New developments
in the STEAM framework

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On behalf of the STEAM team

11 October 2021

New STEAM developments – what is driving us

Capability to simulate all LHC superconducting magnet circuits

Consistently validate, maintain, version our models

Capability to simulate all HL-LHC superconducting magnet circuits

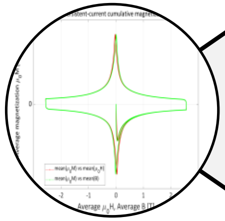
Offer simulation tools to the community

Adapt tools to the needs of HFM (High Field Magnet) studies

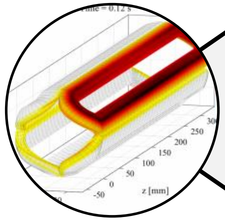
Include all physics relevant for quench protection transients

Include all physics relevant for powering transients

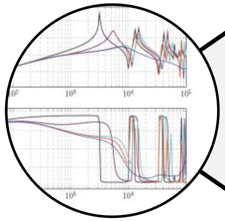
New STEAM developments



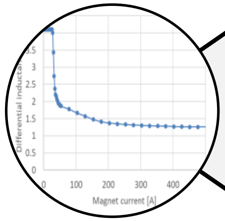
LEDET 2D



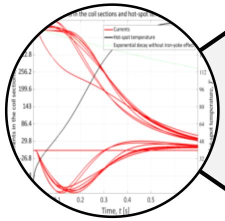
LEDET 3D



PSPICE frequency-domain models

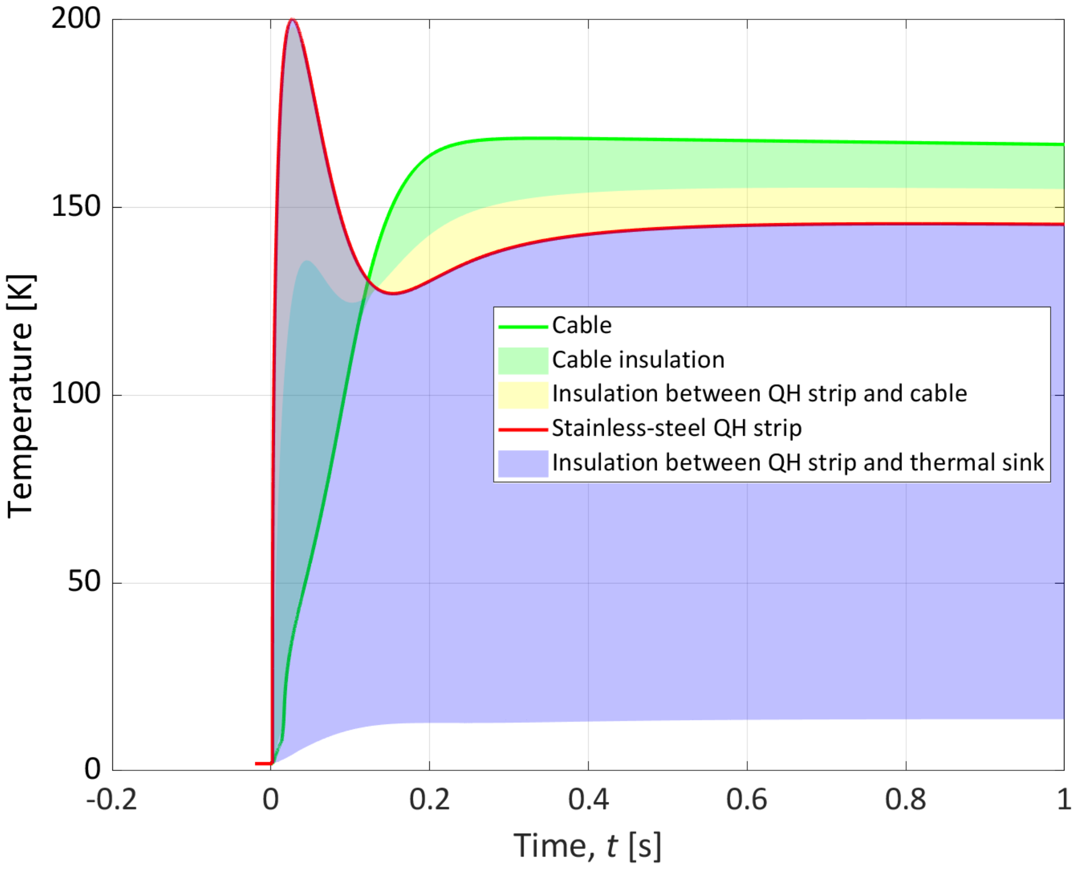


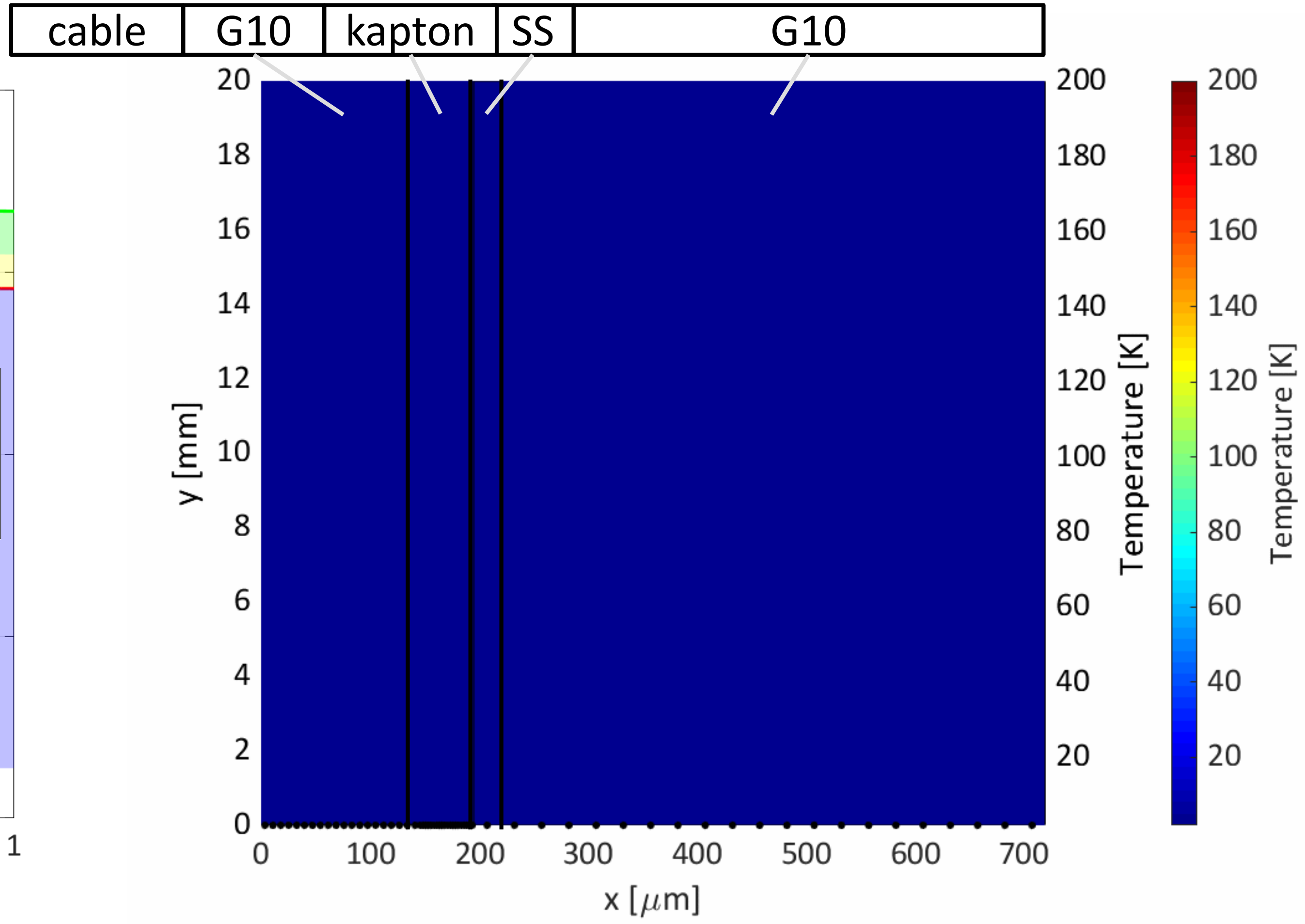
PSPICE component library



Python-based Jupyter/SWAN notebooks

LEDET 2D – Quench heater with dedicated 1D thermal diffusion model

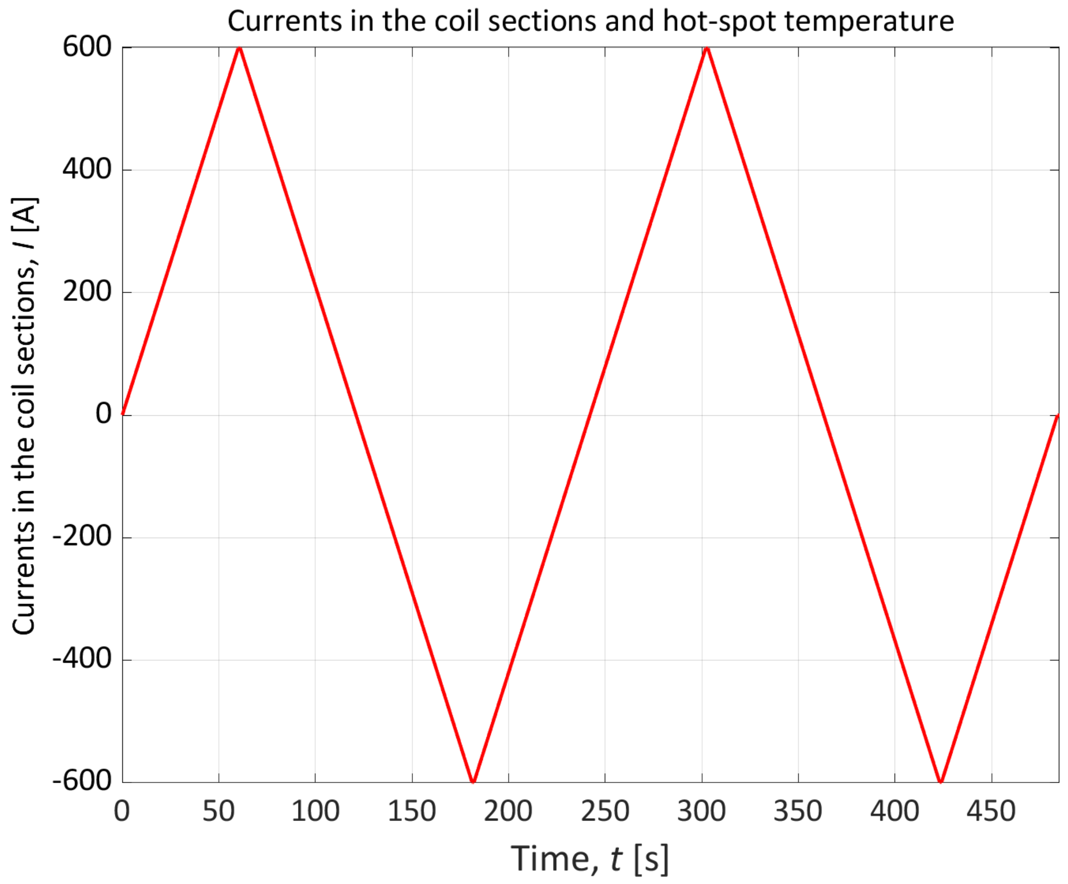


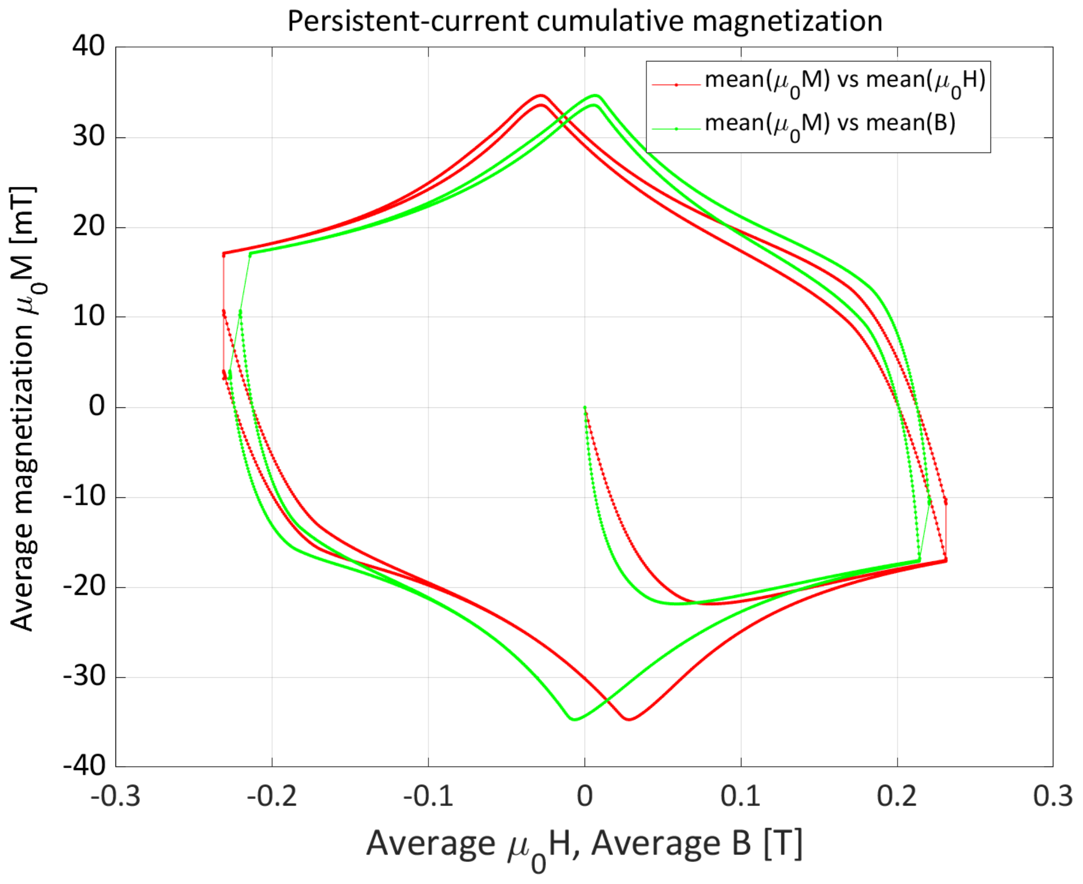


- Multiple layers of insulation between QH and conductor can be defined
- Thermal diffusion solved with a semi-implicit 1D model

E. Ravaioli, "Improved quench heater model in STEAM-LEDET", edms 2320265

LEDET 2D – Persistent currents (aka magnetization, hysteresis) -1



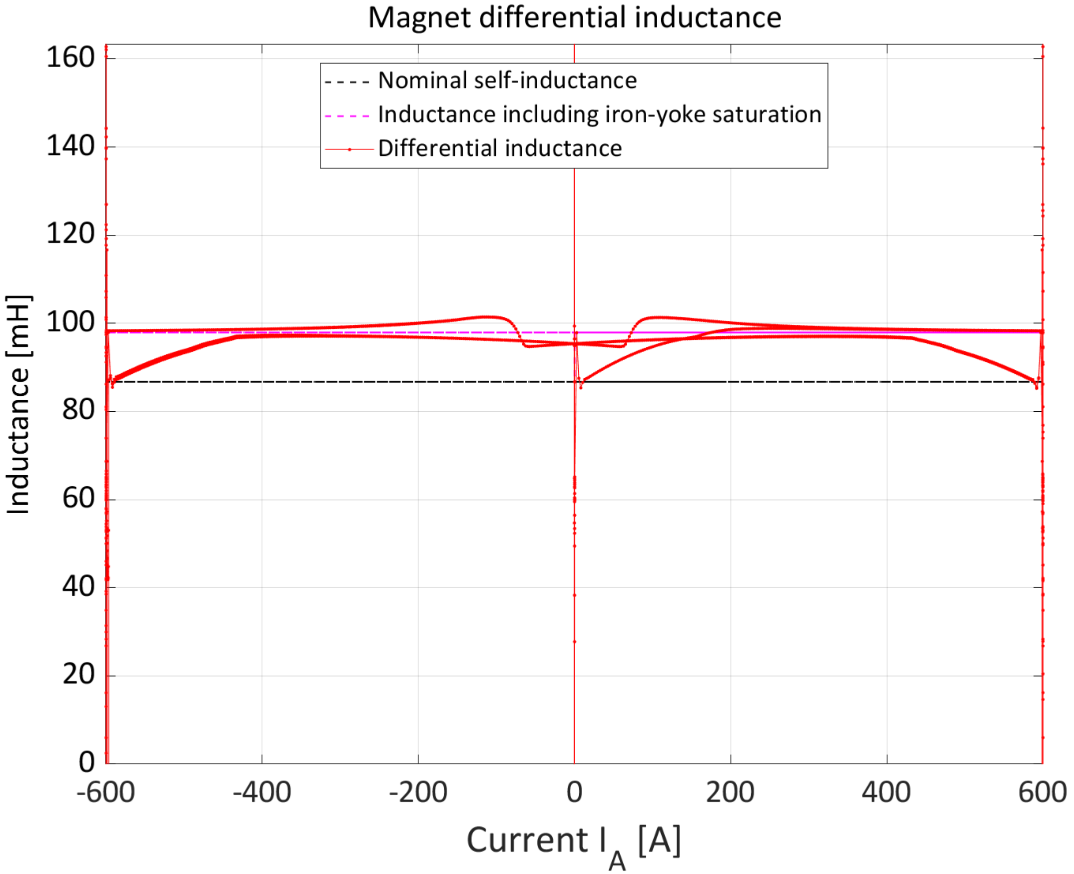


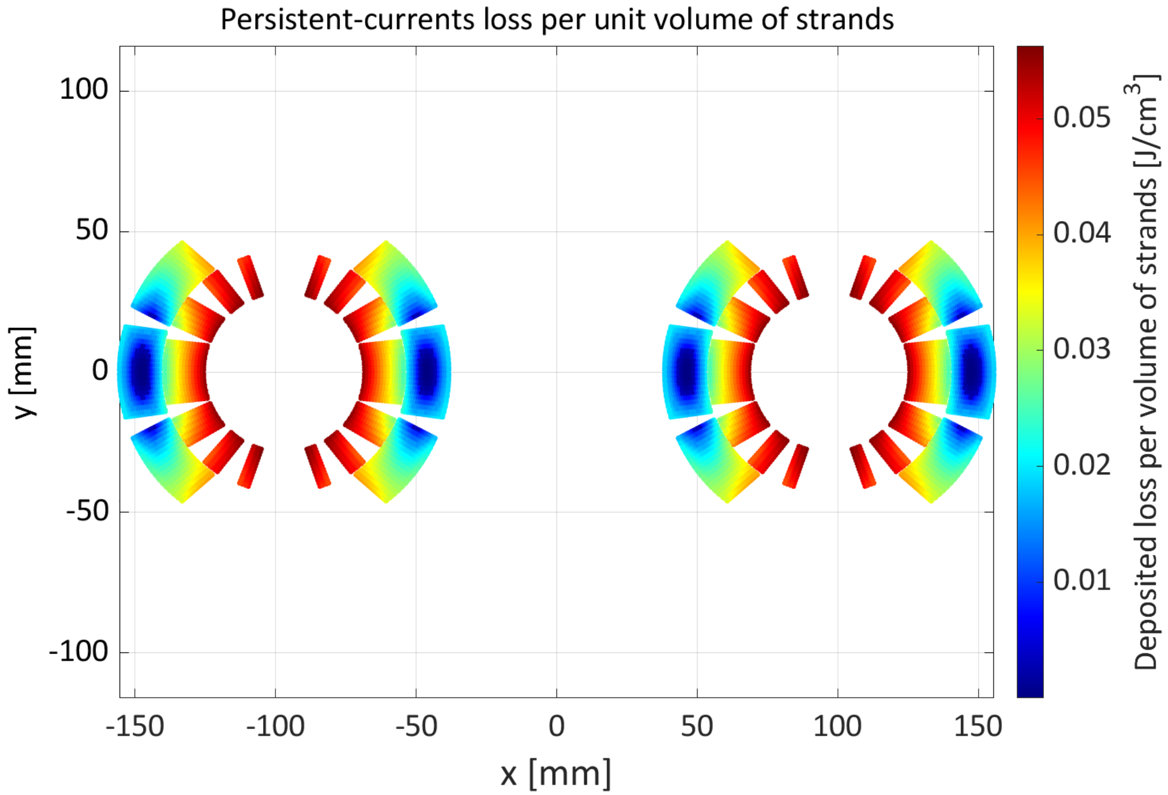
- The persistent currents in the superconducting filaments are calculated semi-analytically for arbitrary powering transients. On the right-hand plot, the average “magnetization” due to persistent currents is shown

E. Ravaioli, "Persistent-currents magnetization in STEAM-LEDET", edms 2418186

A. K. Holk Pedersen, **E. Ravaioli**, "Implementation of persistent-currents feature in STEAM-LEDET models of LHC magnets", edms 2613180

LEDET 2D – Persistent currents (aka magnetization, hysteresis) -2



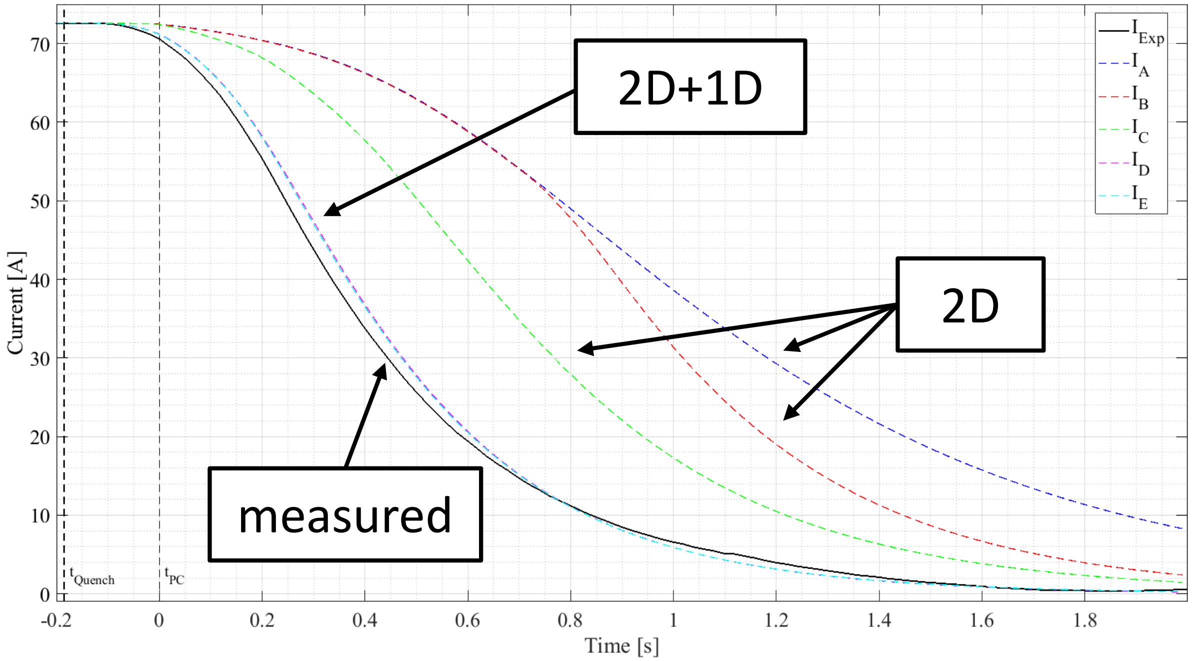


- Effect of persistent currents on the differential inductance included (this effect is typically ~20% at low current)
- Hysteresis loss in each strand included

E. Ravaioli, "Persistent-currents magnetization in STEAM-LEDET", edms 2418186

A. K. Holk Pedersen, **E. Ravaioli**, "Implementation of persistent-currents feature in STEAM-LEDET models of LHC magnets", edms 2613180

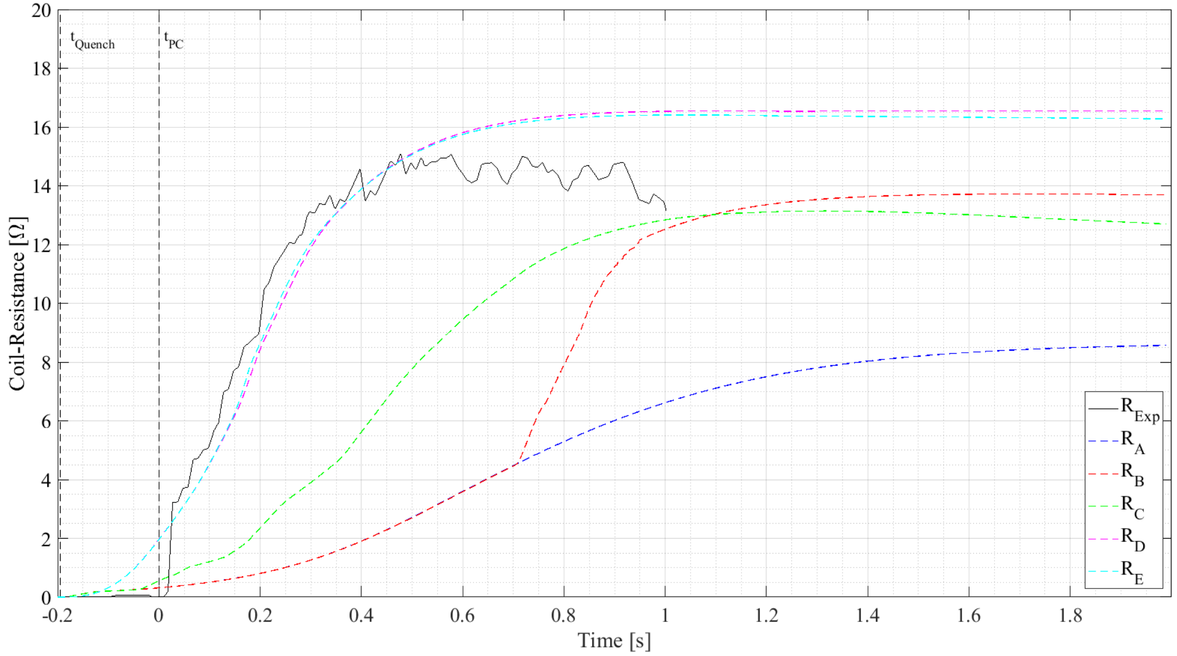
LEDET 2D+1D – 2D model plus analytical quench propagation



2D+1D

2D

measured



Magnet current

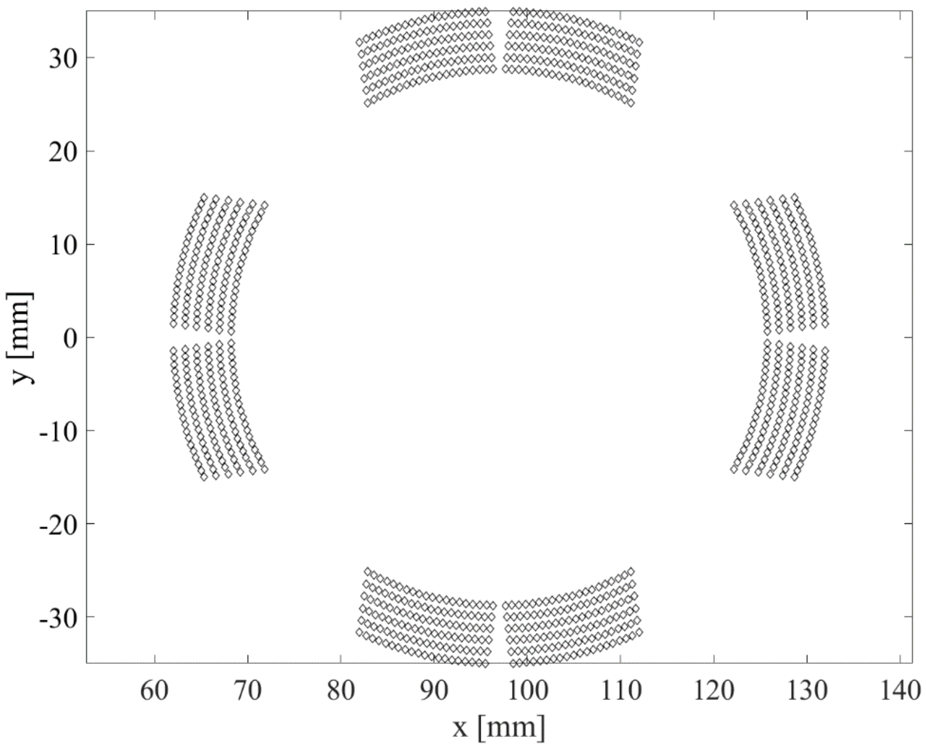
Coil resistance

- The standard 2D model is enhanced by introducing the fraction of longitudinally quenched conductor, which scales the resistance of each turn. Adiabatic quench propagation velocity is re-calculated at each time step.
- Quench propagation between electrically consecutive turns is included

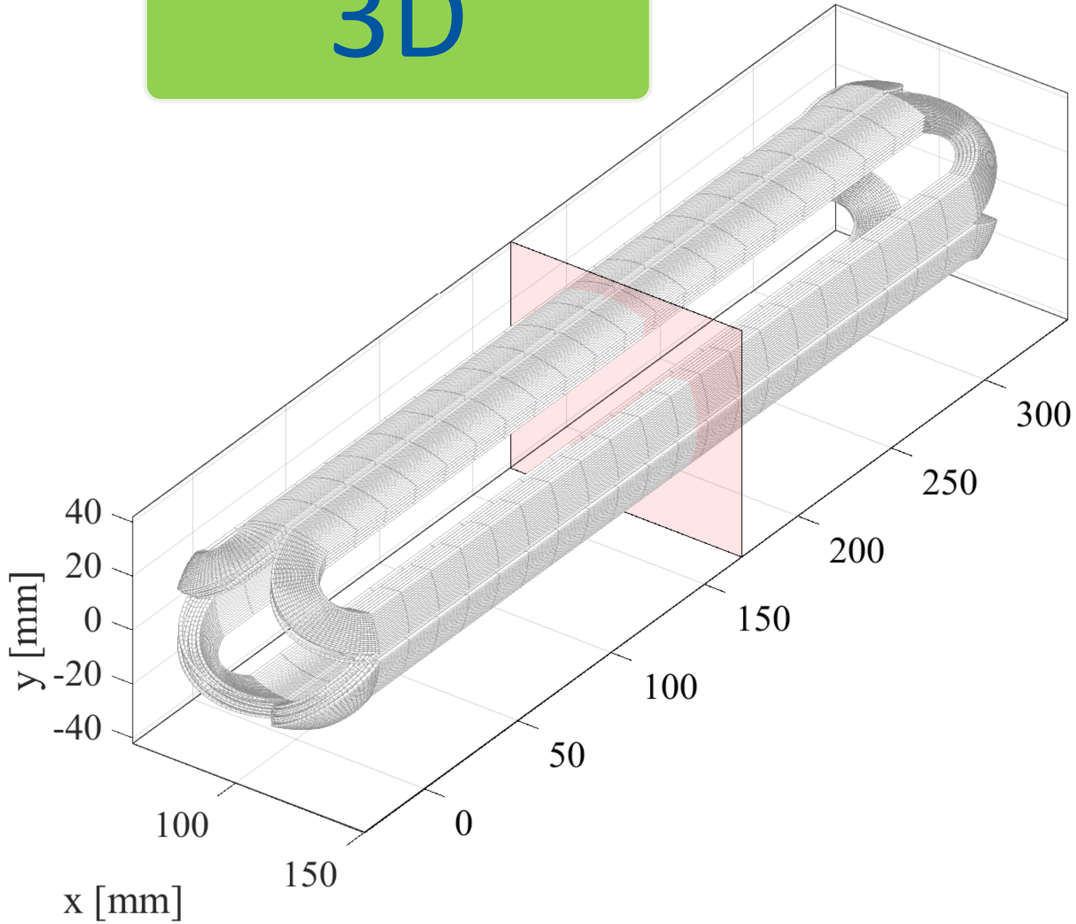
M. Janitschke, **E. Ravaioli**, "STEAM LHC Circuit Library: Generation and validation of the RCBY circuit models", edms 2454471
M. Janitschke et al., "A simplified approach to simulate quench development in a superconducting magnet", IEEE Trans. on Appl. SC, 2021 .

LEDET 3D – Full-scale magnet quench model in 3D -1

2D



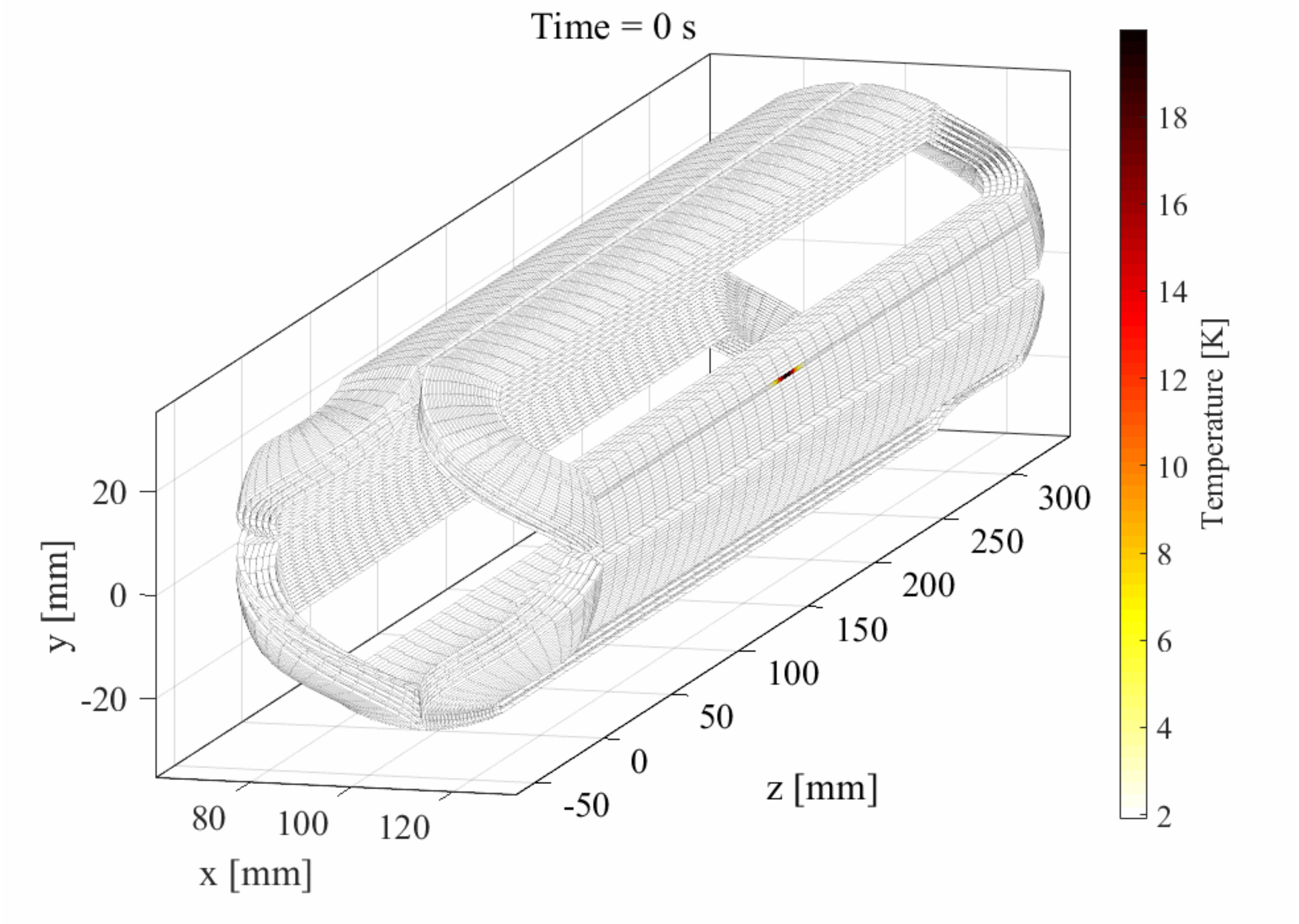
3D



E. Ravaioli, "Simulation of the 3D magnet quench process with the finite-difference method in STEAM-LEDET", edms 2454468

O. Tranum Arnegaard, **E. Ravaioli**, "3D simulations of quench transients in the MQSX magnet using STEAM-LEDET", edms 2613181

LEDET 3D – Full-scale magnet quench model in 3D -2



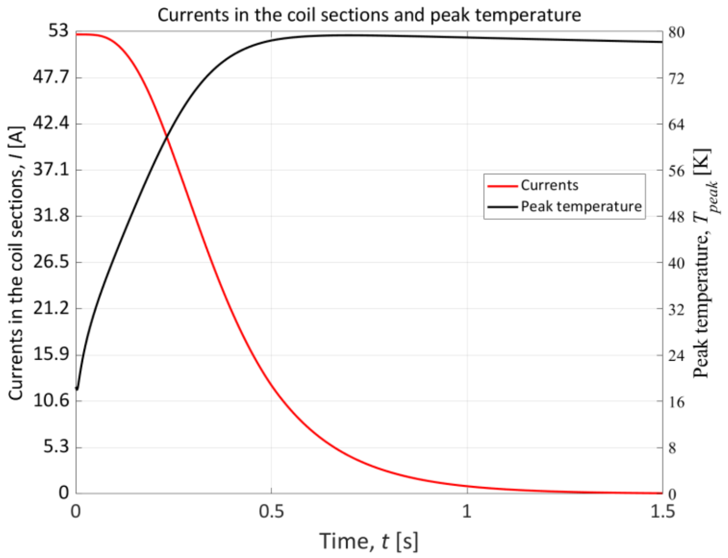
- Thermal diffusion solved in 3D
- The ends geometry is not the real one, but comes with simplifications
- 2D magnetic field is extended to the entire turn (field in the ends is wrong!)
- Adaptive time stepping can be enabled
- Inter-filament coupling loss are included, but their effect on differential inductance is not included
- Quench heaters and CLIQ not included

- A LEDET 2D model can be transformed in a 3D model by adding a entries to the input file
- Typical simulation time <1 hour

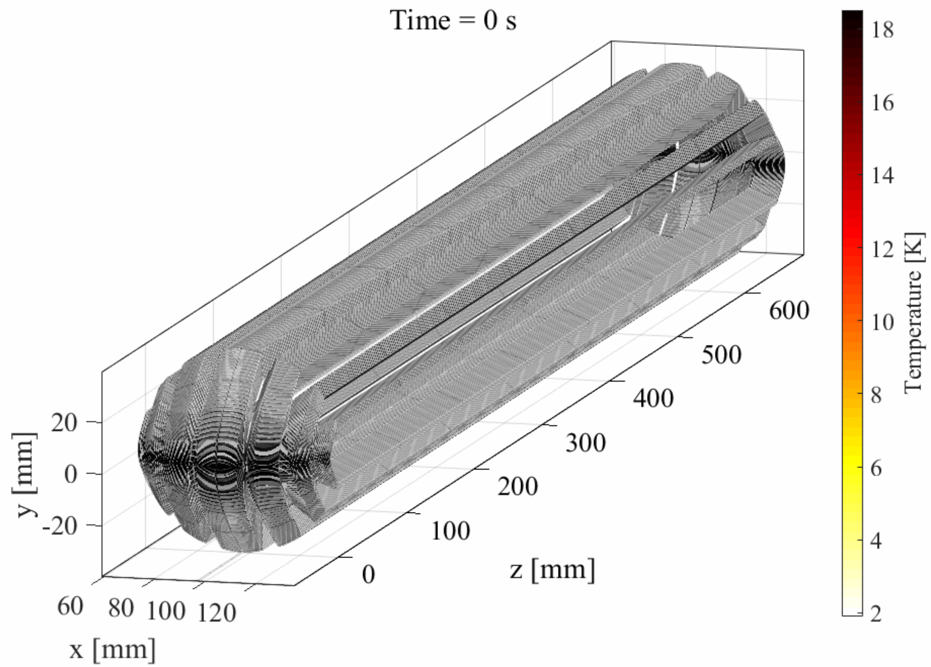
E. Ravaioli, "Simulation of the 3D magnet quench process with the finite-difference method in STEAM-LEDET", edms 2454468
O. Tranum Arnegaard, **E. Ravaioli**, "3D simulations of quench transients in the MQSX magnet using STEAM-LEDET", edms 2613181

LEDET 3D – Full-scale magnet quench model in 3D -3

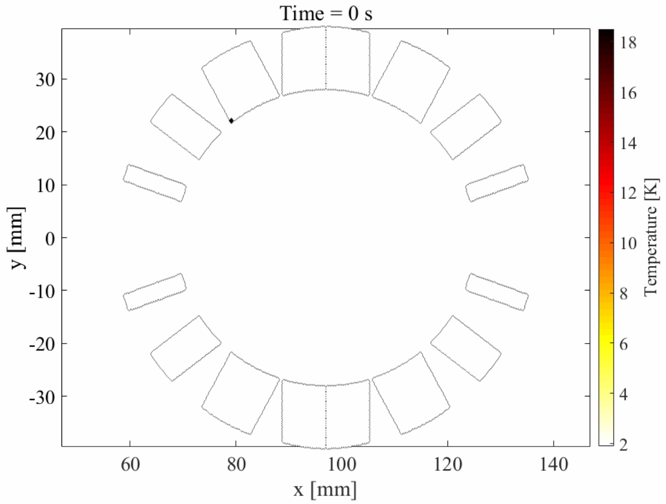
Magnet current and hot-spot T



Temperature evolution in the coil turns



T evolution in coil cross-section

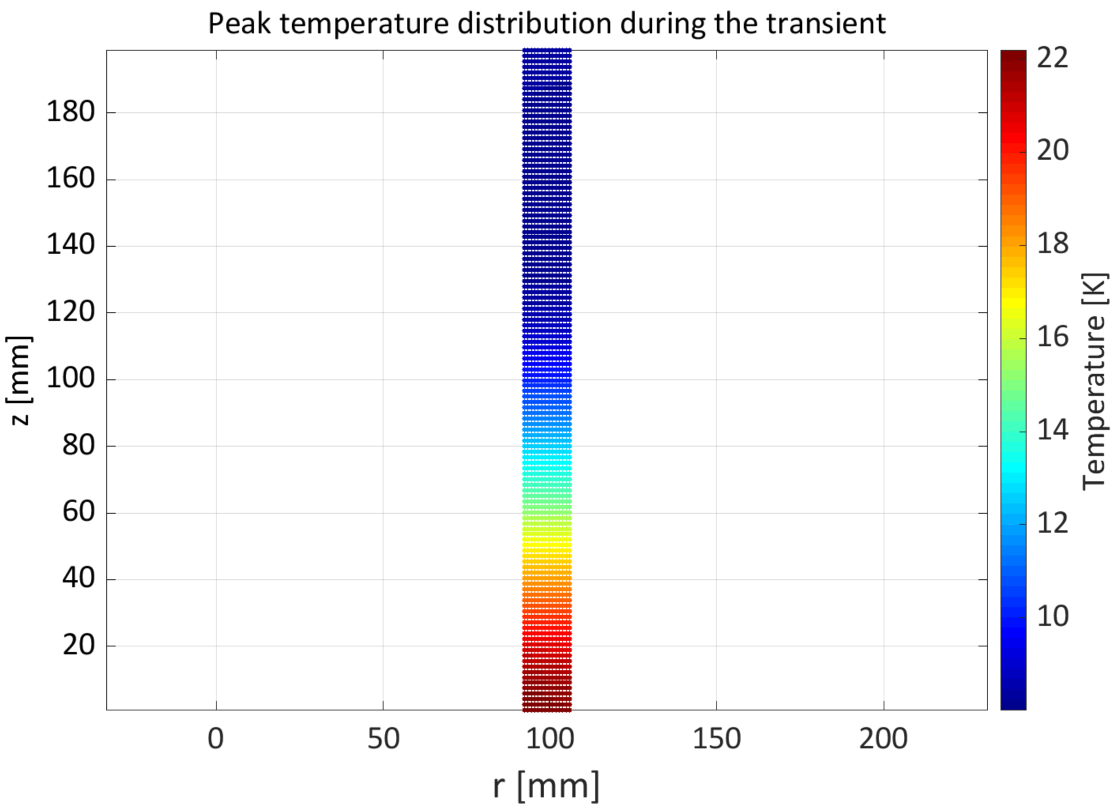


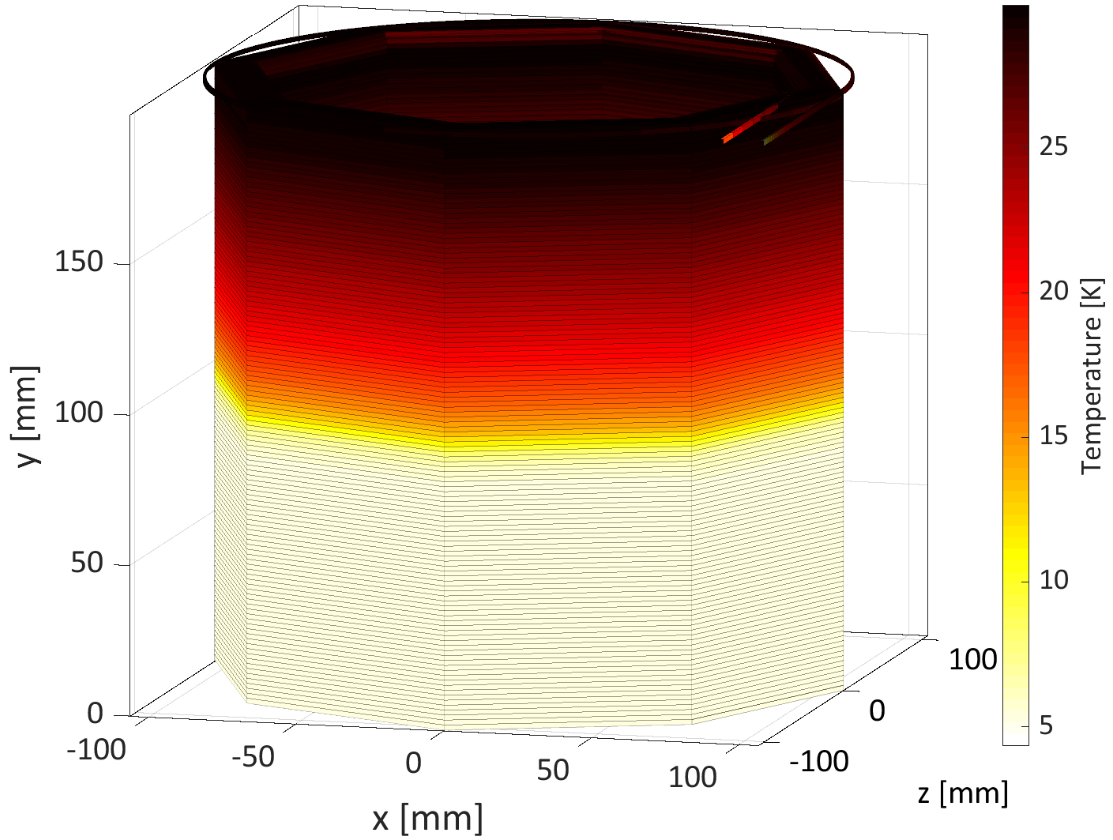
- ✓ 3D model of a self-protecting magnet coil during a quench discharge
- ✓ Coupling loss is included in the simulation
- ✓ Simulation time <1 h

E. Ravaioli, "Simulation of the 3D magnet quench process with the finite-difference method in STEAM-LEDET", edms 2454468

O. Tranum Arnegaard, **E. Ravaioli**, "3D simulations of quench transients in the MQSX magnet using STEAM-LEDET", edms 2613181

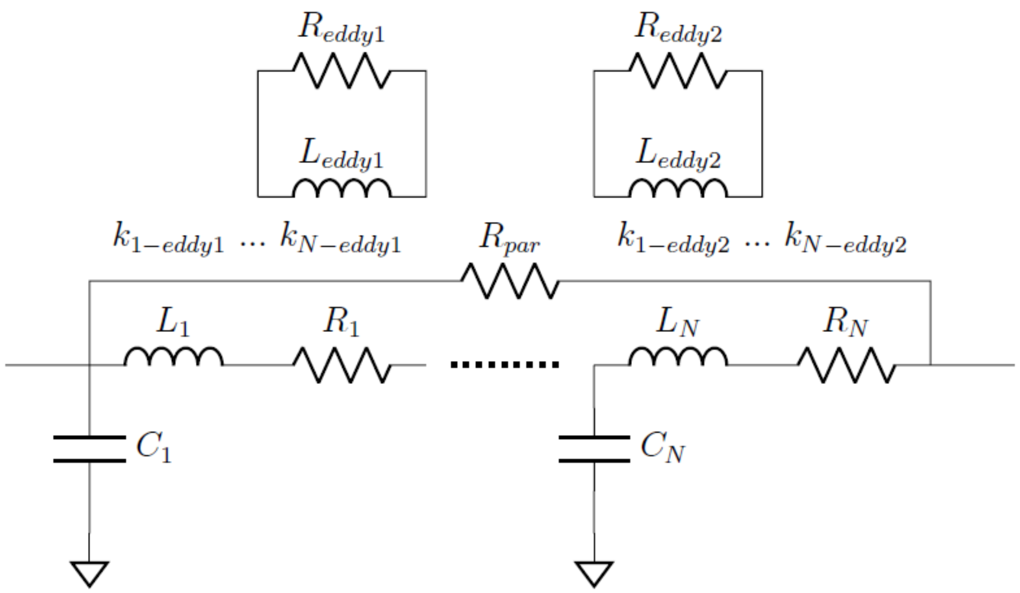
LEDET – Better support for solenoid geometry

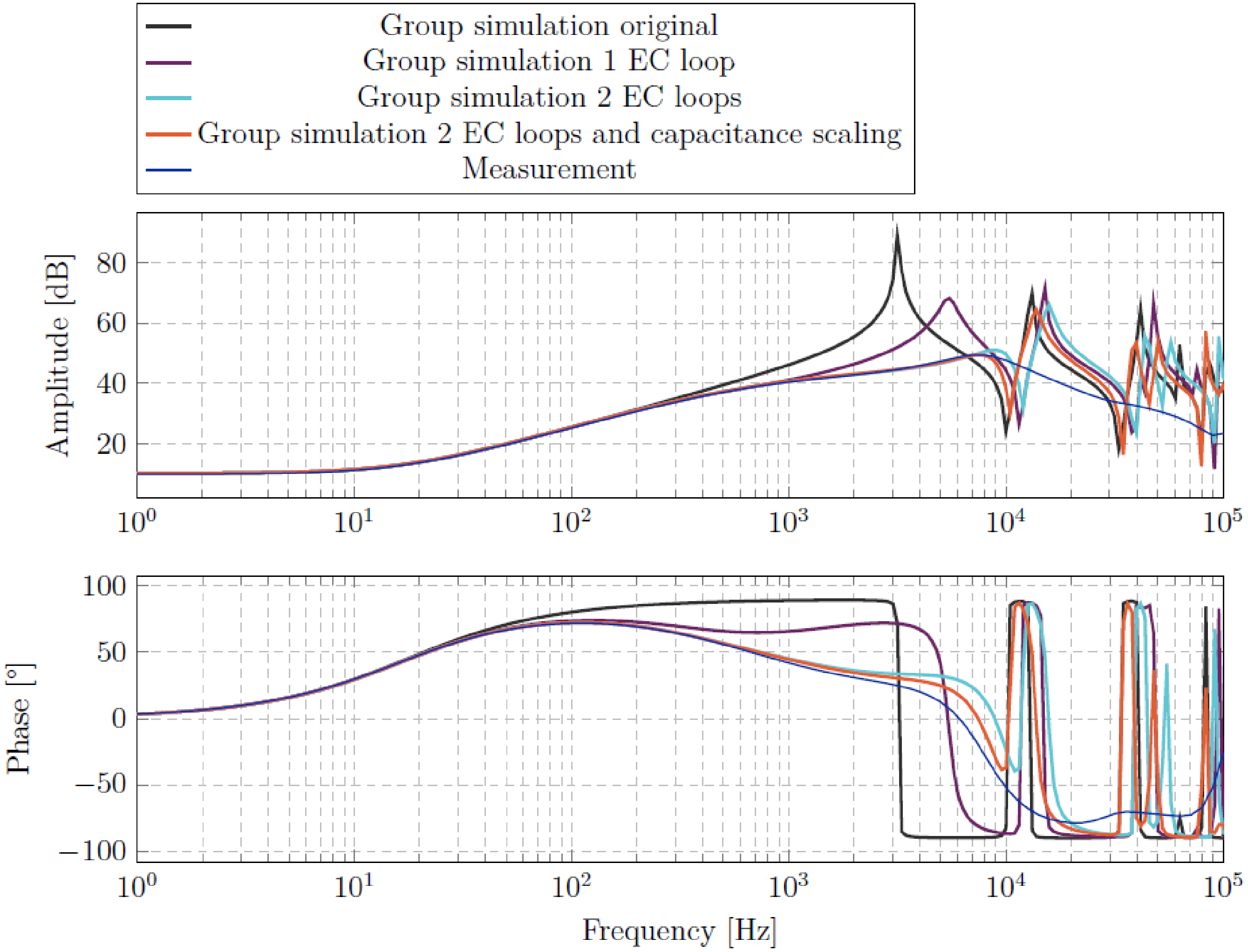




A dedicated flag allows enabling the solenoid geometry, which affects how voltages to ground are calculated, how 3D geometry is generated, and the plot labels

PSPICE – Automatic generation of frequency-domain models



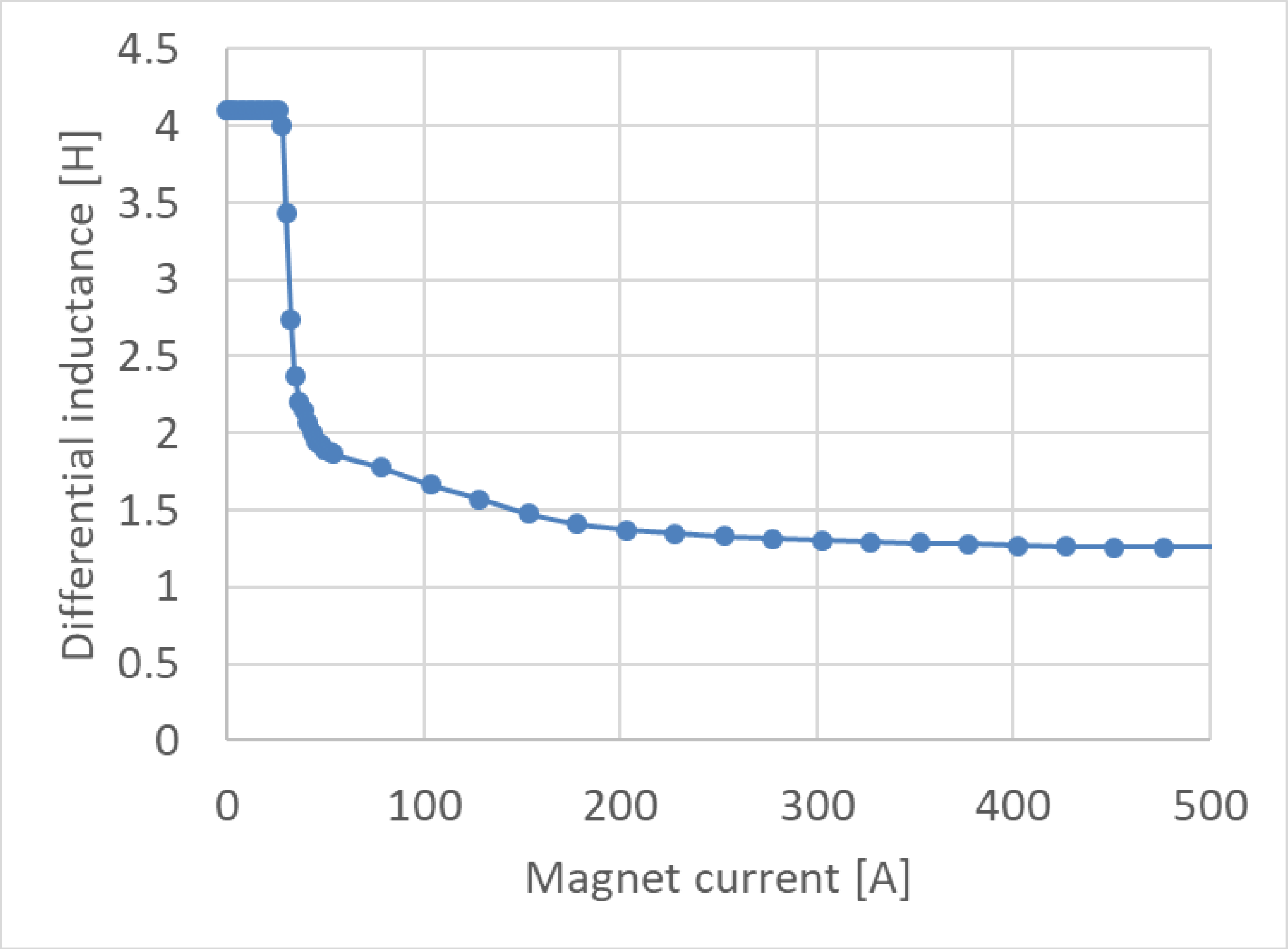


The PSPICE model is generated automatically based on geometry information. It includes:

- Self-mutual inductances
- Stray capacitances
- Eddy-currents effects

A. Frem Wolstrup, "Automatic frequency-domain modelling of SC electromagnets used in the LHC machine at CERN", edms 2455852

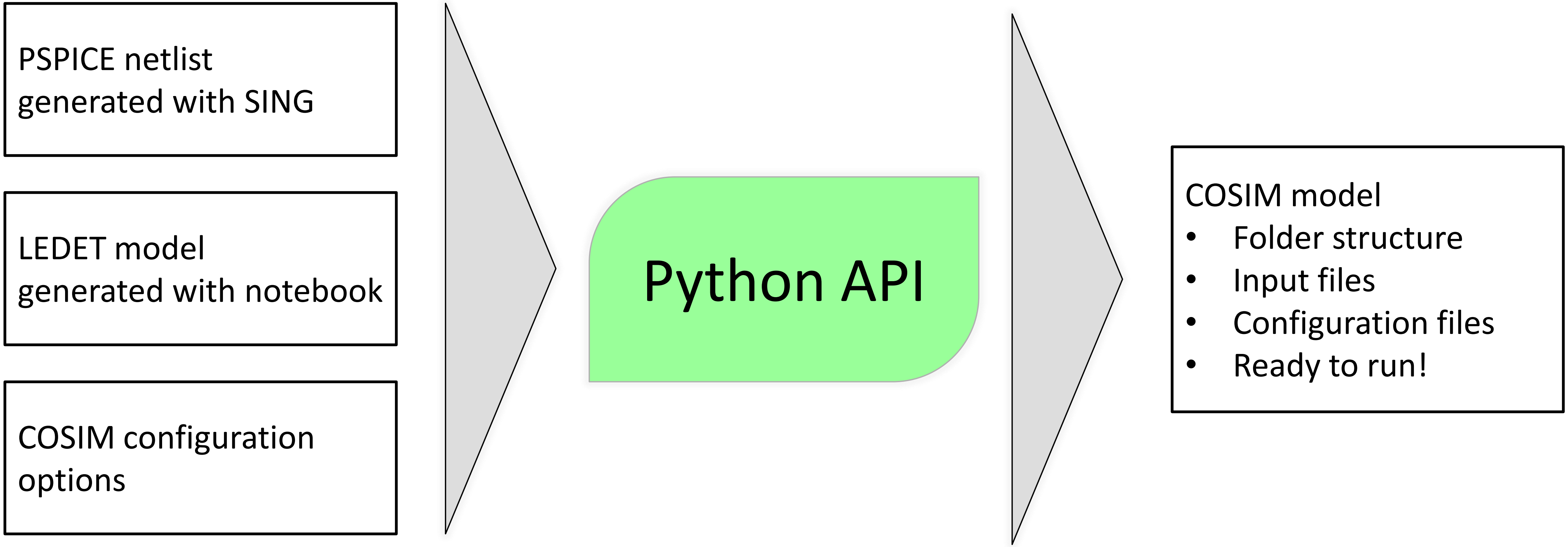
PSPICE component library – Current-dependent inductance



- This component can be used to simulate more realistically the powering of an electrical circuit
- It relies on a look-up table that defines the magnet inductance as a function of its current
- Many such components can be used in the same electrical model (for example in case of magnets in series)

D. Delkov, "PSPICE simulation of electrical transients in the SIS100 dipole circuit"

Notebooks – Automated generation of COSIM models



PSPICE netlist generated with SING

LEDET model generated with notebook

COSIM configuration options

Python API

COSIM model
- Folder structure
- Input files
- Configuration files
- Ready to run!

Much more information in the dedicated talk by **M. Janitschke** at this workshop

Example of a complex COSIM model – 600 A undulator magnet -1

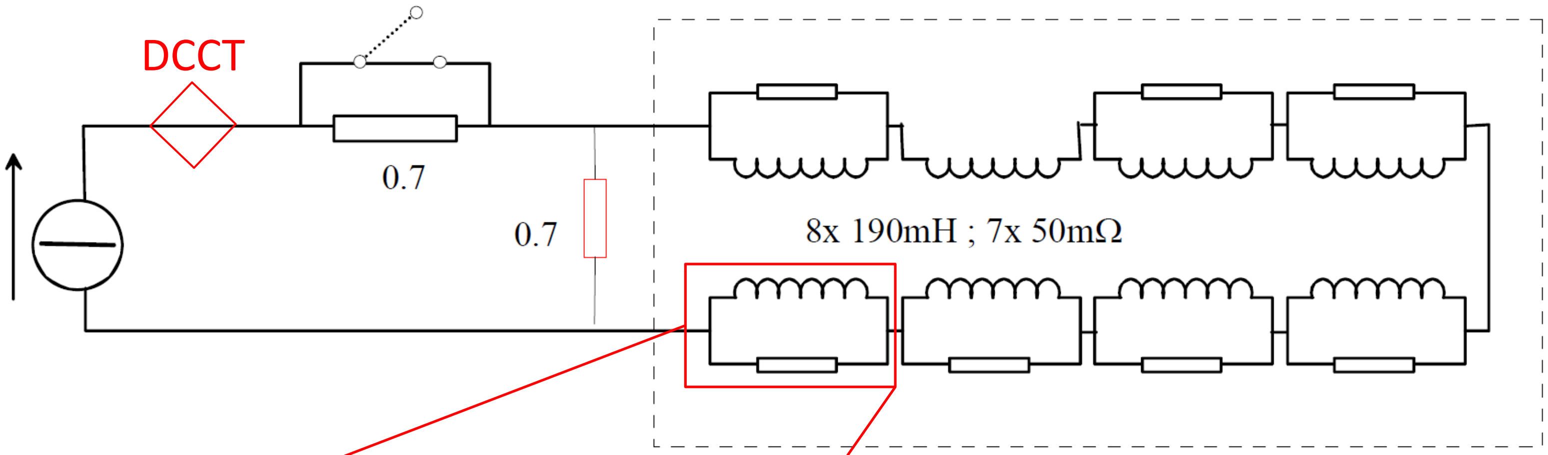
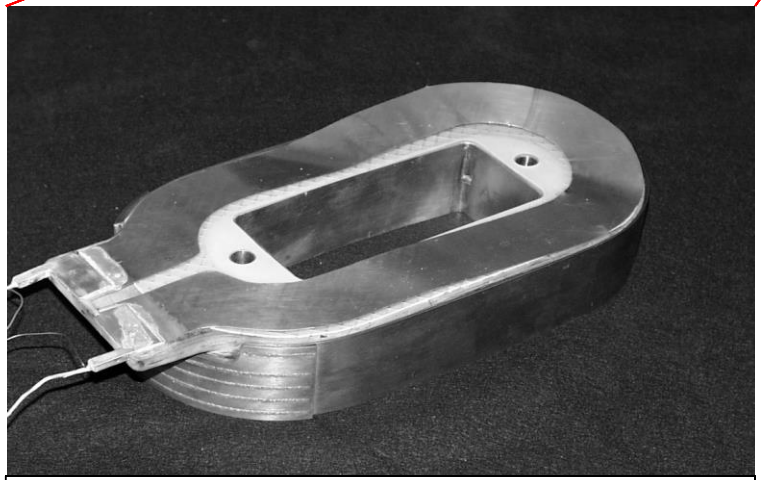
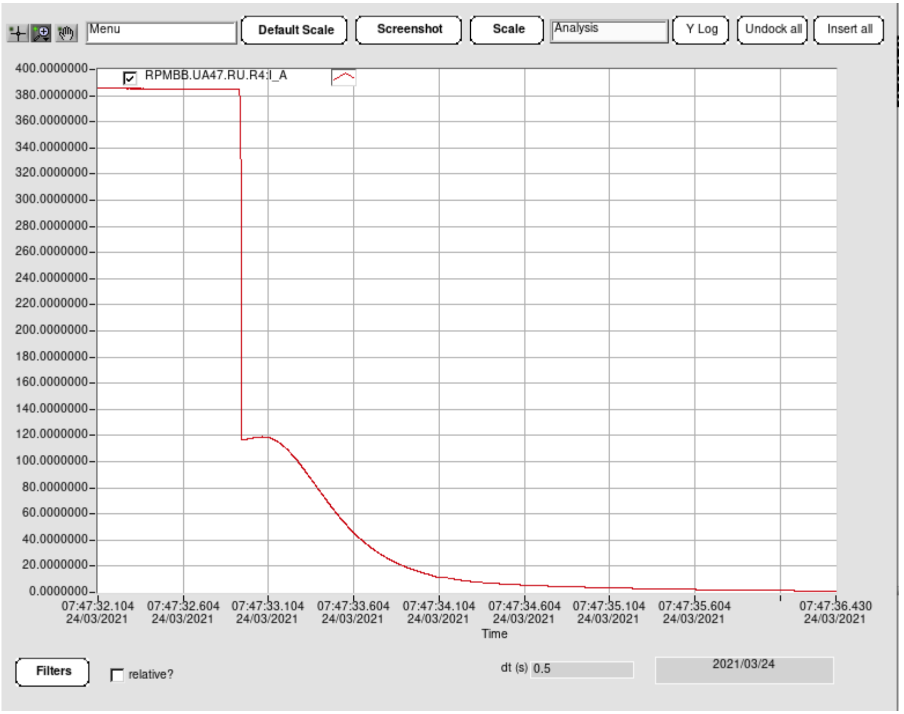


Figure 4: MU-L4 Simplified circuit layout modified



From LHC Project Report 894

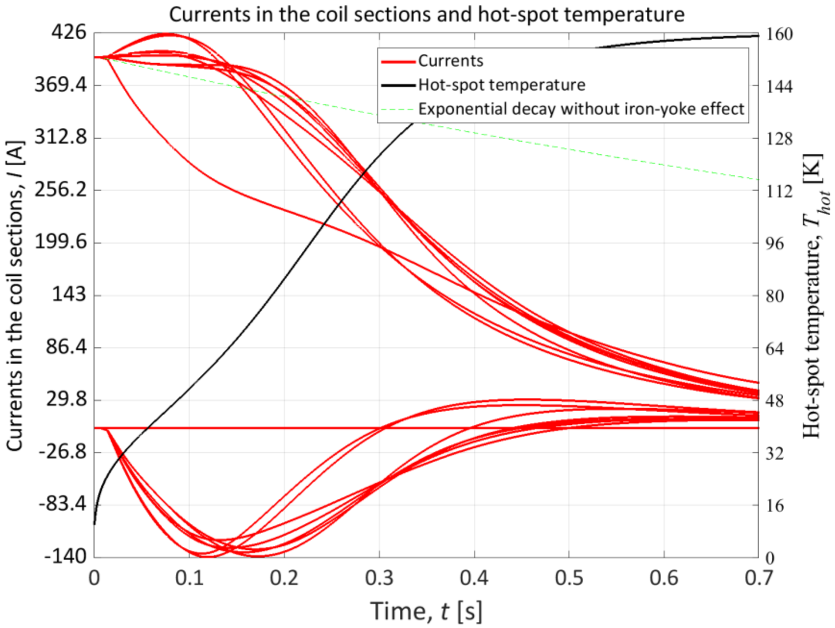


Circuit current measured by the DCCT

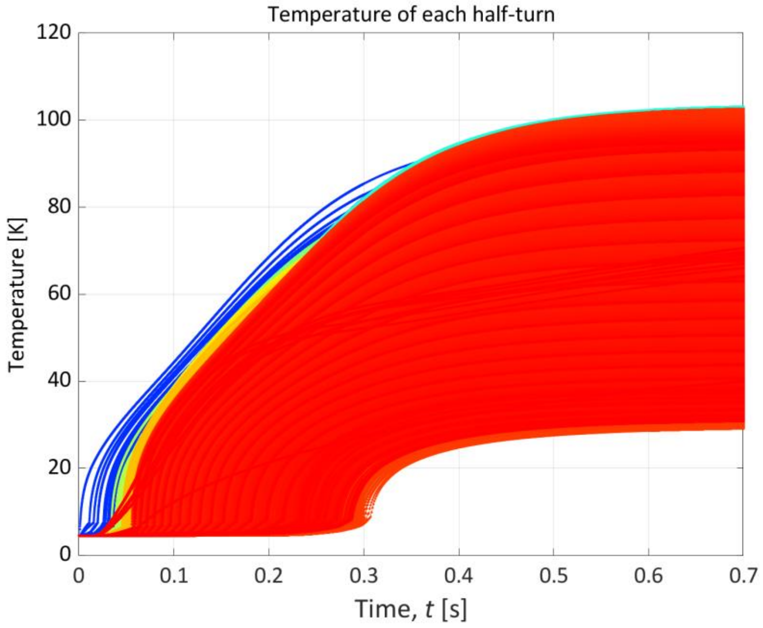
- ✓ This circuit was simulated with a COSIM model coupling a PSPICE electrical circuit and a LEDET model of coils + parallel resistors
- ✓ Note that the parallel resistors also act as quench heaters

Example of a complex COSIM model – 600 A undulator magnet -2

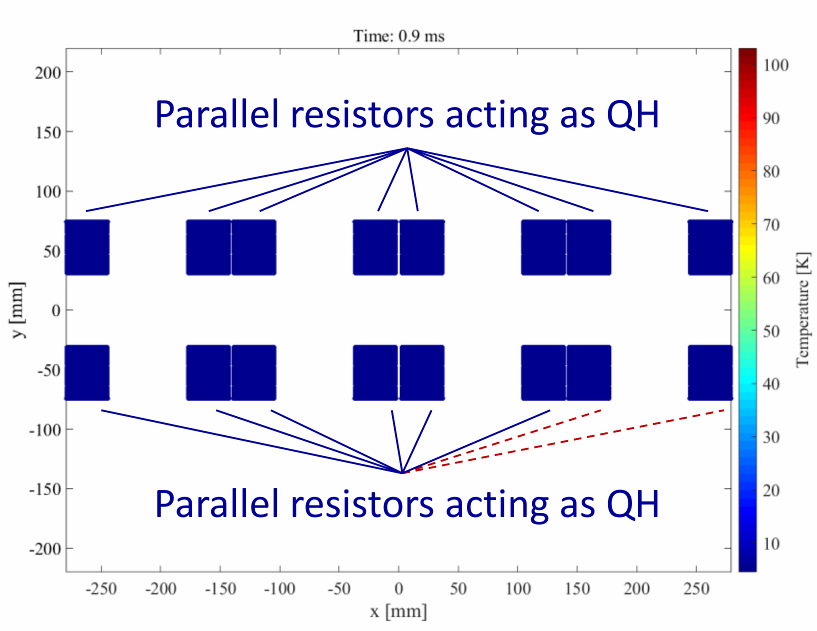
Currents of 8 coils and 7 parallel resistors



Temperature in the coil turns vs time



Evolution of the temperature in the coil turns



Parallel resistors acting as QH

Parallel resistors acting as QH

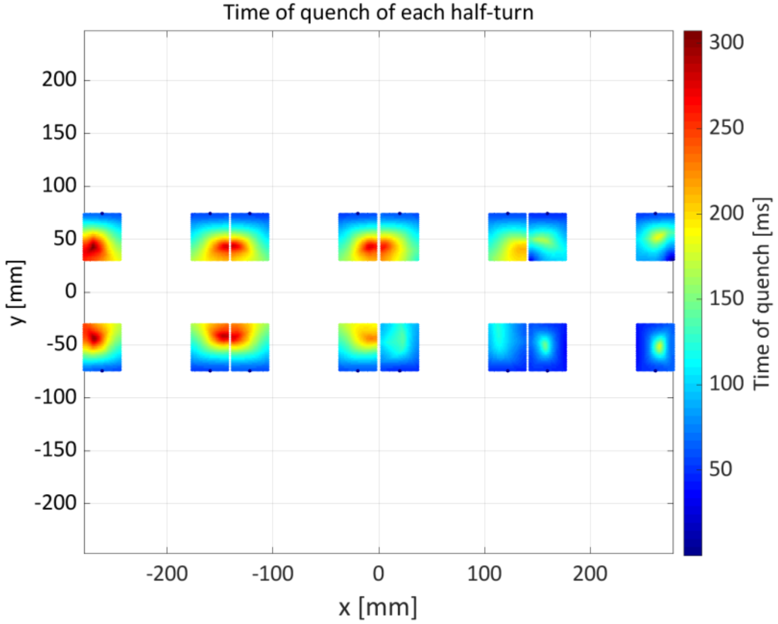
- ✓ To simulate this transient, the software must include quench development, thermal diffusion from the resistors to the turns and among turns, longitudinal quench propagation, mutual coupling between coils and parallel resistors, coupling loss,…

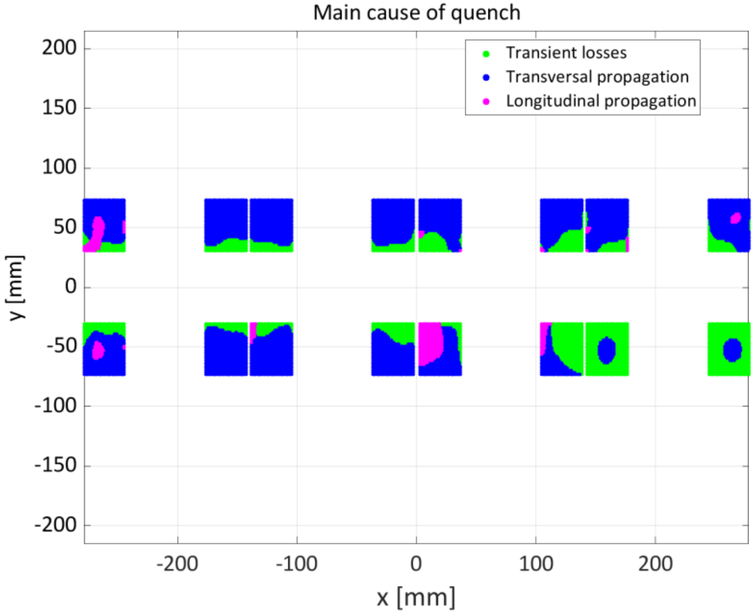
Example of a complex COSIM model – 600 A undulator magnet -3

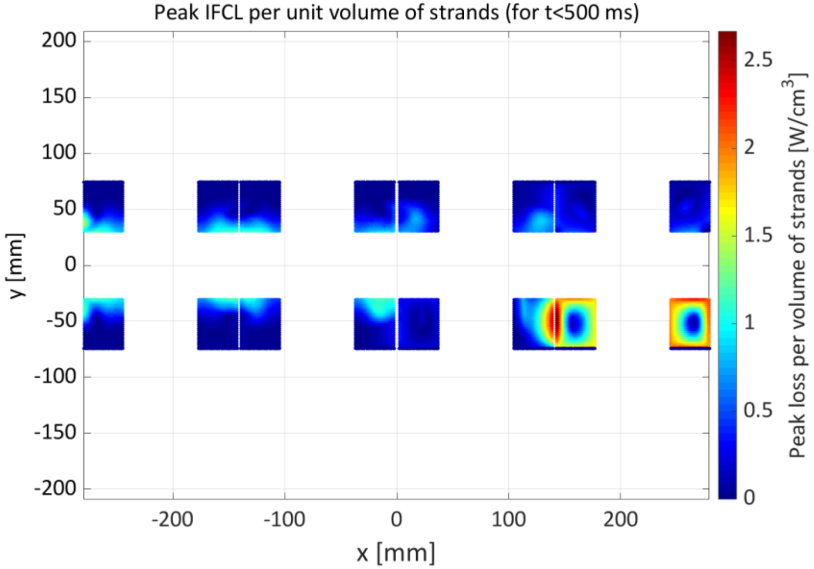
Time of quench for each turn

Main cause of quench for each turn

Peak power deposition due to coupling loss







- ✓ Simulating this transient offers additional insights. In this example, we see the time and cause of quench for each turn, which brings additional understanding of the magnet+circuit behavior
- ✓ In this example, coupling loss is responsible for quenching ~30% of the turns

Work is not over yet...

We‘re constantly developing new features!

If you have ideas, wishes & feedback,
we‘re interested!

https://espace.cern.ch/steam/

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