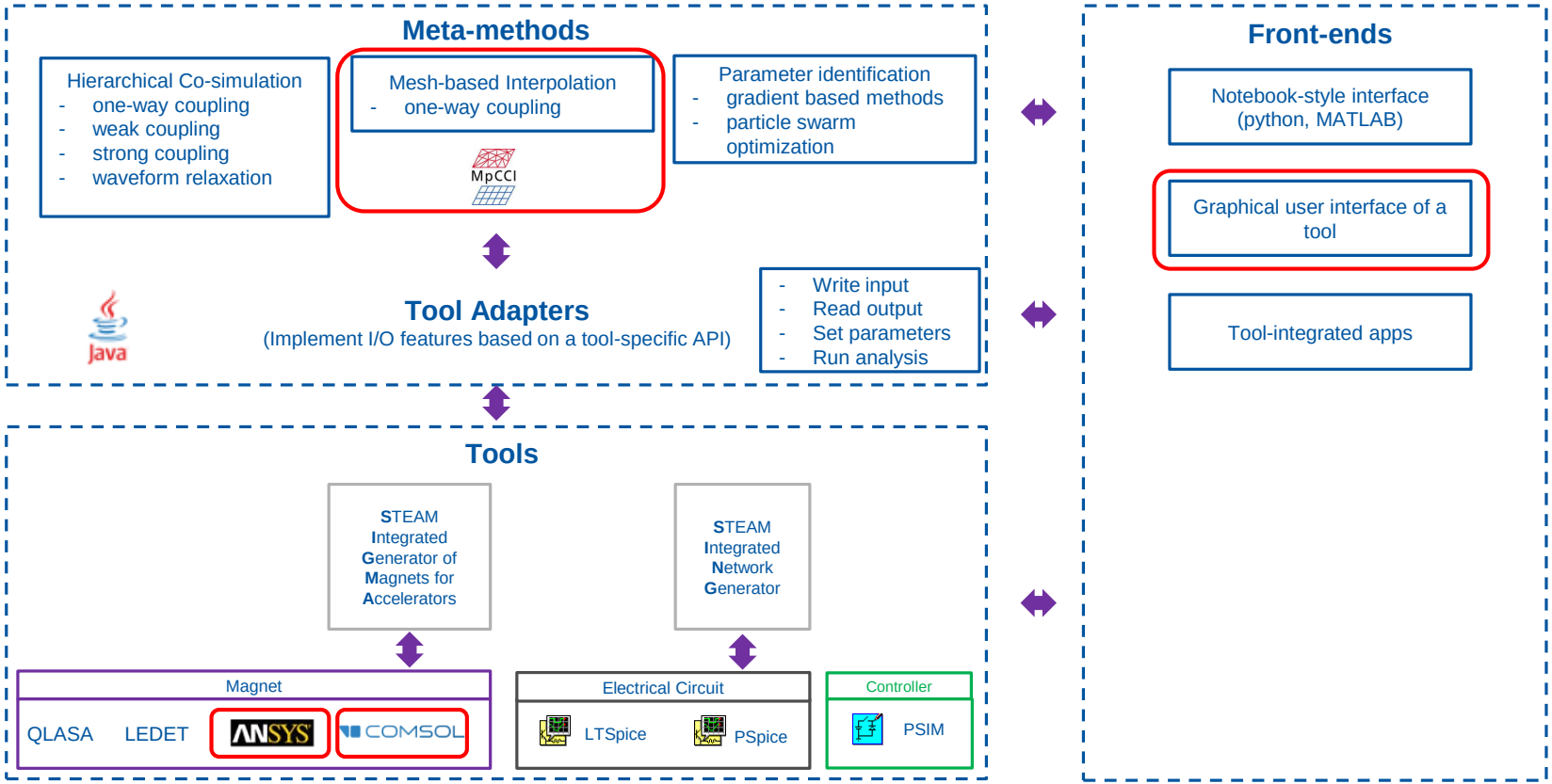
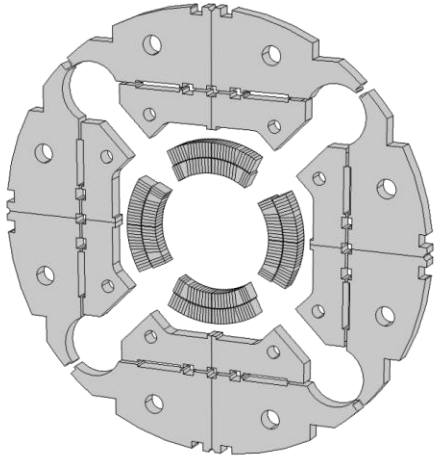
# Co-Simulation Framework for Accelerator Community



# Coupled Field Formulation in COMSOL



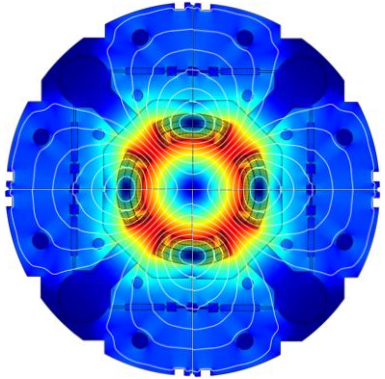
Curl-Curl Equation

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

Heat Balance Equation

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

Total field



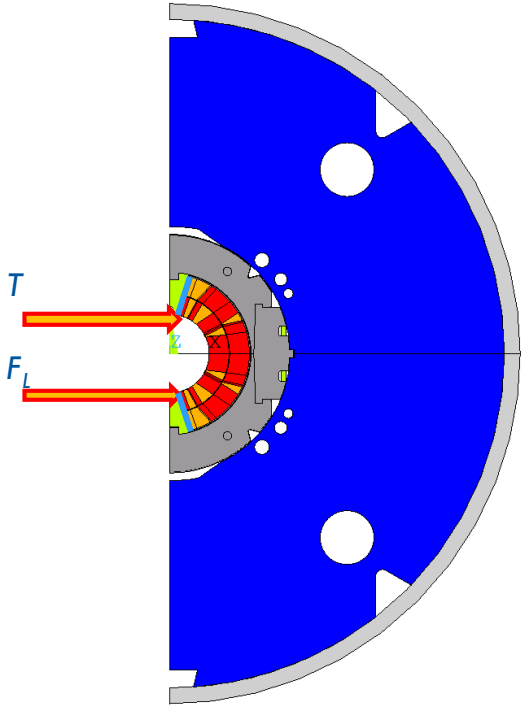
$T$

$F_L$

[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.

# Mechanical Model in ANSYS APDL

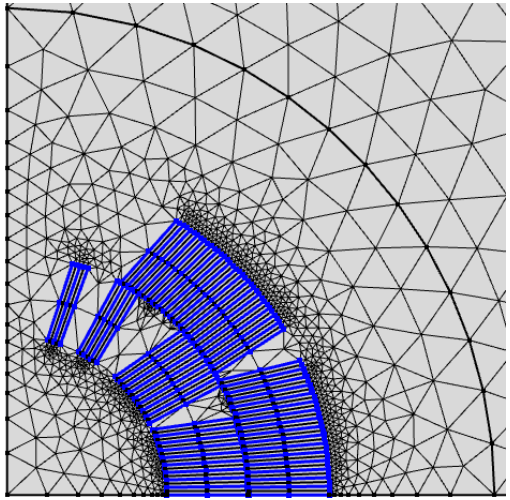
- Reuse a validated mechanical model written in ANSYS APDL.
- Predict the internal stress states during a quench protected with CLIQ for $Nb_3Sn$ magnet.
- Transfer temperature and Lorentz-force from 2-D COMSOL field model.
- Use one of the standard industry tools for generic mesh-based data interpolation.
- MpCCI by Fraunhofer SCAI supports
  - mesh-based interpolation
  - uni-directional coupling
  - bi-directional coupling.



# 1. Mesh-Based Interpolation Between Two Models

Magneto-Thermal Model

COMSOL



Coupling Environment

MpCCI

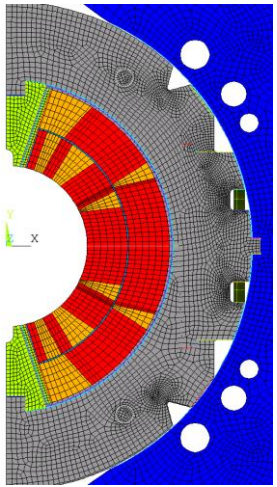
$T$ → $\hat{T}$

$\vec{F}_L$ → $\widehat{\vec{F}_L}$

Mesh-based interpolation

Mechanical Model

ANSYS



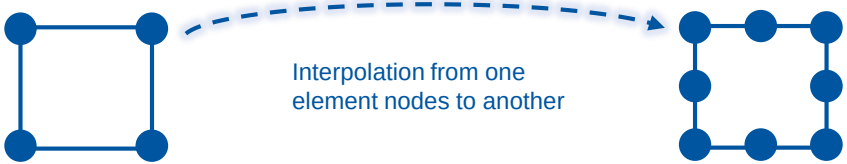
# 2. Transfer of Quantities - Mesh Definition

COMSOL MpCCI ANSYS

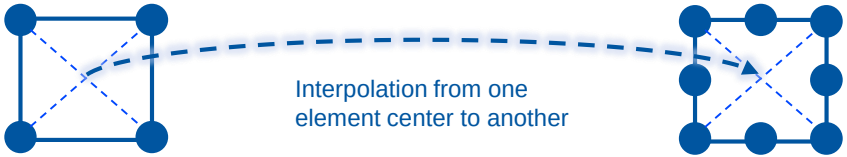
1. Temperature – element nodes

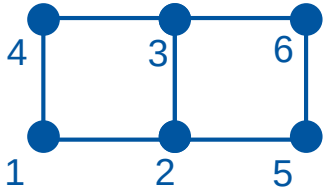
Element Type : QUAD

Element Type: PLANE183




2. Lorentz force – element barycenters




1. Nodal positions

| # | x | y | z |
|---|---|---|---|
| 1 | $x_1$ | $y_1$ | $z_1$ |
| 2 | $x_2$ | $y_2$ | $z_2$ |
| … | … | … | … |

2. Element connectivity (with orientation)

| # | id1 | id2 | id3 | id4 | … | id8 |
|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 3 | 4 | 0 | 0 |
| 2 | 2 | 5 | 6 | 3 | 0 | 0 |

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# 3. 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 based on MpCCI API.

COMSOL

```
comsolModel.runTransientStudy();

adapter.init();

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

adapter.exit();
```

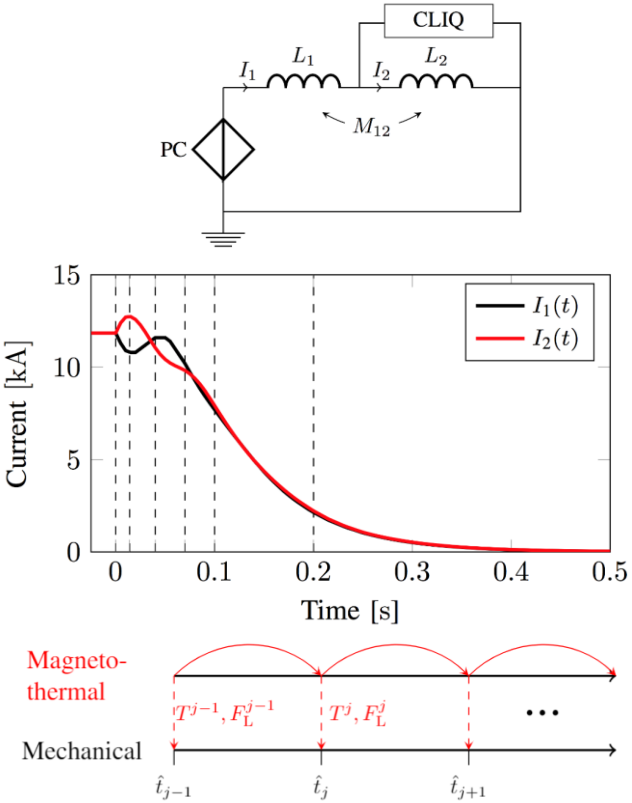
ANSYS

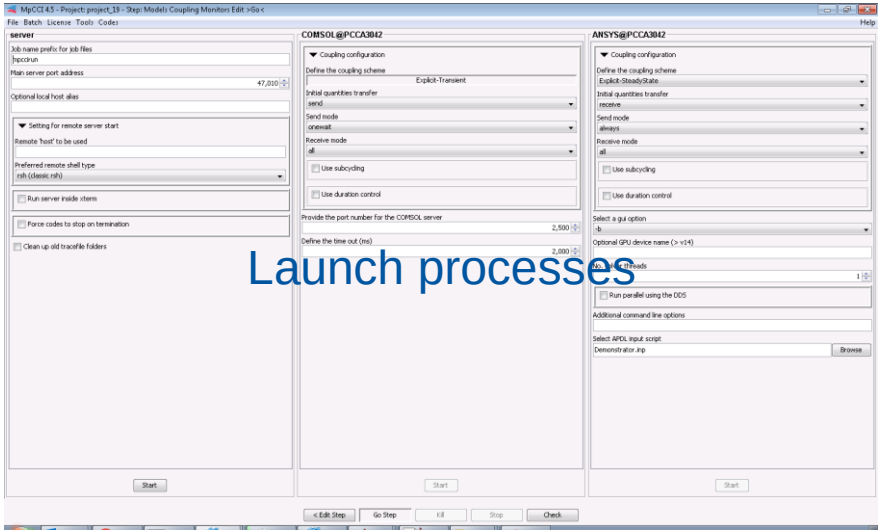
```
~mpcci,settag,-1,0
~mpcci,init,2D

*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 termination.

# 4. Automated Data Transfer



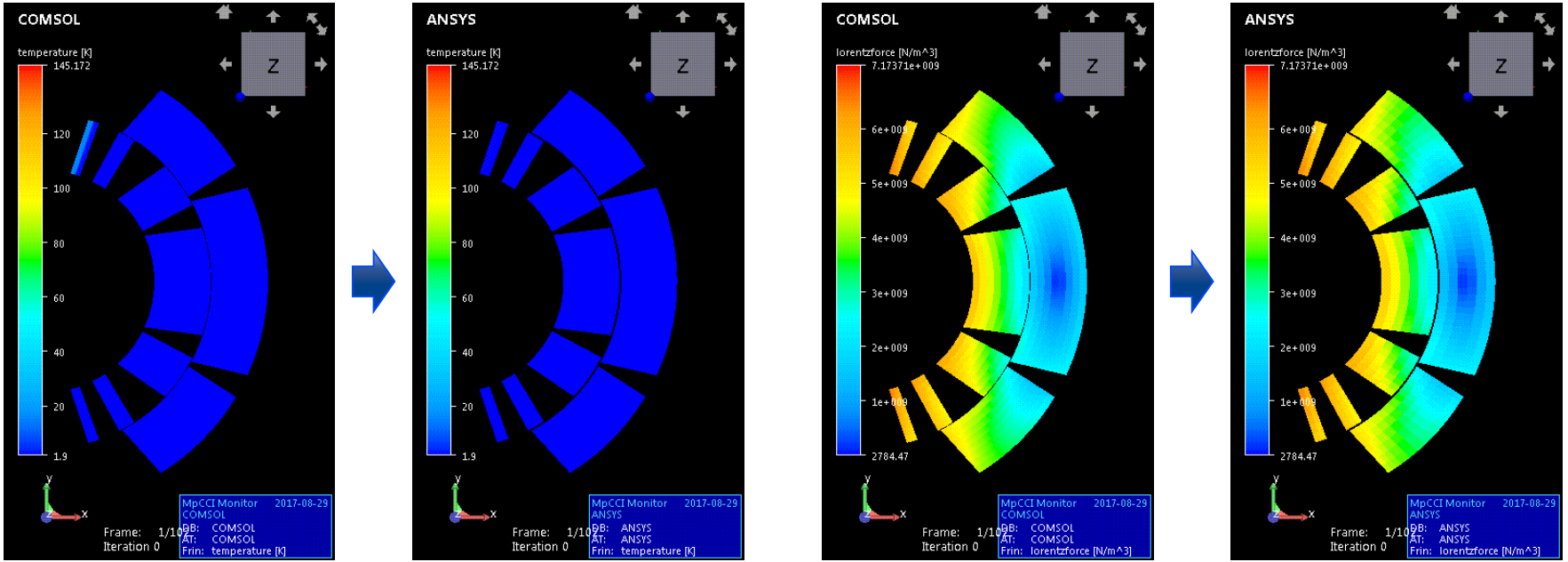




Launch processes

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.

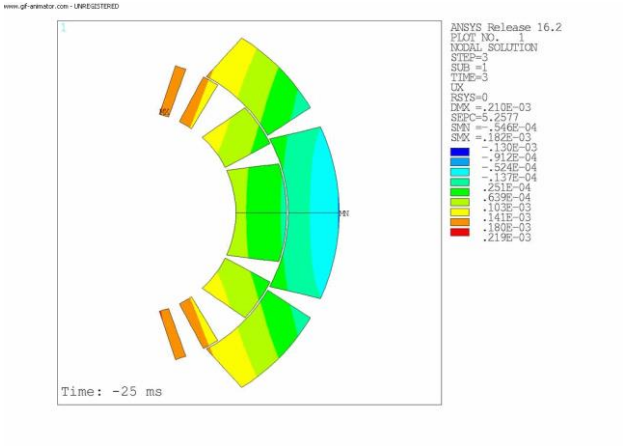
# 5. Data Transfer at Sample Times



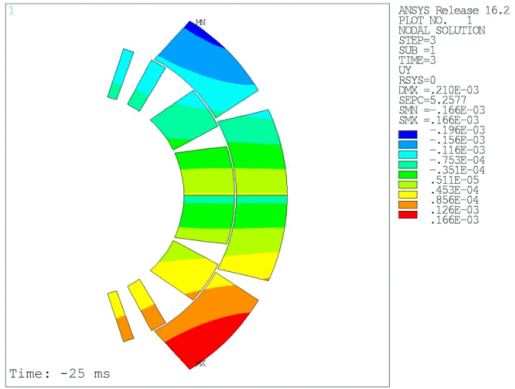

Data transfer preview in MpCCI GUI

# 5. ANSYS Results

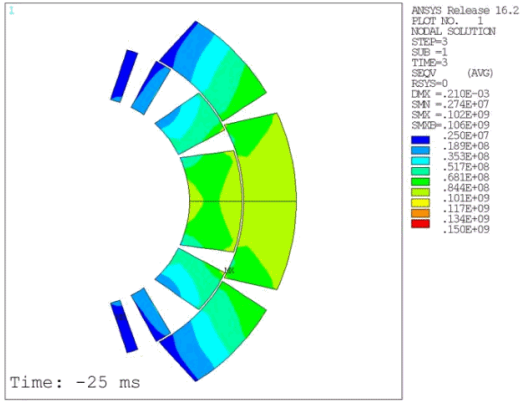
x-displacement




y-displacement




von Mises stress




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

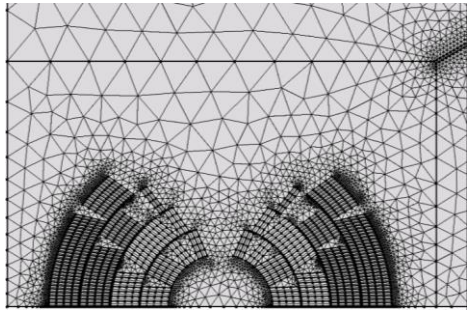
# Application to Future Circular Collider Main Dipole Designs

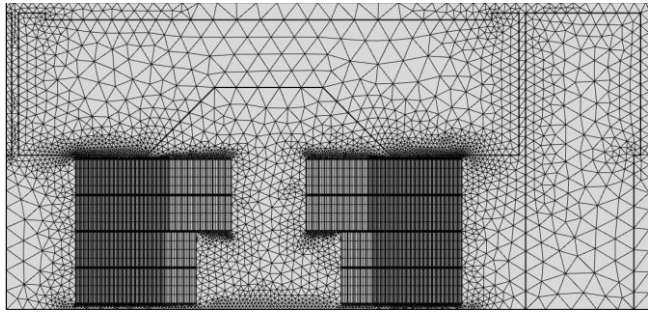
Cos-Θ

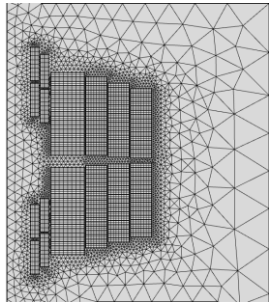
Block Coil

Common Coil*

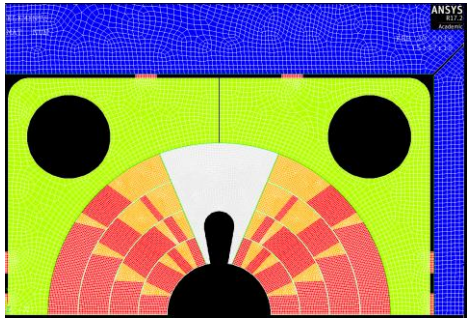
COMSOL

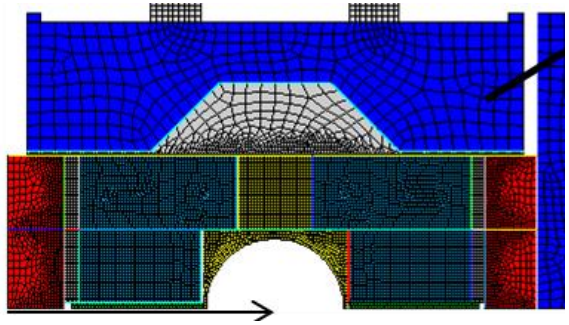


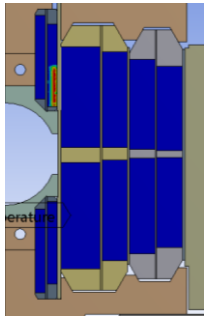




ANSYS







*Semi-automatic workflow with Workbench

# Conclusion

1. One-way coupling of magneto-thermal and mechanical models was developed and applied to the case of a standalone 11-T magnet protected by CLIQ system
2. MpCCI coupling environment (http://mpcci.de) was employed to perform mesh-based interpolation for exchange of temperature (over nodes) and Lorentz force (over elements)
3. Superimposed effects of electromagnetic and thermal stresses play a relevant role during magnet protection and should be carefully studied
4. Developed algorithm is generic and can be applied to analysis of more accurate mechanical models of 11-T magnet as well as other magnets
5. MpCCI is a generic coupling environment supporting over 10 FEM tools allowing for time transient studies and coupling of multiple models

# Where to go from here?

If MpCCI is an option, then

1. develop code adapters for FLUKA and Autodyn
    1. Read mesh definition
    2. Read distributed quantities
    3. Write distributed quantities
    4. Run model
    5. Set relevant parameters
2. integrate these code adapters with MpCCI
    1. Extend GUI and software itself to support additional code adapters
3. Test the coupling scheme

- FLUKA-ANSYS/LS-DYNA COUPLING IS NOT IMPLEMENTED IN WORKBENCH.
- APDL COMMANDS ARE REQUIRED TO IMPORT FLUKA DATA.

APDL supported by MpCCI!

Courtesy A. Perillo-Marcone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