
CERN

MQ Simulation & Validation

D. Pracht

On behalf of the **STEAM team** (Emmanuele Ravaioli, Matthias Mentink, Michał Maciejewski, Lorenzo Bortot, Akrivi Liakopoulou)

Thanks a lot for your help!

Thanks a lot for the data: Gerard Willering

Also thanks a lot to: Marco Prioli

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Checklist for this presentation

1. Why protecting a superconducting magnet? ☐
2. Procedure to generate a magnet model in SIGMA-COMSOL ☐
3. Cross-check of electro-magnet model with other programs: ROXIE ☐
4. Cross-check of electro-thermal model with other programs: LEDET ☐
5. Updating the model with Quench heaters (QHs) ☐
6. Updating the model with heat exchange between layers and poles ☐
7. Validation against test results from SM18 ☐

Superconducting magnets

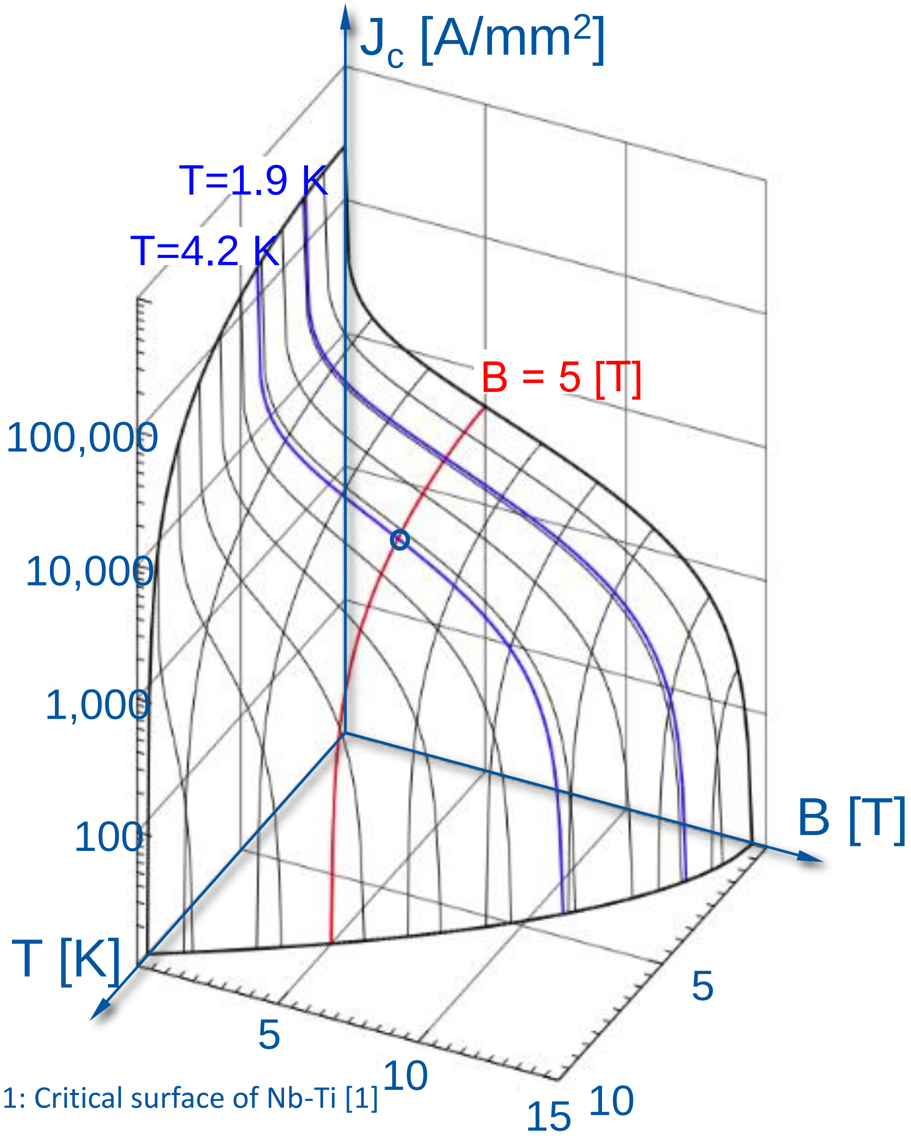


Fig. 1: Critical surface of Nb-Ti [1]

Why superconducting magnets?

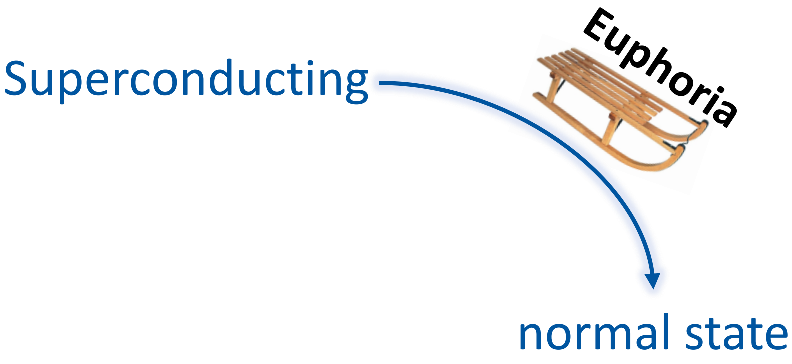
- Vanishing electrical resistance
- Current densities
- Magnetic field

The limitations of use are the usual suspects:

- Current density
- Applied magnetic field
- Temperature

Together: critical surface

What is a quench?



A quench is :

- the status change from superconducting to normal state

Changing the state by:

- temperature, magnetic field, or current density changing

Typical causes for a quench:

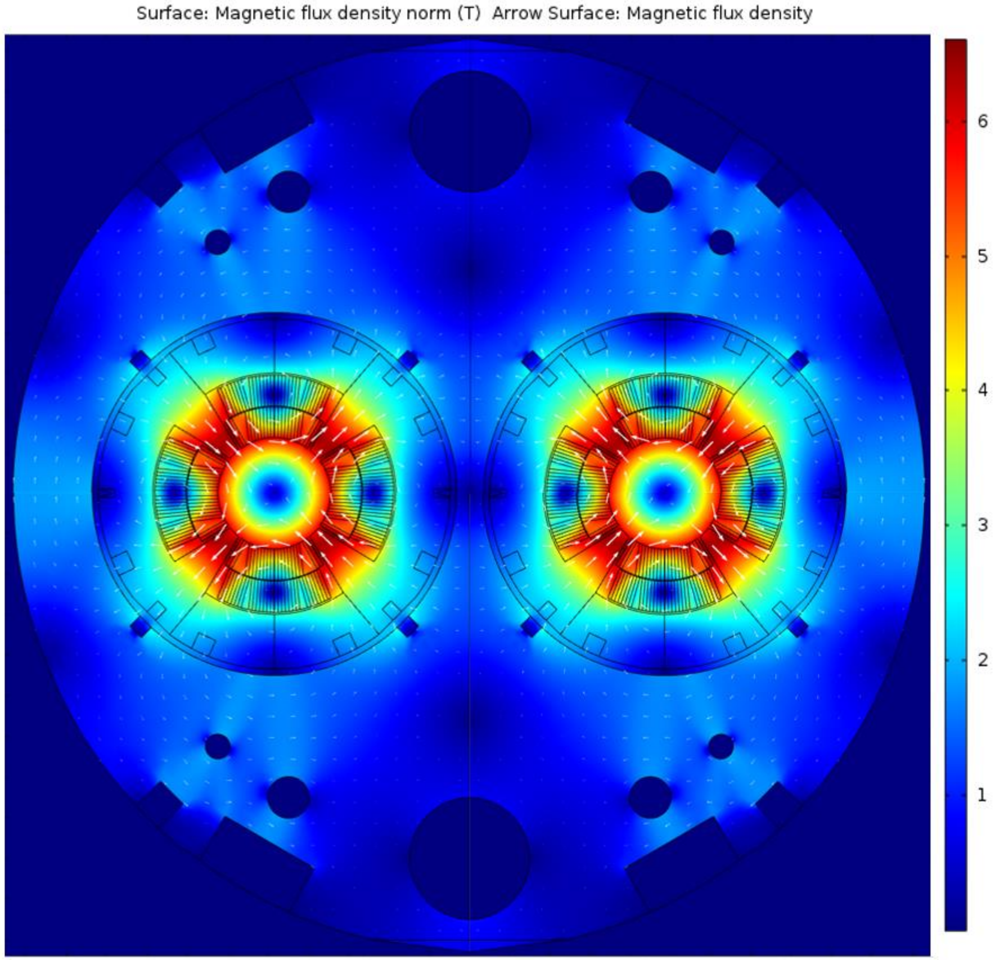
- Mechanical effects
- Heat Leaks
- Loss of insulation vacuum
- Electro-magnetic transients
- Beam loss
- Cracking epoxy impregnation of the coil

Quench in a unprotected, high-energy magnet will likely result in:

- High ohmic loss
- High peak temperature
- Loss of control of the stored energy in the magnet
- High voltages across the magnet
- High mechanical stresses

Even energy deposition in the order of μJmm^{-3} is enough to quench!

LHC Main Quadrupole magnet



Main Quadrupole:

- The quadrupole magnets focus the particle beams, controlling their width and height
- 2 types of circuits are present
- RQF means focusing in the <u>horizontal plane</u>
- RQD means de-focusing (but focusing in the <u>vertical plane</u>)
- Quench protection based on quench heaters (QHs) and cold by-pass diodes

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Motivation

What is the final goal?

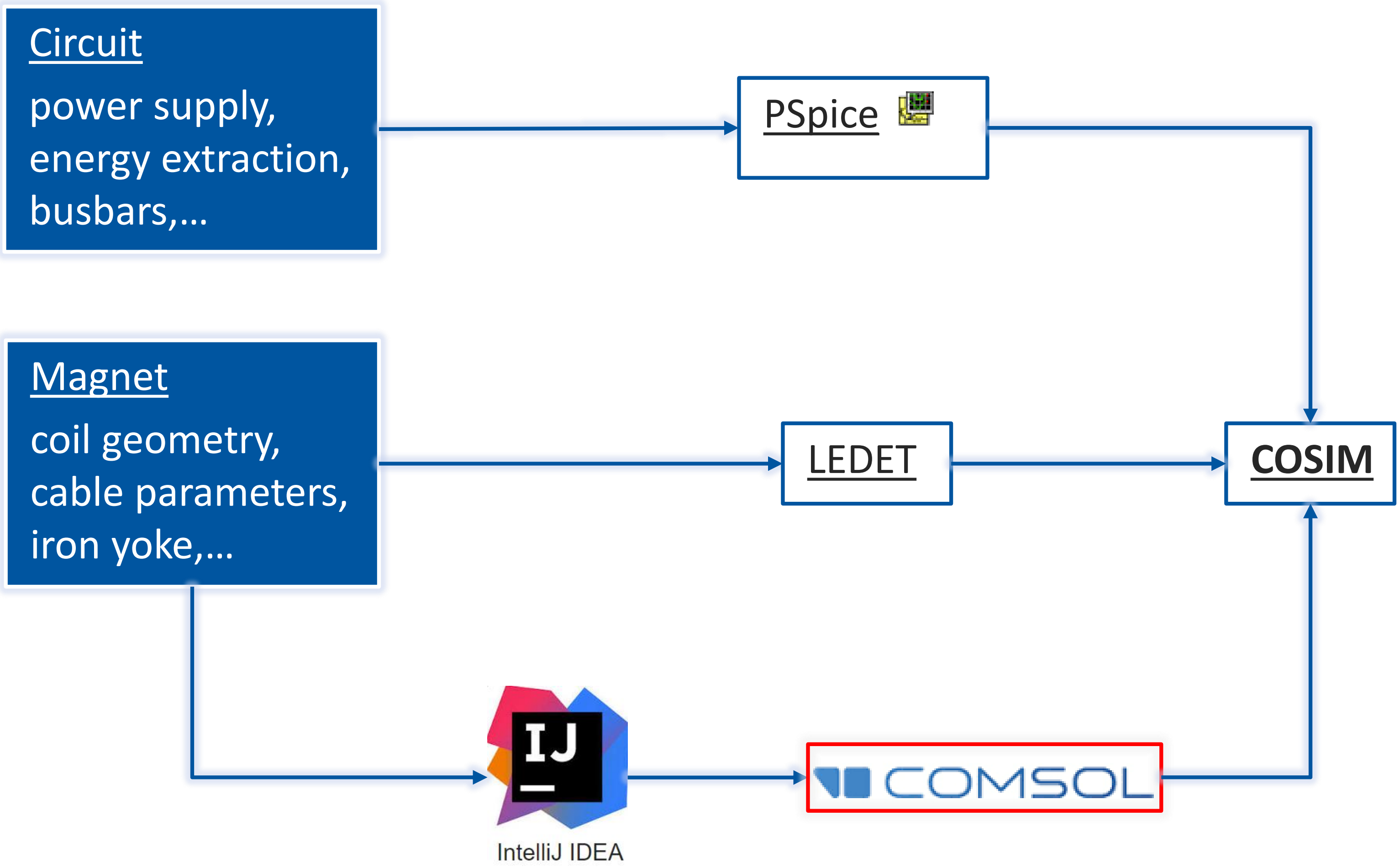
- To have a circuit library for all LHC circuits (RB, RQX, RQF/RQD,...)
- To have more magnet models within STEAM
- To constantly optimize STEAM-SIGMA for semi-automatic model generation

My task within the STEAM team

1. Develop the MQ magnet model
    1. SIGMA-COMSOL
    2. LEDET
2. Develop the RQD/RQF circuit model in PSPICE
3. Combine point (1) and (2) within COSIM
4. Validate points (1), (2) and (3)
5. Document the models and the results

Generate a model

How to generate a geometry for the model using SIGMA?



Circuit

power supply,
energy extraction,
busbars,…

Magnet

coil geometry,
cable parameters,
iron yoke,…

PSpice

LEDET

COSIM

IntelliJ IDEA

COMSOL

Generate the model

Check against other codes

Validate against test results

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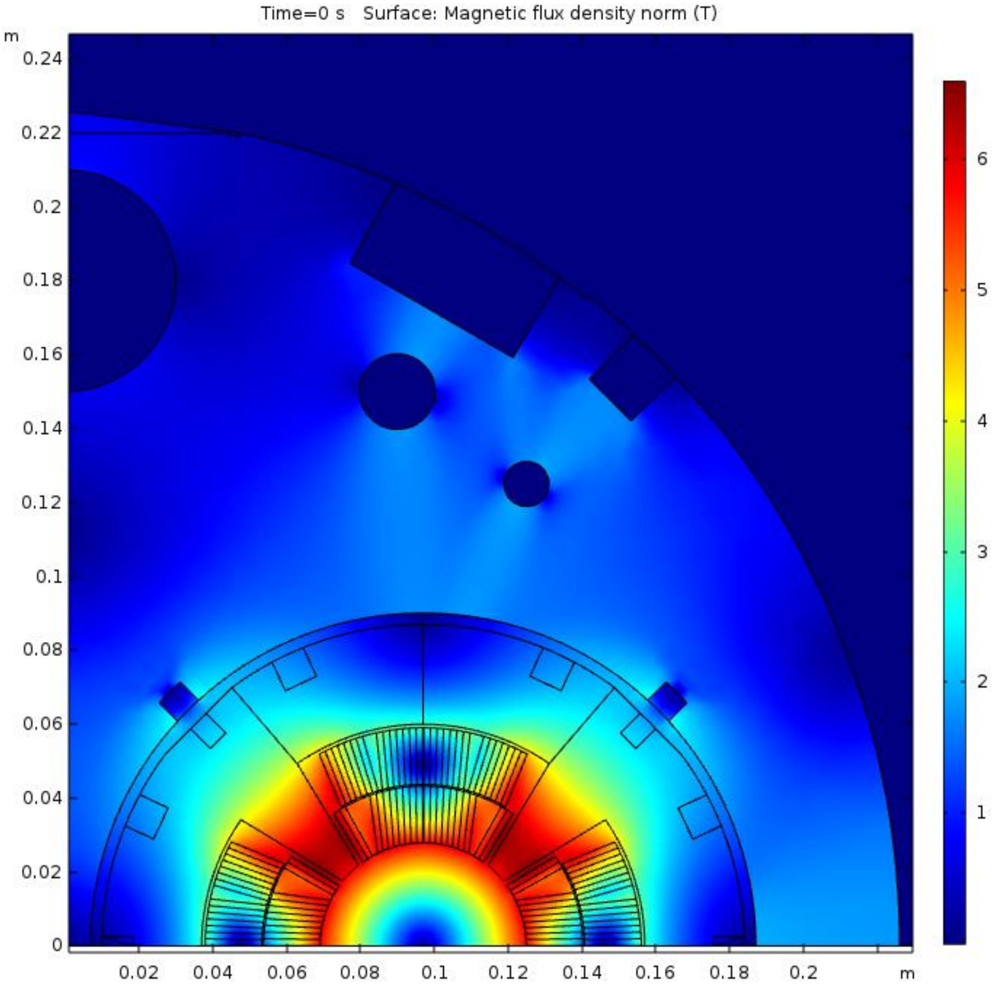
Electro-magnetic model

Comparison with ROXIE



Difference between the peak fields at I = 11.2 kA

Peak field in the ROXIE Simulation

- B = 6.68 T

Peak field in the COMSOL Simulation

- B = 6.60 T

Difference: ΔB = 0.08 T

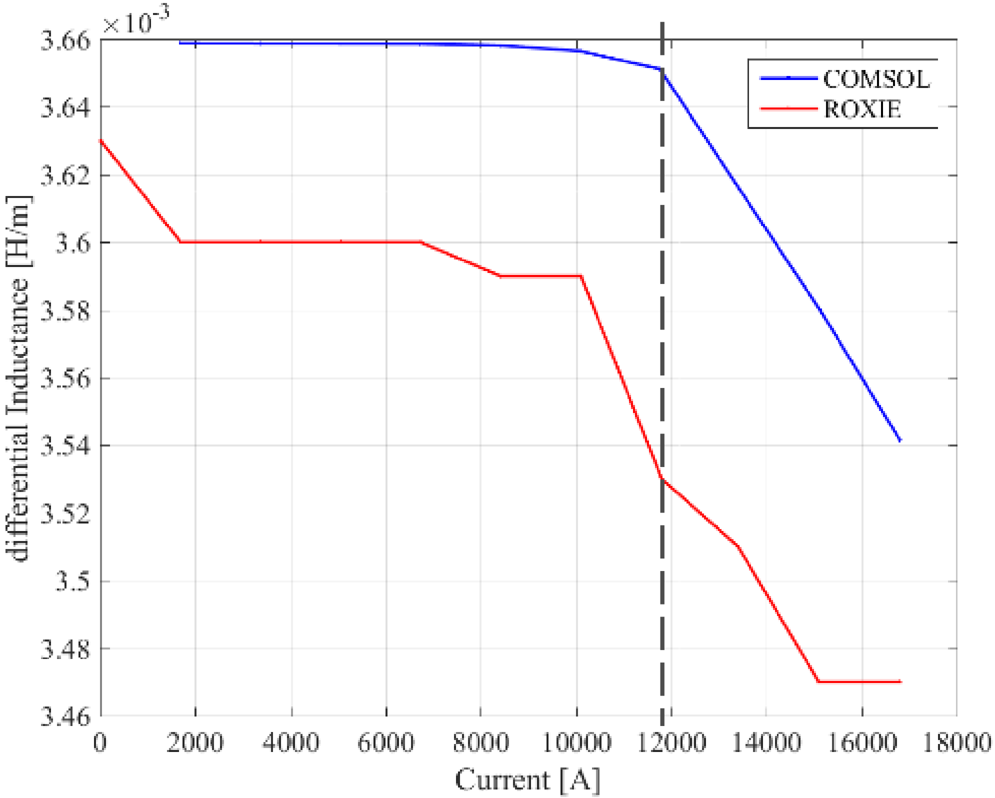
→ 1.2 %

Good agreement with ROXIE

Electro-magnetic model

Comparison with ROXIE

Differential Inductance per unit length over current



ROXIE:

$L_{diff}' = 3.53 \cdot 10^{-3}\, Hm^{-1}$

$L_{diff} = 3.1\, m \cdot 3.53 \cdot 10^{-3}\, Hm^{-1}$

= **10.94 mH**

COMSOL:

$L_{diff}' = 3.65 \cdot 10^{-3}\, Hm^{-1}$

$L_{diff} = 3.1\, m \cdot 3.65 \cdot 10^{-3}\, Hm^{-1}$

= **11.32 mH**

Generate the model

Check against other codes

Validate against test results

Difference at nominal current:

- $\Delta L_{diff}' = 1.2 \cdot 10^{-4}\, Hm^{-1} \longrightarrow 3.32\ \%$
- The difference is not negligible, but not too large

Fair agreement with ROXIE

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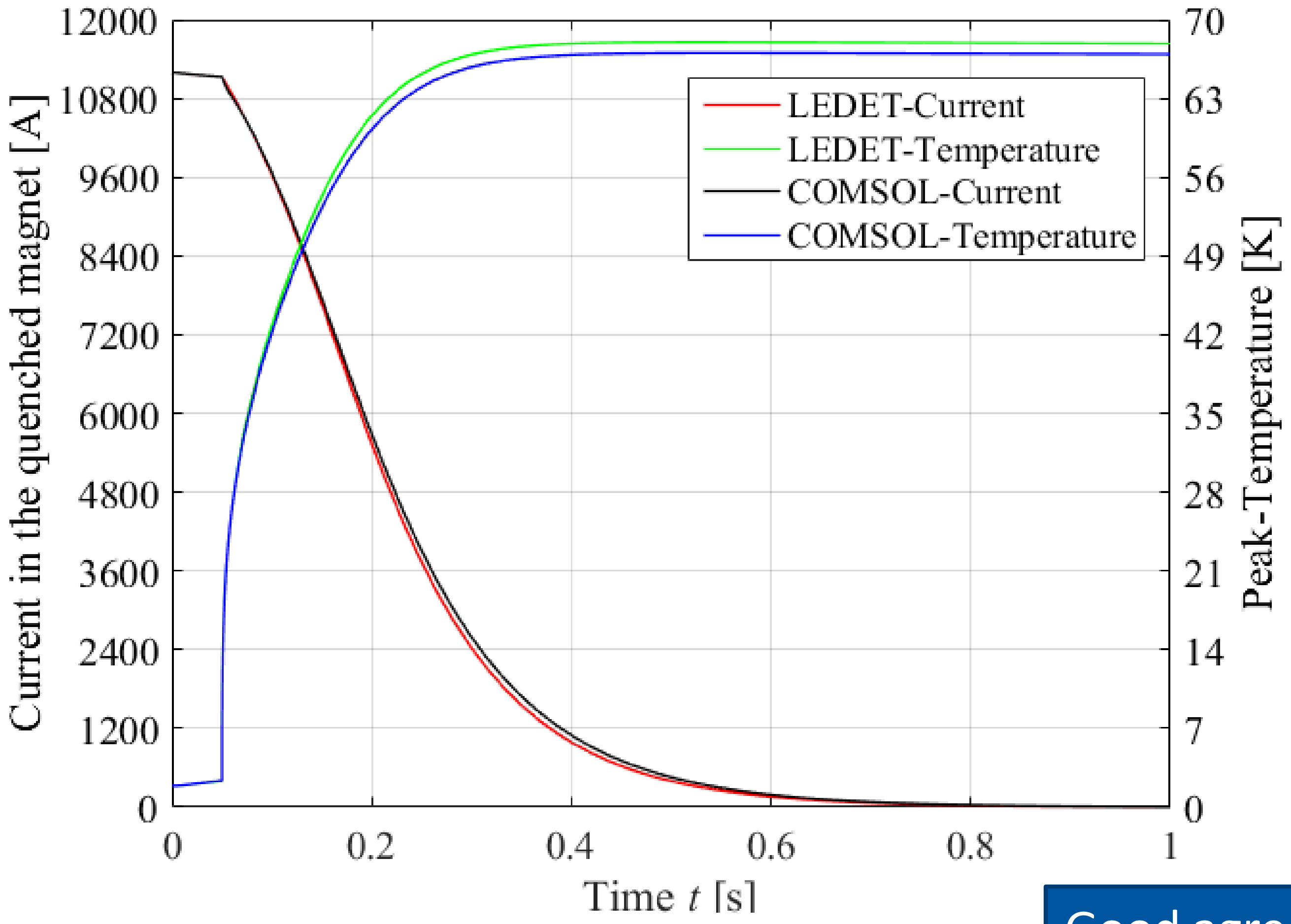
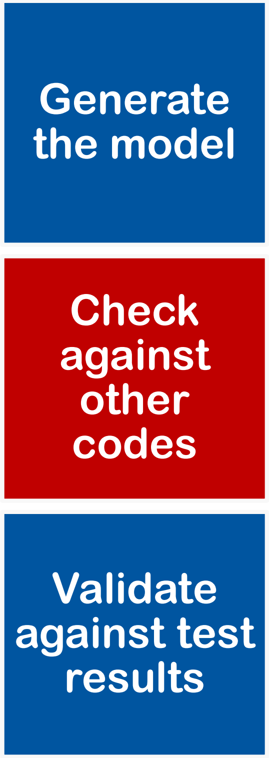
Electro-thermal model

Current / Peak temperature over time

Comparison with LEDET





Good agreement with LEDET

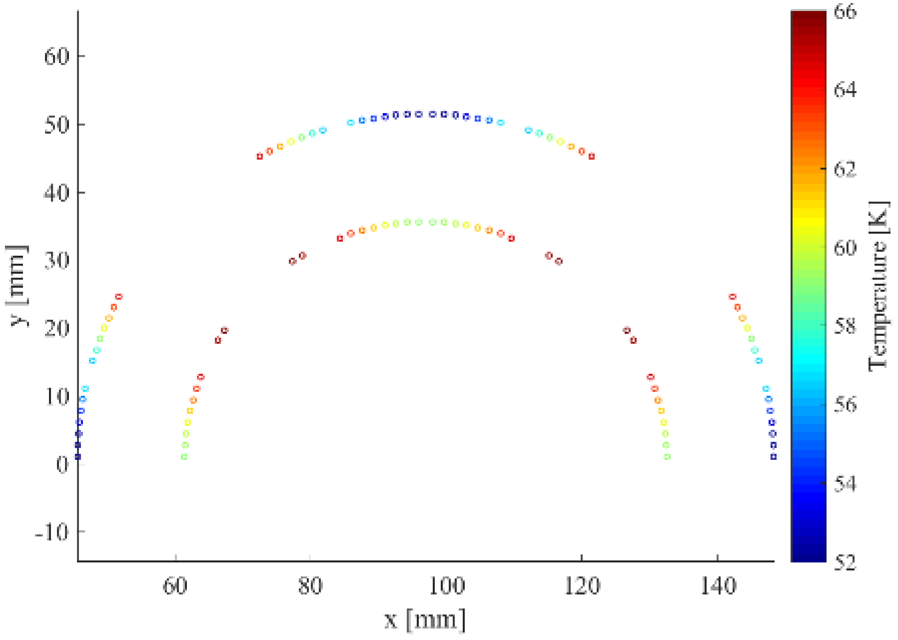
- LEDET uses adiabatic assumptions
- COMSOL shows the Peak-temperature in the half-turn (peak-field)

Electro-thermal model

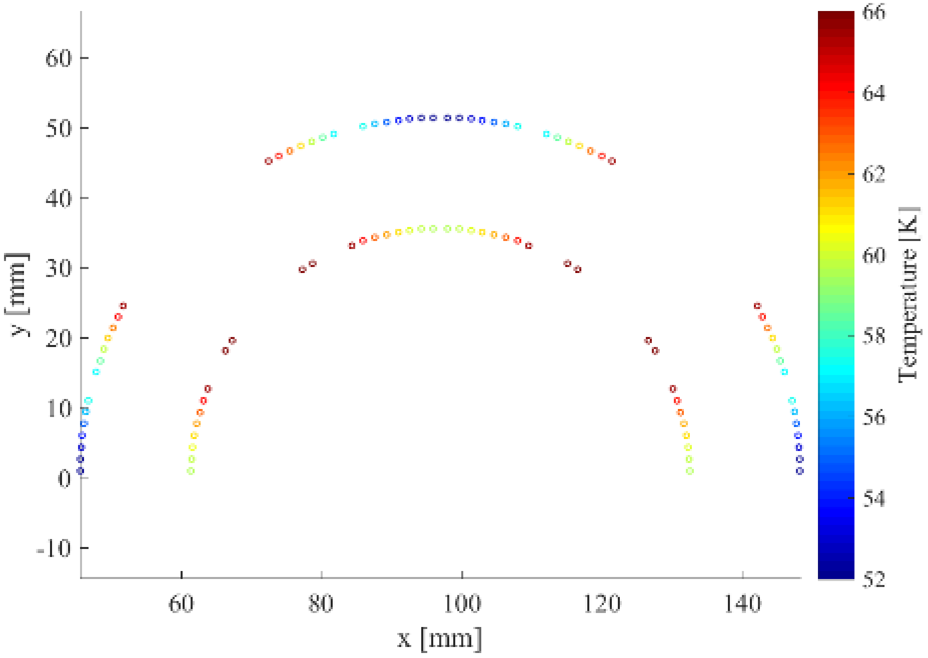
Comparison with LEDET

2D – temperature plot at 0.5 s

COMSOL



LEDET

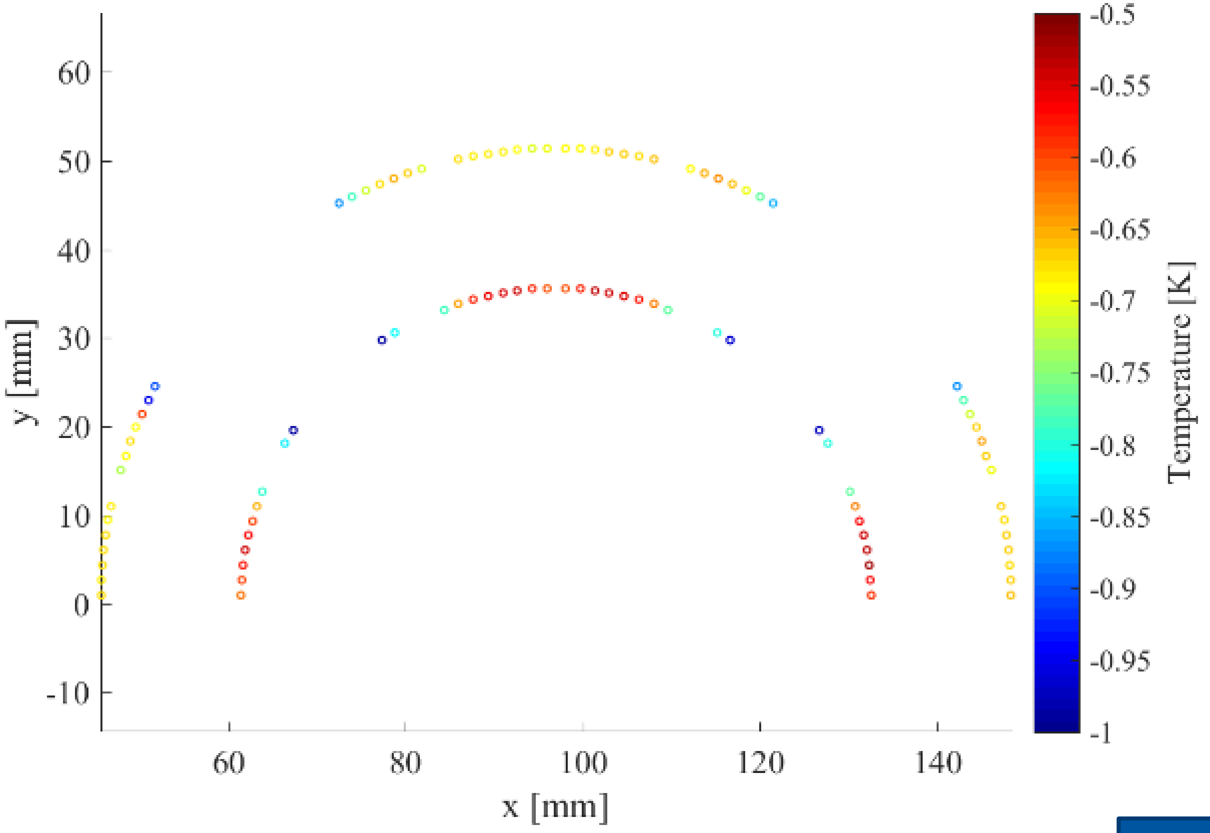


Electro-thermal model

Comparison with LEDET

2D – temperature plot at 0.5 s

$T_{COMSOL} - T_{LEDET}$



ΔT-plot shows:

- Temperature from LEDET higher (adiabatic assumption)
- In general: $|\Delta T_{max}| \approx 1$ K

Good agreement with LEDET

Electro-thermal model

Comparison with LEDET

Some other simulations…

Nr.	IFCC	$R_{crowbar}$ [Ohm]	Current [kA]	Quench position	fraction He [-]	Agreement
1	no	0.0005	11.2	-	0.0000	✓
2	no	0.02	11.2	-	0.0000	✓
3	no	0.09	11.2	-	0.0000	✓
4	yes	0.0005	11.2	whole magnet	0.0000	✓
5	yes	0.0005	11.2	1 half-turn	0.0000	✓
6	yes	0.0005	11.2	whole magnet	0.0551	✗
7	yes	0.0005	11.2	1 half-turn	0.0551	✗

Presented results

Closer look into the He-functions

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Quench Heaters (QHs)

What is a quench heater?

- QHs are part of the protection system
- QHs are thin stainless steel strips, glued to the layers of the magnet
- Heating up most of the coil in case of a quench
- Powered by a dedicated voltage supply

Scenario:

1. Quench is detected
2. Quench heaters are powered
3. Large part of the coil is transferred to the normal state
4. ~~Excessive temperature in small volume~~ → **small temperature growth in large volume**
5. Energy distributed over large magnet volume

Generate the model

Check against other codes

Validate against test results

Quench Heaters (QHs)

What is a quench heater?

Fig. 2: 11 T Nb_3Sn dipole magnet [2]

Generate the model

Check against other codes

Validate against test results

<u>Heating stations: stainless steel strips</u>

- Concentrate the energy deposition
- Distributed along the magnet length

<u>Copper strips:</u>

- Keep the resistance of the strips low

Quench Heaters (QHs)

Procedure for adding QHs in COMSOL:

Idea and Development: Matthias Mentink

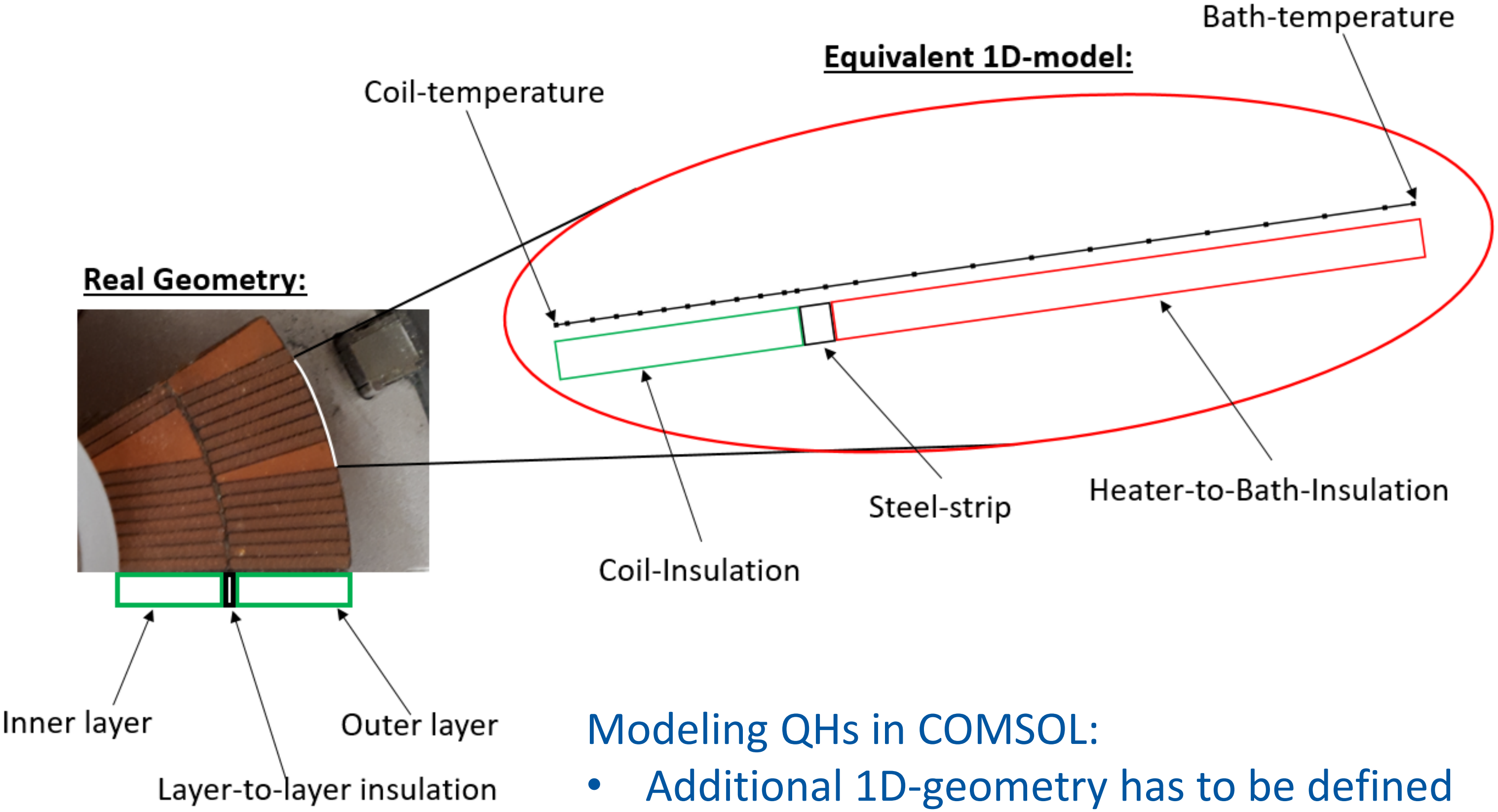

Fig. 3: Cross section of the LHC-MQ magnet

Generate the model

Check against other codes

Validate against test results

Modeling QHs in COMSOL:

- Additional 1D-geometry has to be defined
- Assign materials, properties,…
- Coupling the 2D and 1D geometry

Implementation and writing the tutorial: D. Pracht

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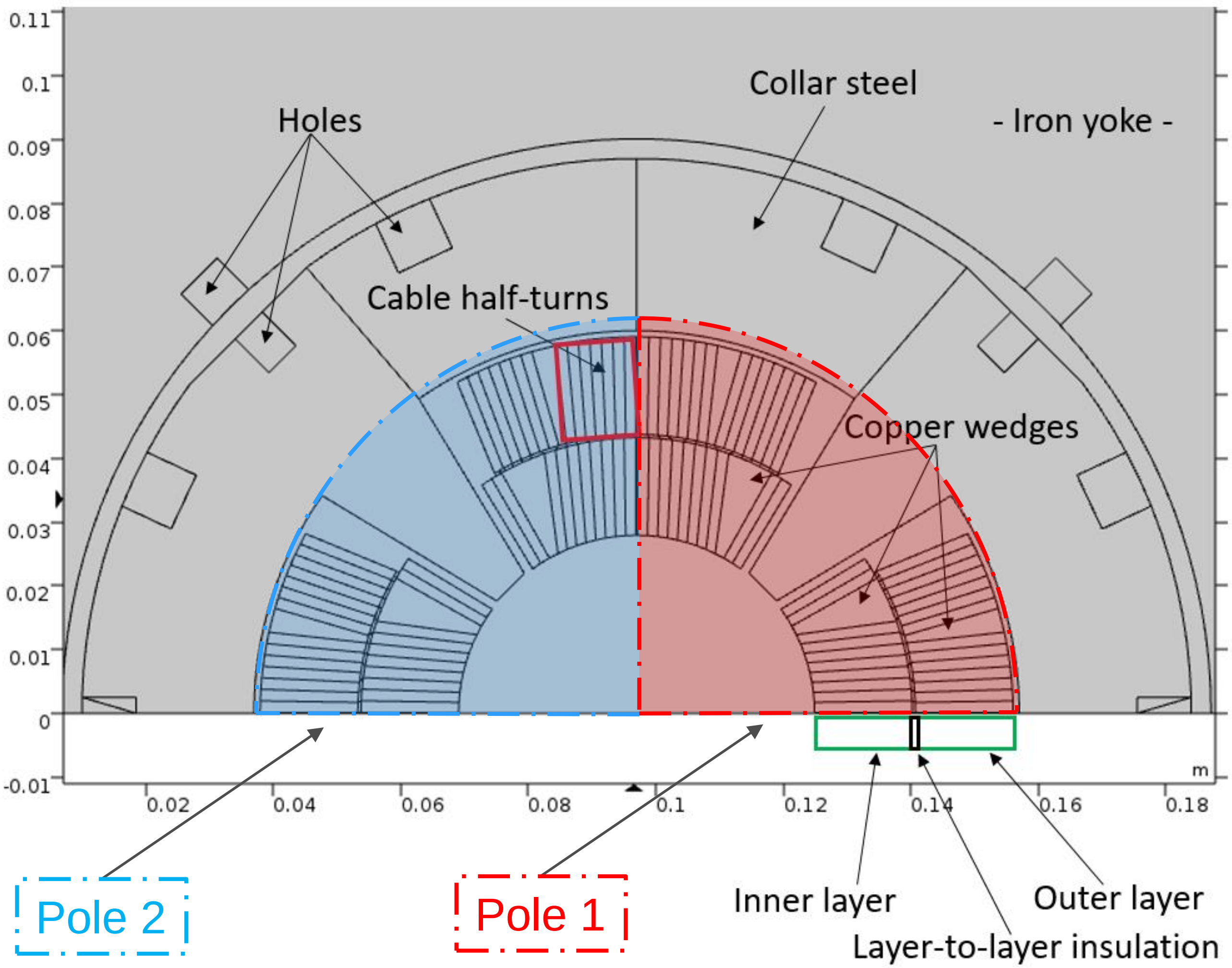
Modeling heat exchange

Idea and Development: Matthias Mentink



Heat Exchange between half-turns

- automatically in SIMGA

Heat Exchange between layers and poles

- manually in COMSOL

Implementation and writing the tutorial: D. Pracht

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Validation against measurements

Test campaign in SM18

- Different current levels
- Different magnets
- We choose:
  - MQLAD532-2-MQLAD532-2--A0606190953-a04-0--tdms.
  - At 11.69 kA and at (XXX) kA

Generate the model

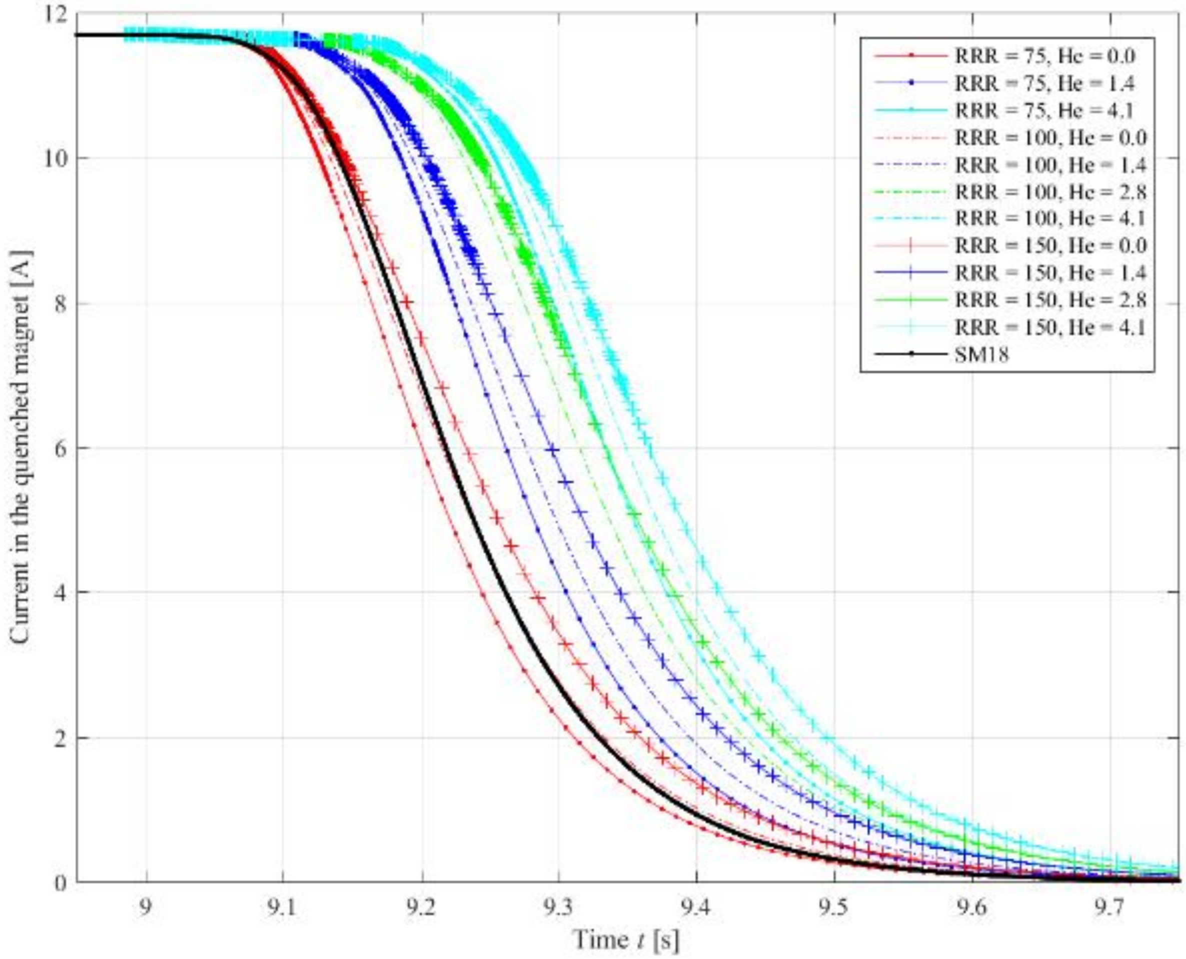
Check against other codes

Validate against test results

Validation against measurements

Current over time. Different RRR, Different He-fraction

Validation against test results



Generate the model

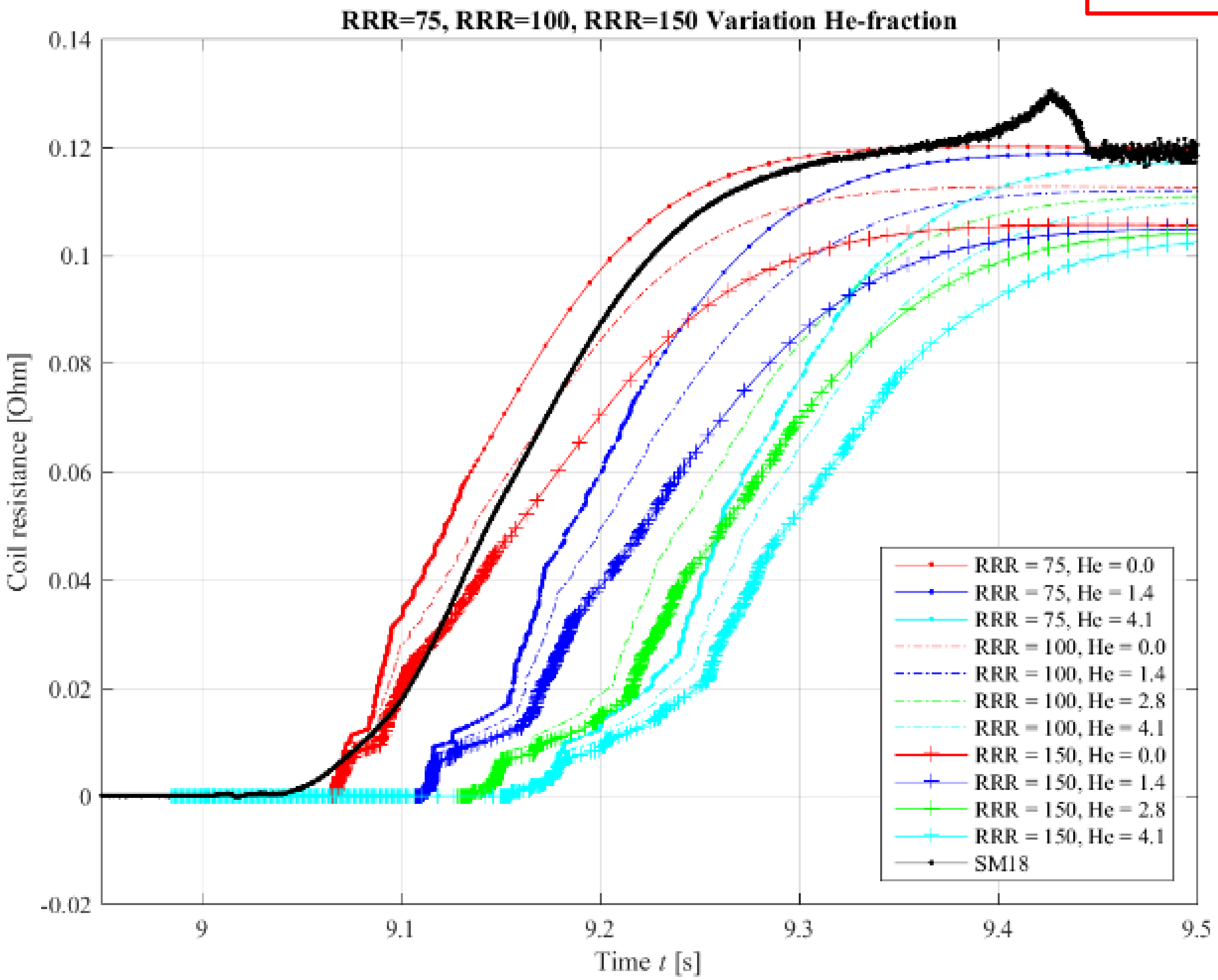
Check against other codes

Validate against test results

Validation against measurements

Current over time. Different RRR

Validation against test results


RRR=75, RRR=100, RRR=150 Variation He-fraction

Generate the model

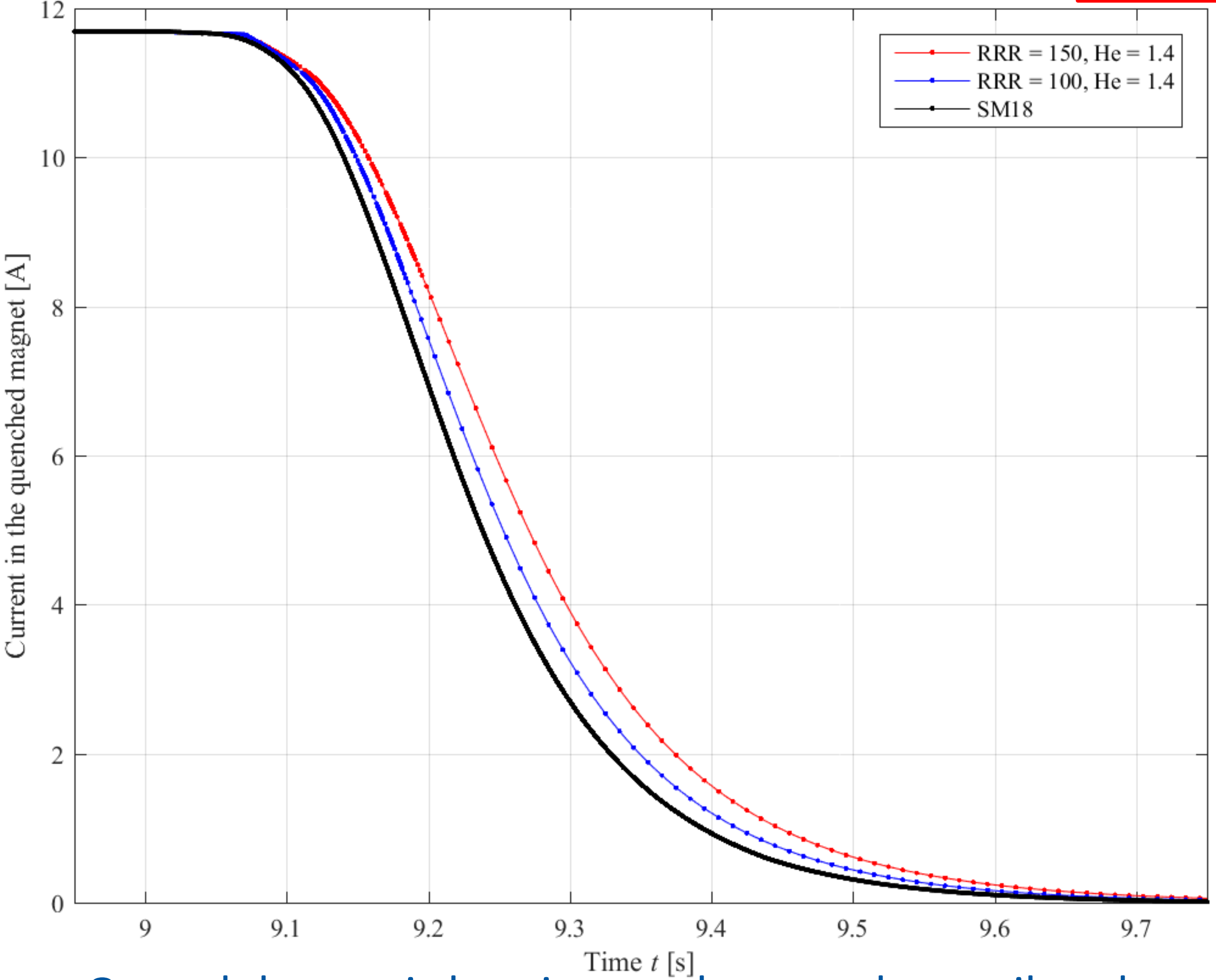
Check against other codes

Validate against test results

Validation against measurements

Current over time. Different RRR

Validation against test results



Generate the model

Check against other codes

Validate against test results

Quench heater is heating up the complete coil at the same time

Conclusion and Outlook

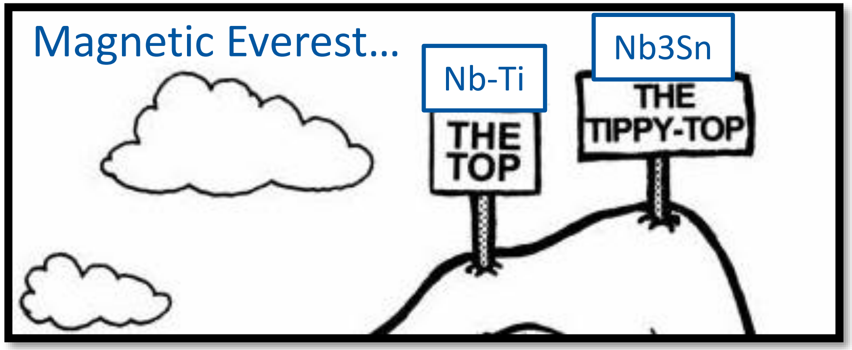
Conclusion:

- Cross-check of electro-magnet model with other programs: ROXIE
- Cross-check of electro-thermal model with other programs: LEDET
- Validation against the test results from SM18 in progress

Next steps:

- Finish the circuit in PSPICE
- Combine the LEDET magnet model and PSPICE circuit model in COSIM
- Prepare documentation

Thank you for your attention!



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[2] “Accelerator Magnet Quench Heater Technology and Quality Control Tests for the LHC High Luminosity Upgrade”. Bachelor Thesis. F. Meuter. Geneva, 02.2017.

[3] “Protection-related studies on HL-LHC Nb3Sn–based magnets in SM18”. Presentation. M. Mentink, E. Ravaioli. Geneva, 08.2018.

[4] “SIGMA Documentation”. Geneva, 08.2018.

[5] “CLIQ: A new quench protection technology for superconducting magnets”. Ph.D. Thesis. E. Ravaioli. Enschede, 2015.

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