Simulation of Electro-Thermal Transients in Superconducting Accelerator Magnets with COMSOL Multiphysics

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Introduction:

The distributed model of a superconducting accelerator magnet has to take into account several coupled physical domains, governed by highly nonlinear equations that are distributed on:

- spatial scales ranging from several meters to sub-millimetres and
- time constants going from microseconds to hundreds of seconds.

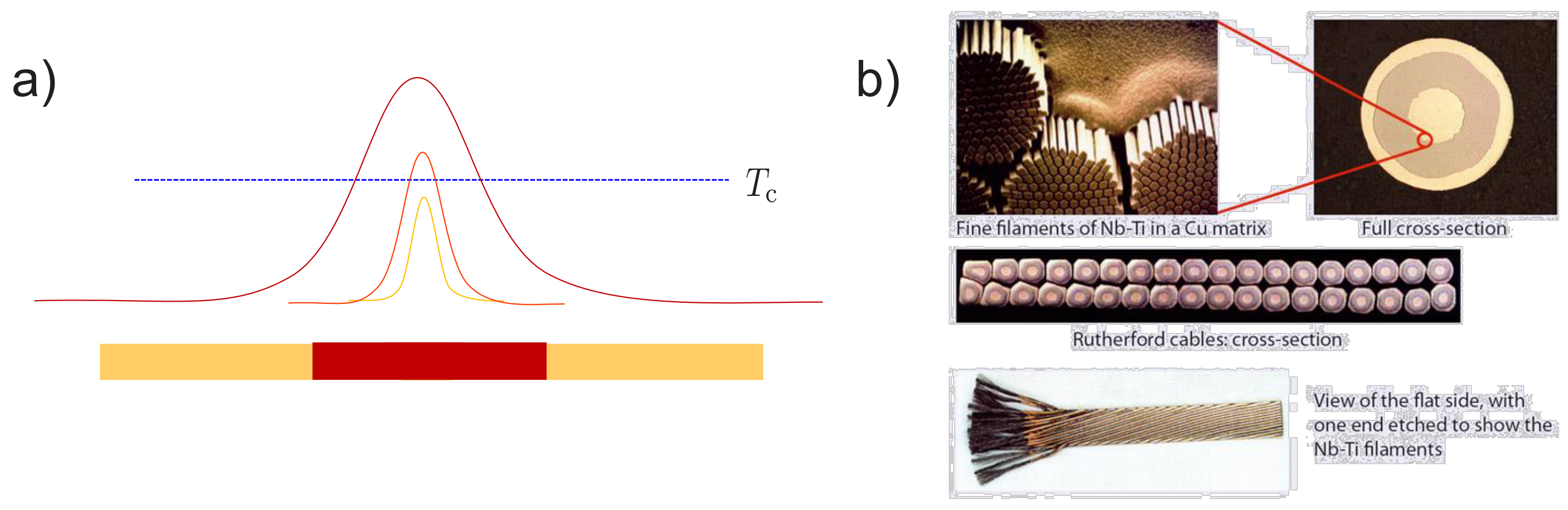


Figure 1. Quench propagation (a) in a superconducting wire (b)

A quench is a sudden transition from the superconducting to the normal conducting state, in which the energy stored in the magnetic field is released as Ohmic losses.

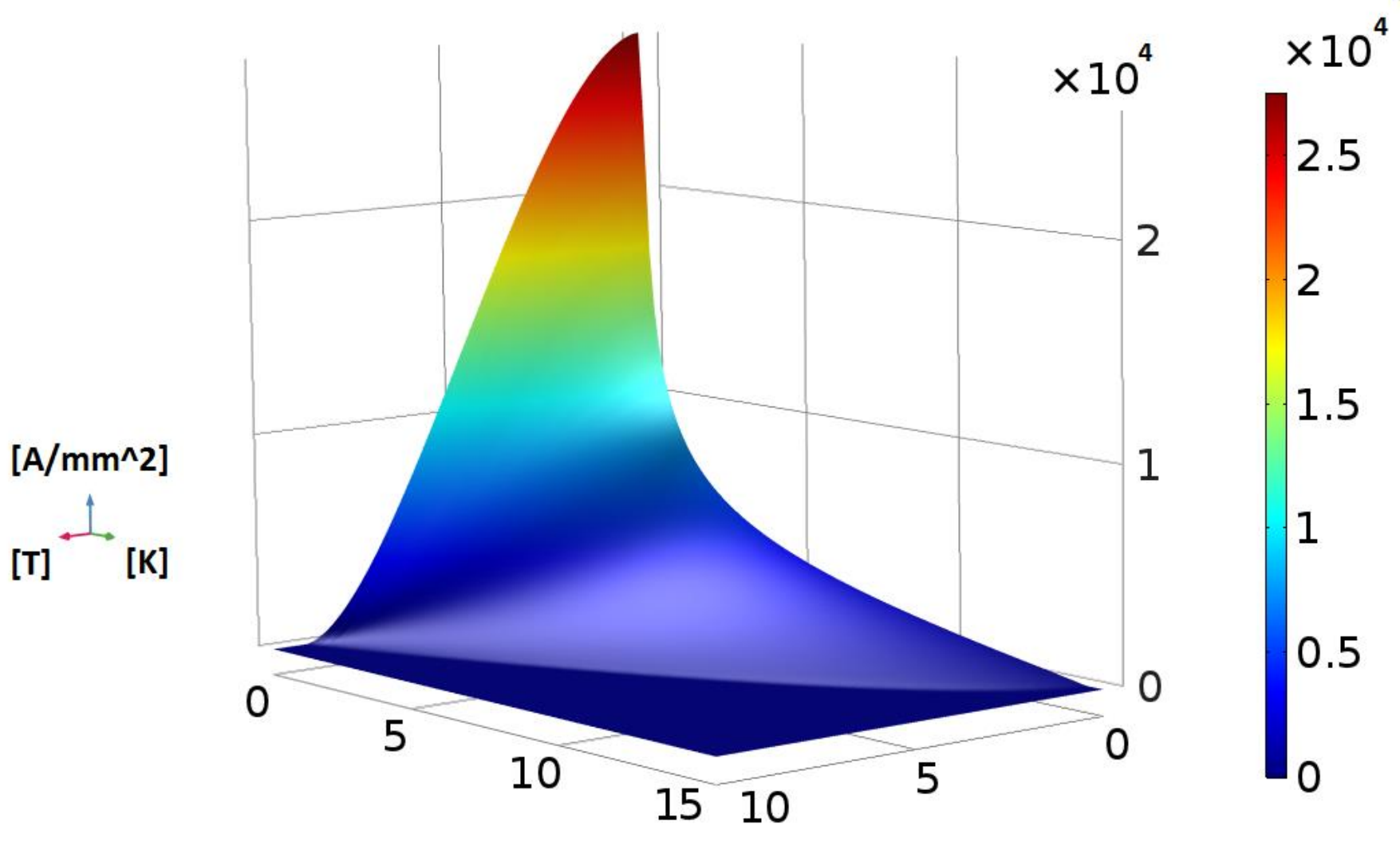


Figure 2. Critical surface for superconductivity

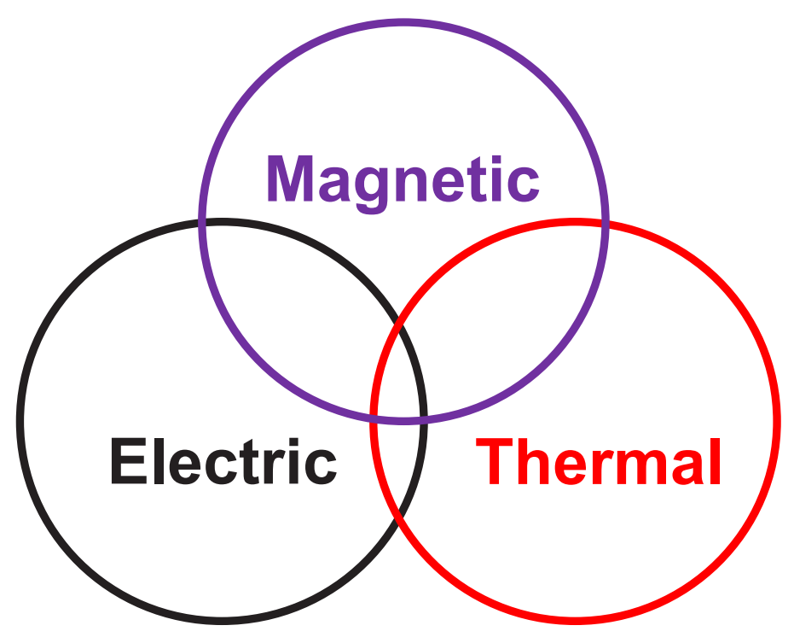


Figure 3. Coupled physical domains

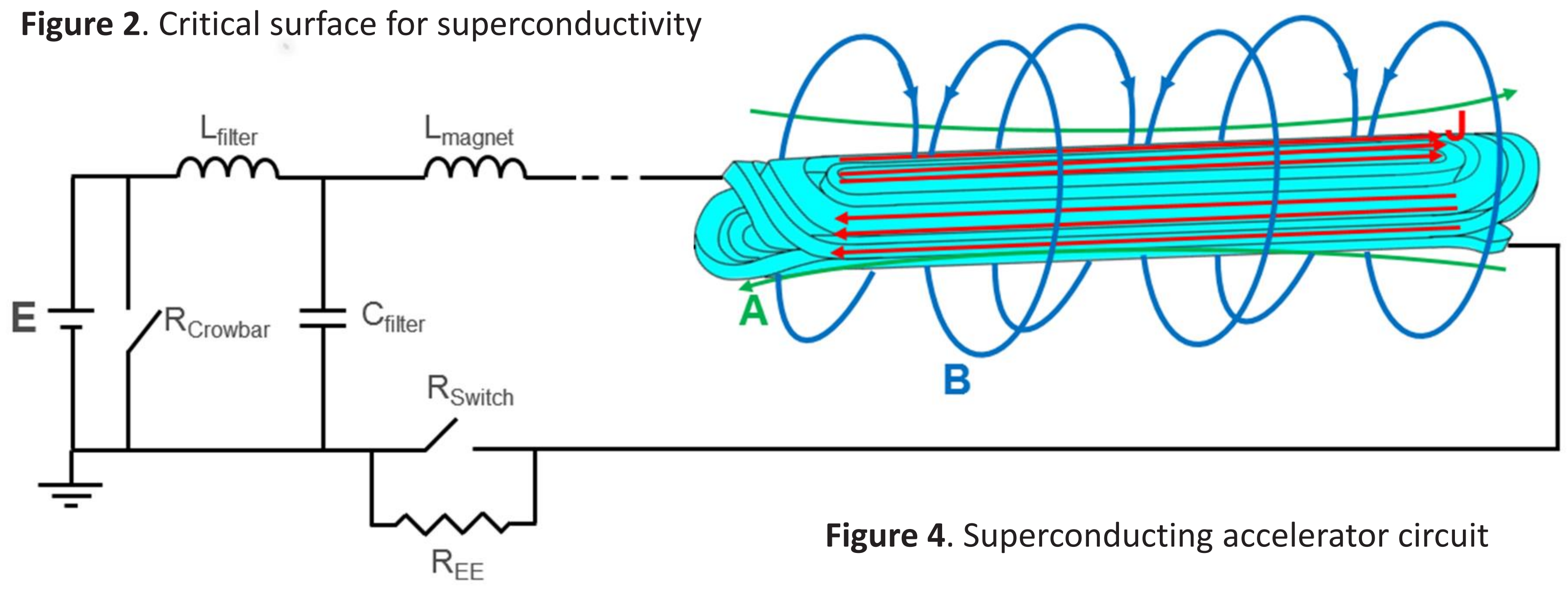


Figure 4. Superconducting accelerator circuit

Computational Methods:

The construction of the magnet cross-section is implemented discretizing the coil at the level of single turns. Each turn is treated as a basic brick, over which the material properties and physics laws are homogenized.

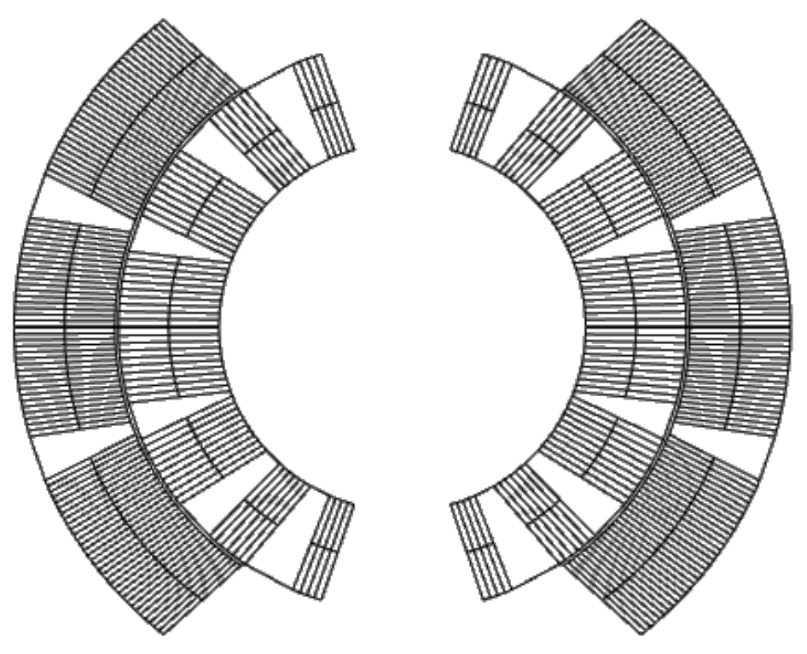
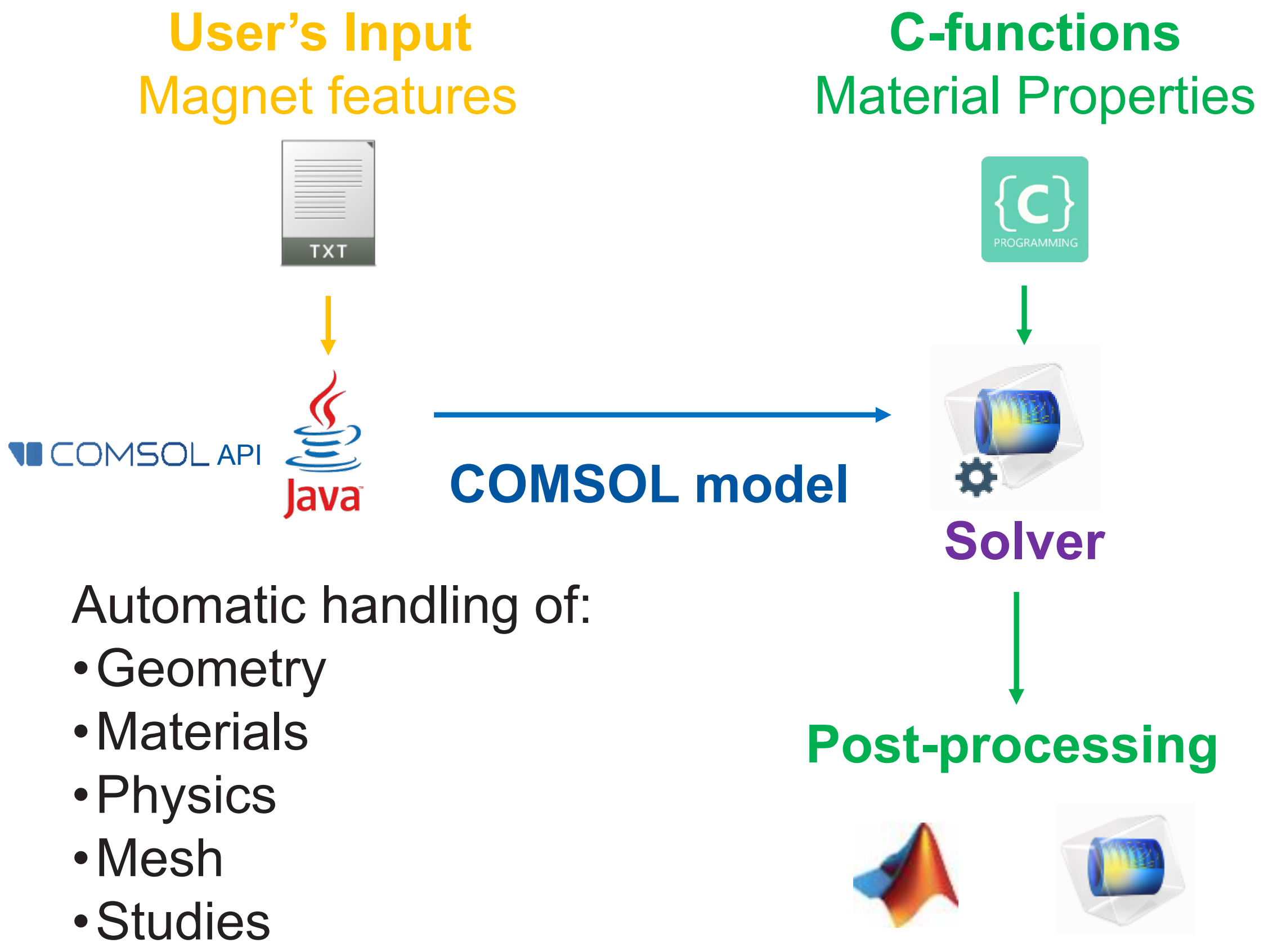


Figure 5. LHC main dipole

Since the model usually involves hundreds of turns, the model is automatically built through an external Java framework that uses extensively the COMSOL API.



User's Input
Magnet features

C-functions
Material Properties

COMSOL model

Solver

Post-processing

Automatic handling of:
- Geometry
- Materials
- Physics
- Mesh
- Studies
- Results

Figure 6. Automated COMSOL workflow

Magnetic Fields

A-formulation is used to solve the magnetic field

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}$$
$$\boldsymbol{B} = \nabla \times \boldsymbol{A}$$

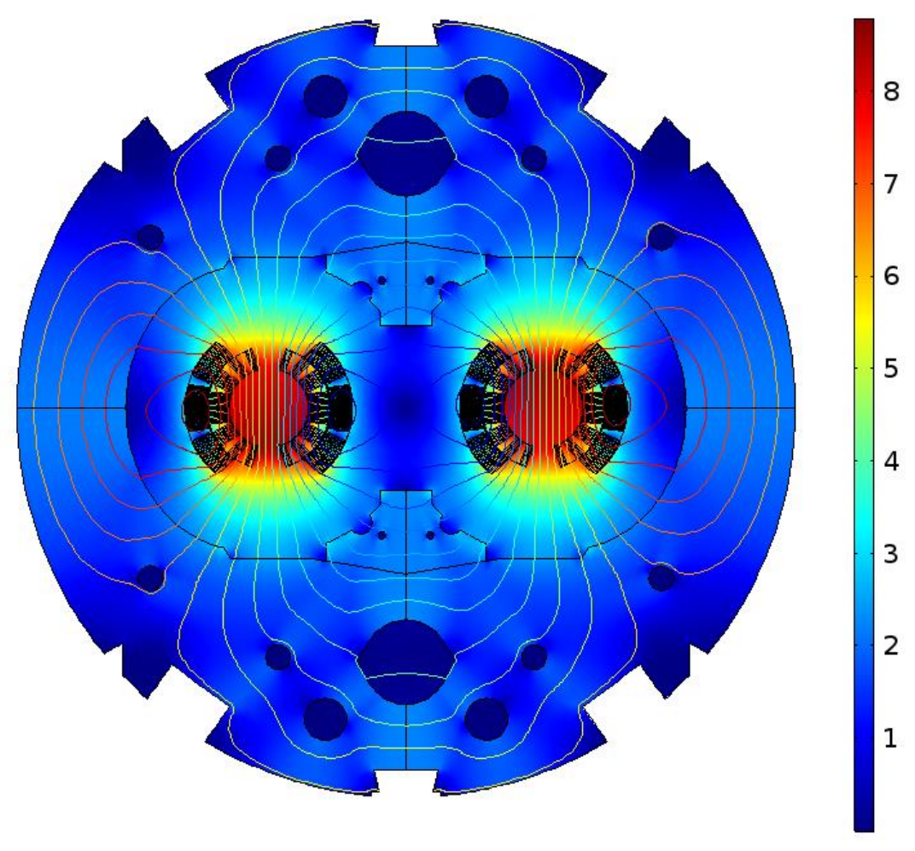


Figure 7. Magnetic field in the LHC main dipole

The electrodynamic formulation of eddy-currents relates directly the magnetic flux change with the induced equivalent magnetization

$$\mu_0 \boldsymbol{M} = -\tau\, \partial_t \boldsymbol{B}$$

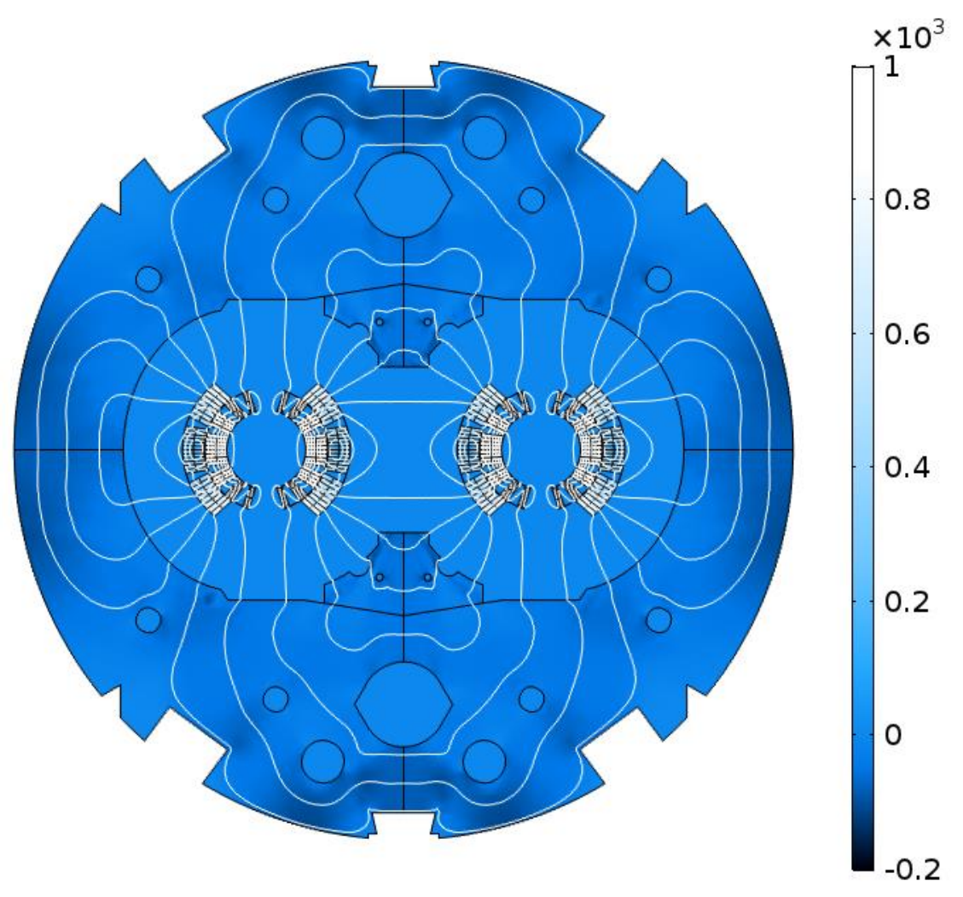


Figure 8. Effect of coupling currents on magnetic field map

Heat Transfer in Solids

Model implements heat balance equation with nonlinear material properties

$$\rho C_p \partial_t T + \nabla \cdot \boldsymbol{q} = \boldsymbol{Q}$$
$$\boldsymbol{q} = -k \nabla T$$

In case of a quench, Ohmic losses contribute to heat source (**Q**).

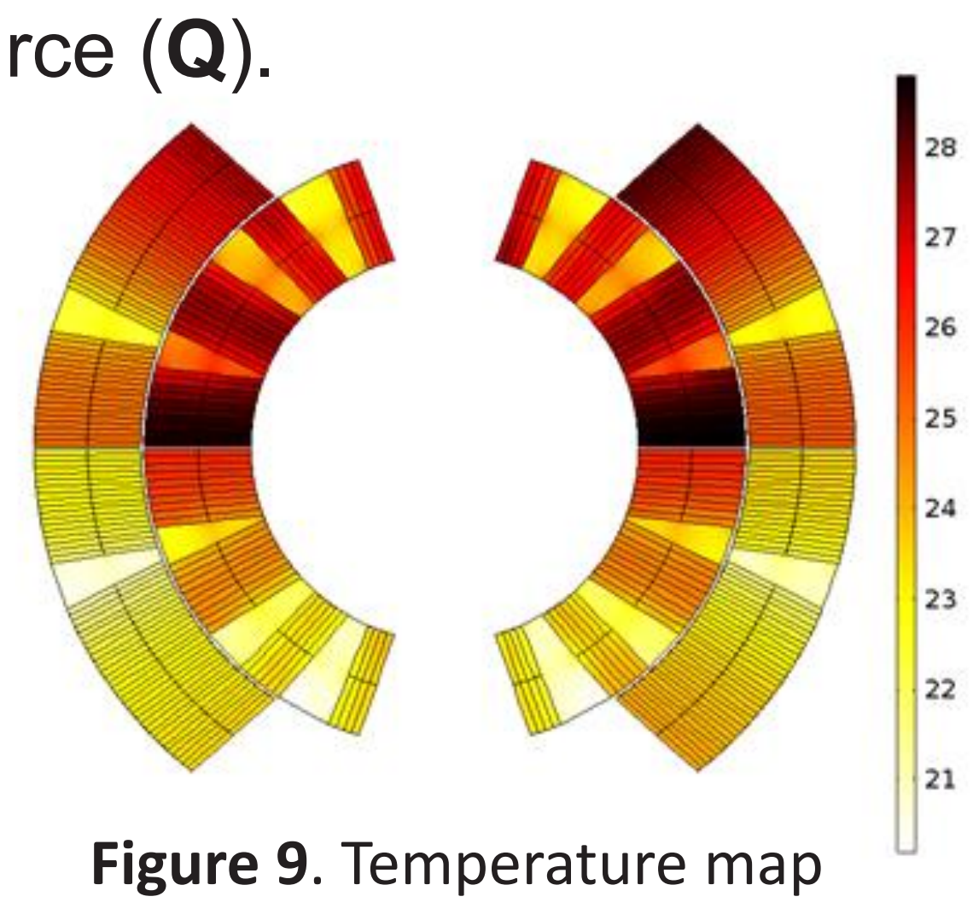


Figure 9. Temperature map

Magnetic power density represents the specific losses deposited by coupling currents

$$\partial_t W = \boldsymbol{M}\, \partial_t \boldsymbol{B}$$

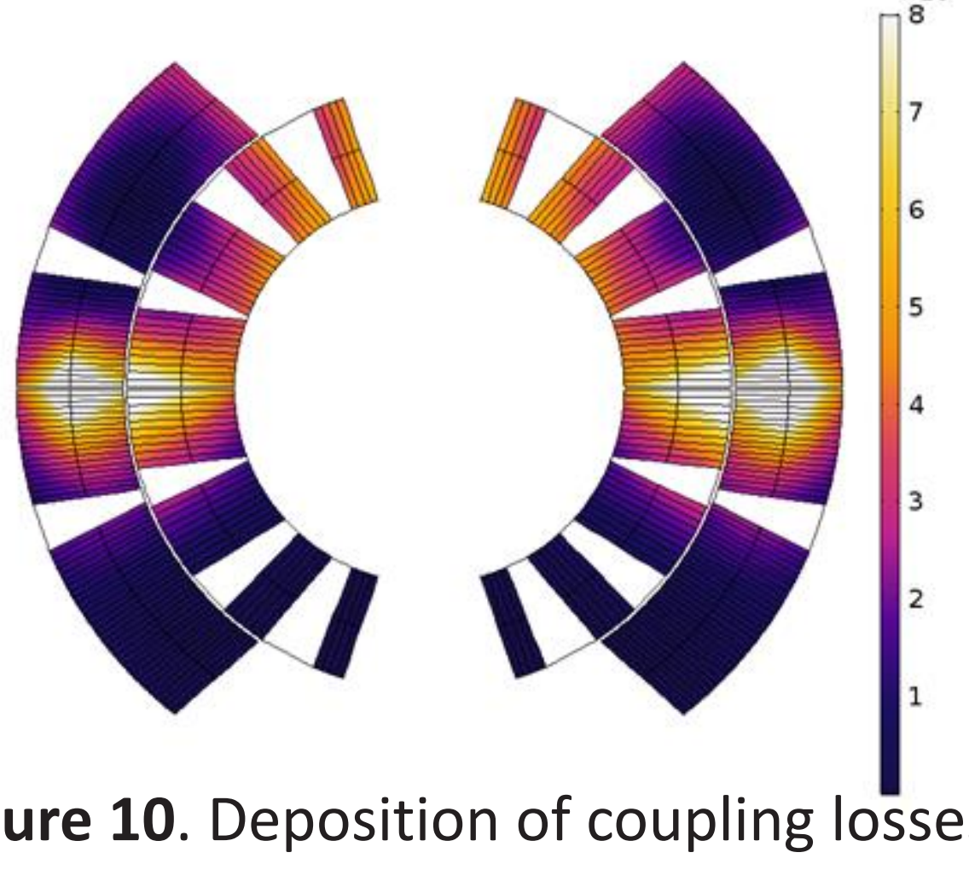


Figure 10. Deposition of coupling losses

Conclusions:

The developed workflow allows to automatically generate COMSOL 2D models, which account for:

- Magneto-thermal multi-physics
- Coupling currents' magneto-thermal effects
- Iron saturation
- Nonlinear materials at cryogenic temperature
- Turns' insulation, through the thin-layer feature

It is possible to resolve the electro-thermal transient in the magnet's cross-section, with the emphasis on

- Turn-to-turn, layer-to-layer heat propagation
- Peak temperature (hot-spot)
- Lorentz forces acting on the coil
- Voltage distribution in the coil

Future work:

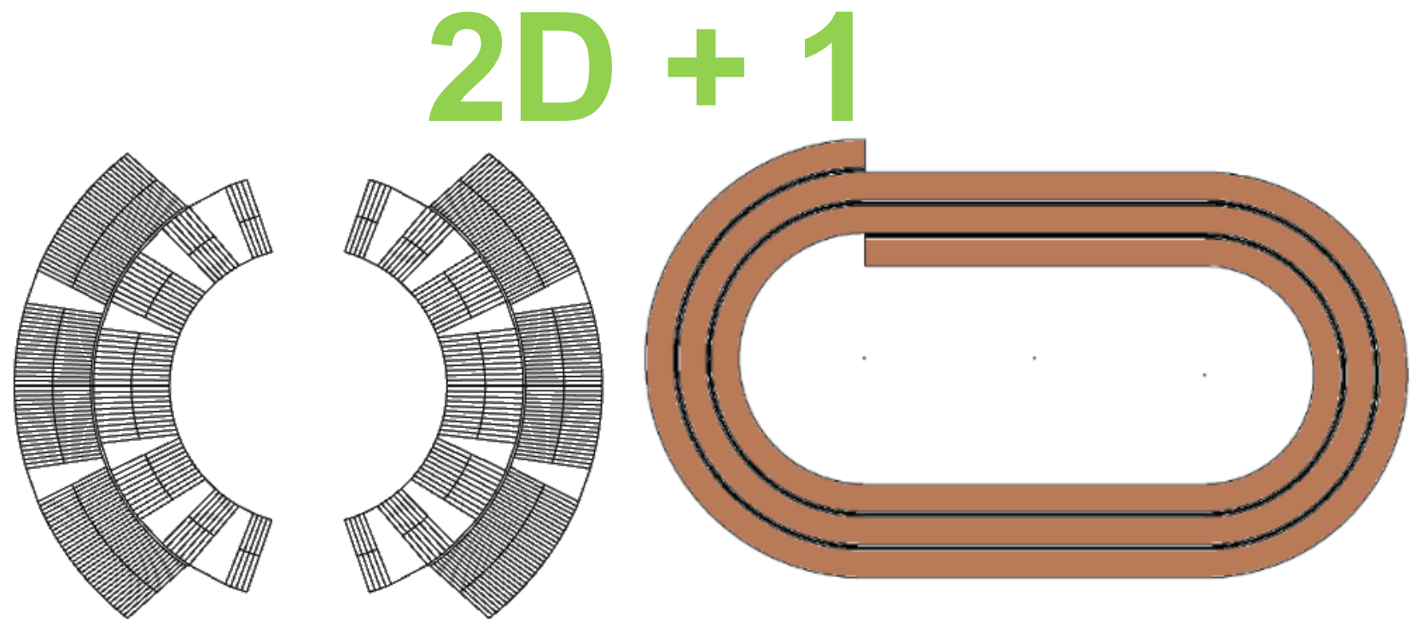


Figure 11. Geometry of 2D and 1D models

Quench initiation and propagation is critical to design appropriate quench detection and protection systems.
We study longitudinal (along a turn) and transverse (turn to turn) propagation by means of 1D models with adaptive mesh refinement.
Appropriate coupling between exisitng 2D and 1D models would greatly expand our modelling capabilities.

Eventually, we aim at expanding our consistent FEM formulation and model development workflow to build 3D models of superconducting accelerator magnets.

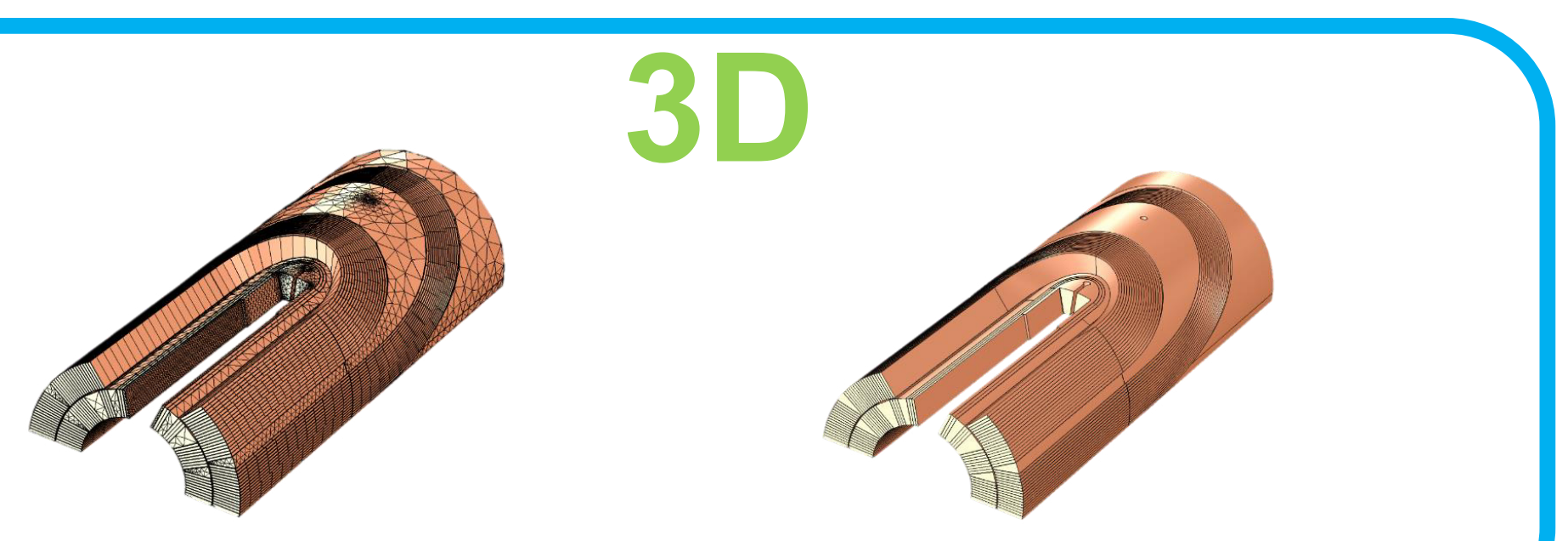


Figure 12. 3D models with structured and unstructured mesh

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