Finite Element Analysis of Magneto-Thermal Transient Effects in Superconducting Accelerator Magnets

Master Thesis in Advanced Mechanical Engineering
Lodz University of Technology

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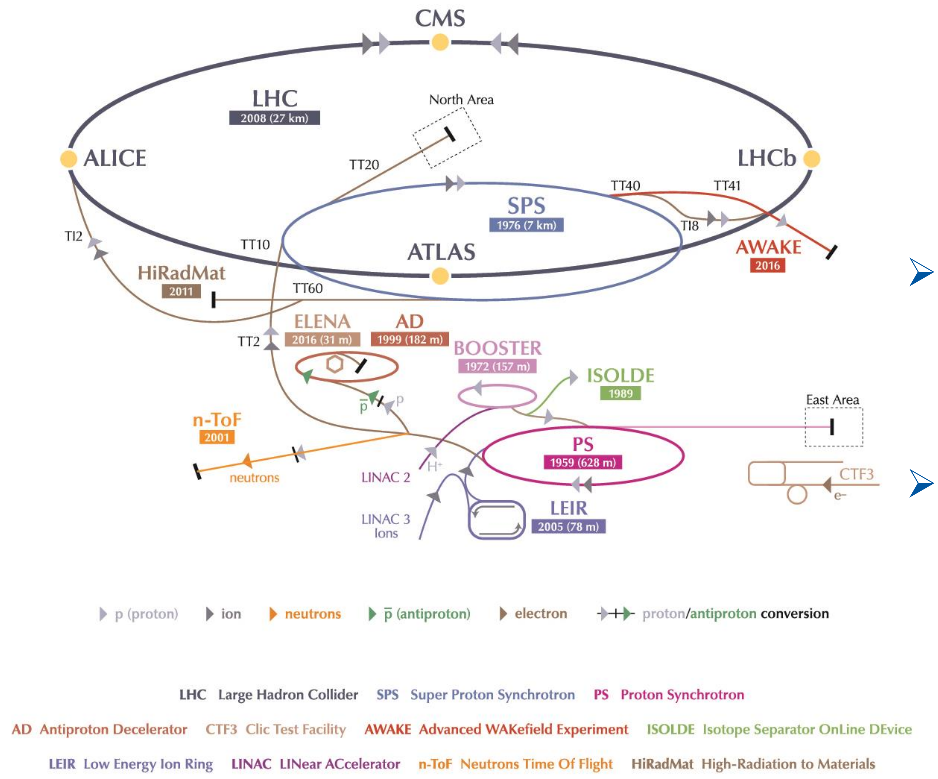
About CERN



- **European Organisation for Nuclear Research (CERN)** – aims at performing research in fundamental particle physics.
- **Large Hadron Collider (LHC)** – is the largest component of the CERN accelerator complex.

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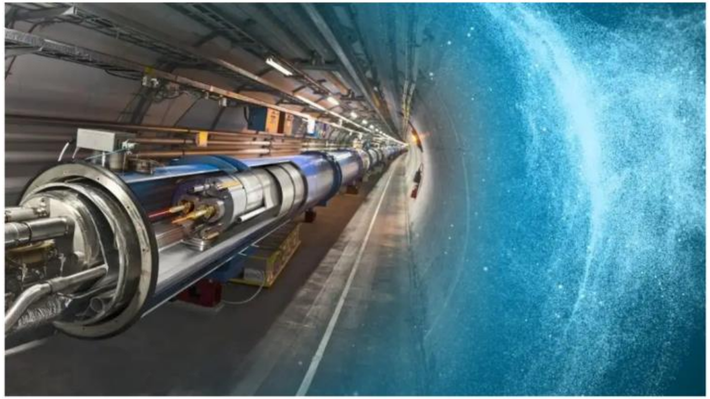
About LHC



- Composed of multiple types of superconducting magnets operating in the temperature range of $T \in (1.9\,;4.2)$ K.
- Currently upgraded to High-Luminosity LHC aiming to increase the frequency of particle collisions.

→Superconducting magnets are protected against uncontrolled quench*.

→Evolution of quench parameters (hot-spot temperature, peak voltage-to-ground) predicted with numerical methods.

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*Transition from the superconducting to the normal conducting state.

Challenges in Proposed Quench Simulations

Solution of the heat balance PDE with a heat source → $$\gamma c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial \vec{r}}[k \frac{\partial T}{\partial \vec{r}}] + q_v$$

1. High non-linearities of thermo-electric material properties
   (e.g. $k_{Cu} \in (250, 1700)$ W/mK for $T \in (1.9, 20)$ K)

2. High temperature differences in occurrence of quench
   (tens of Kelvins)

→ 3D FEM modelling is impractical (dense mesh, small time step)
→ computation time of several weeks for a full-scale coil

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Aim of Thesis and Research Questions

Aim of work:

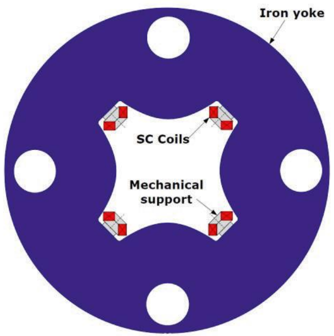
Simulate the discharge of the skew quadrupole and validate the results against available measurements.

Research questions:

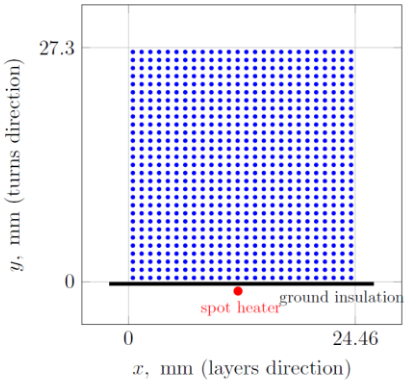
1. Can a multidimensional quench analysis be efficient numerically?
2. Can a computationally efficient simulation be conducted in ANSYS?

Skew Quadrupole – Geometry and Measurements

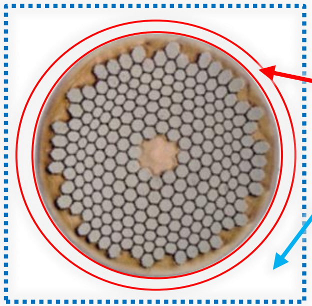
Magnet cross-section

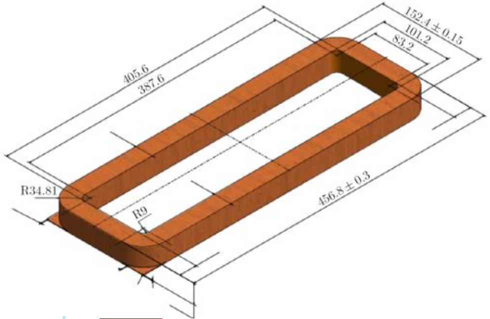


Coil cross-section



Strand cross-section (Cu+Nb-Ti)





Measurements

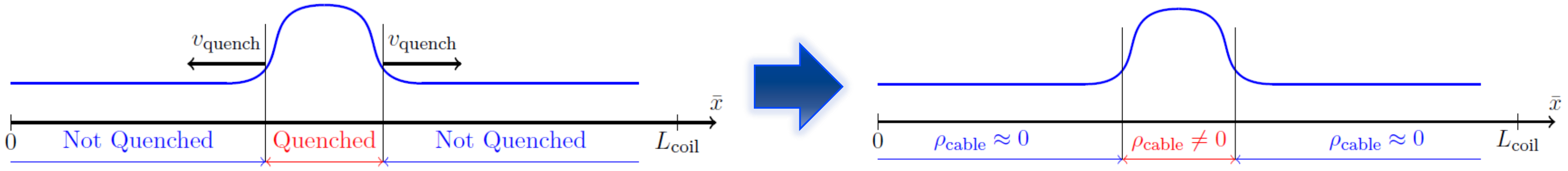
→ T_{bath} = 4.3 K

→ I_{init} = 86 A

→ Quench propagation must be analysed in an 812 metres long cable.

Computation Efficiency – Quench Velocity-Based Approach

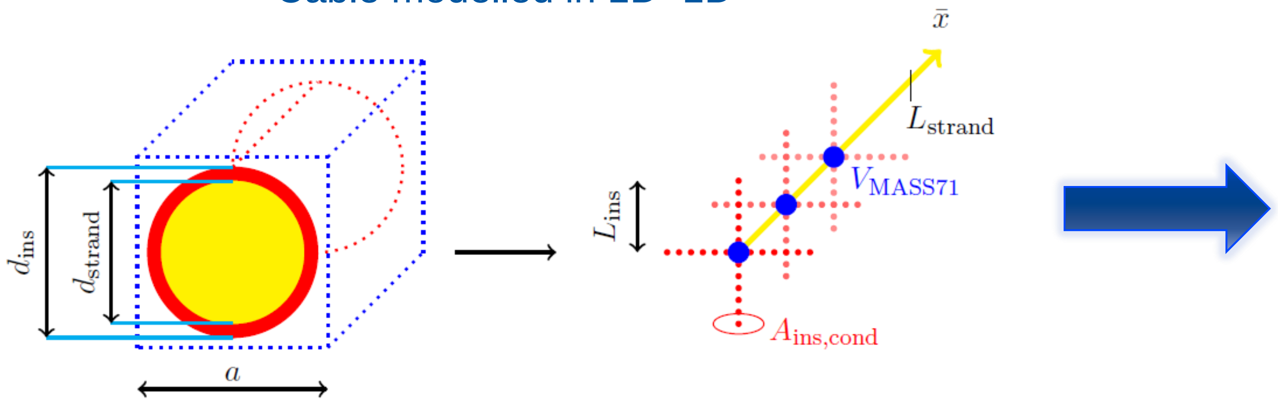
1. v_{quench} stabilises at constant *I* and *B* → calculated in advance in 1D numerical models
2. No need to accurately resolve the quench front → longitudinal mesh relaxed
3. Number of DOFs reduced → acceptable computation time
4. Quench solution approximated → error estimation required



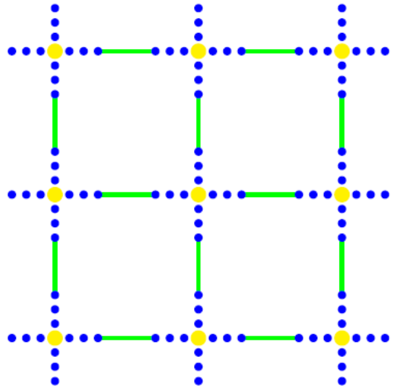
→ Algorithms implemented in Python

ANSYS Modelling – Skew Quadrupole

Cable modelled in 1D+1D



Insulation layers coupled thermally



ANSYS model: → longitudinal (quench velocity-based) + transverse heat conduction

→ strand material properties as *f(T, B)*

insulation material properties as *f(T)*

Analysis Workflow

Create a 2D magnetic map as a function of current.

↓

Create a quench velocity map as a function of current and magnetic field.

↓

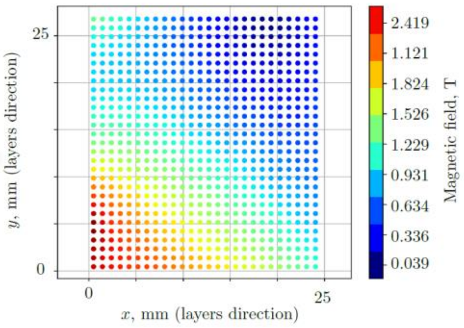
Find minimum propagation zone for the quench initiation.

↓

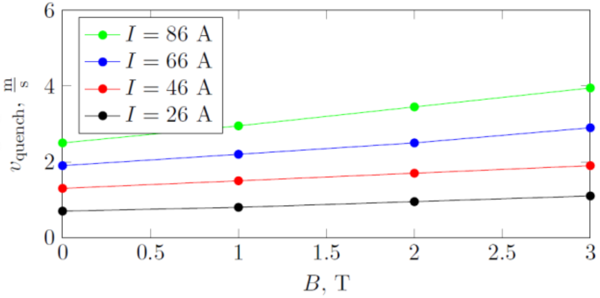
Conduct a multi-strand analysis of a high-order corrector.

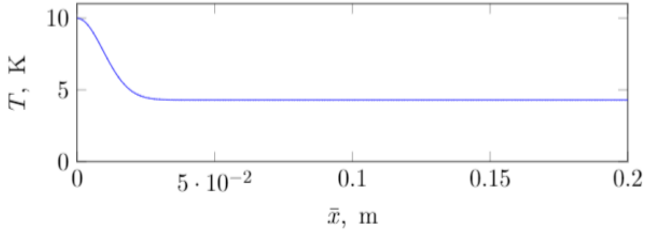
→ Three cases considered

u_{resin}	elements in coil
0.0	476 528
0.5	531 574
1.0	531 574



→Material properties are updated as the simulation continues.





→Both steps based on a standard analysis conducted with short 1D+1D models.

→E_{input} = 0.15 J

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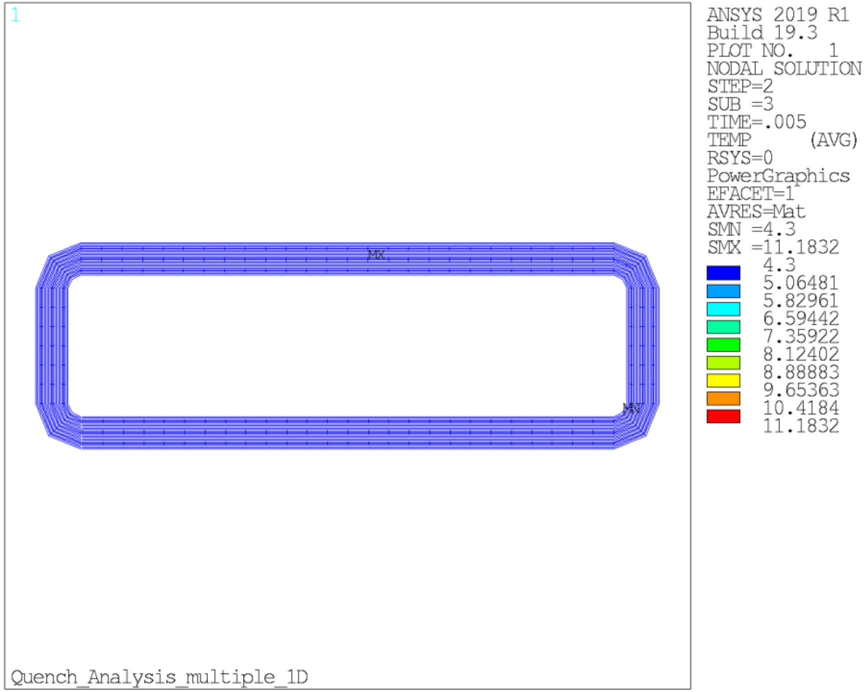
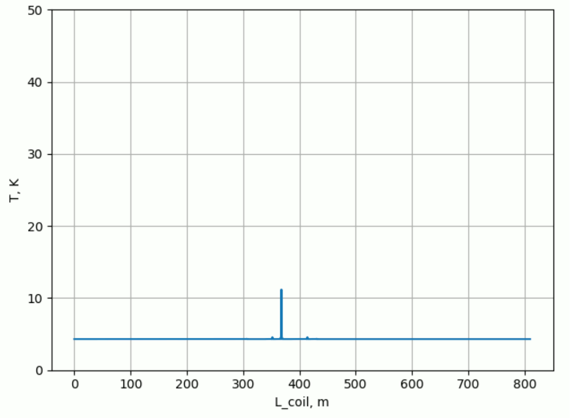
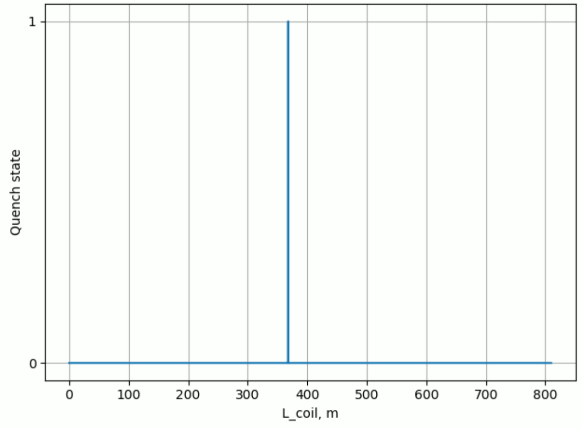
Results – Case $u_{resin} = 0$



Temperature distribution over time

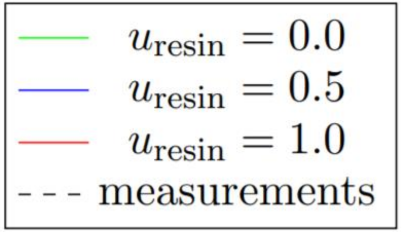


Quench propagation over time



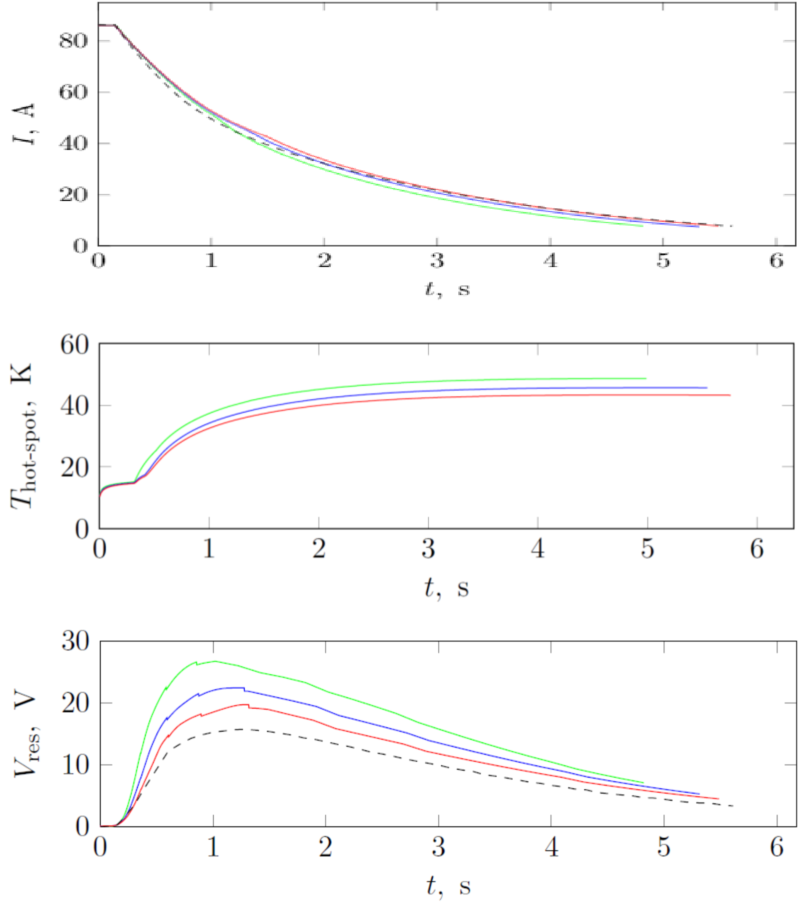
Results – All Cases

Legend



	u_{resin}=1.0	u_{resin}=0.5	u_{resin}=0.0
$T_{hot\text{-}spot}$, K	43.4	45.7	48.7
$E_{r,\ v\_quench}$	-13.5%	-13.5%	-13.5%
$T_{hot\text{-}spot,\ corr}$, K	**50.1**	**52.9**	**56.3**

	u_{resin}=1.0	u_{resin}=0.5	u_{resin}=0.0	measurements
V_{res}, V	19.8	22.5	26.8	15.8
$E_{r,\ v\_quench}$	-20%	-20%	-20%	-
$V_{res,\ corr}$, V	**24.7**	**28.1**	**33.6**	**-**
$E_{r,\ meas}$	**56%**	**78%**	**113%**	**-**



Summary

1. $u_{resin} = 0$ → highest hot-spot temperature
2. Computation time of ≈ 1 week
3. Overestimated temperature in the model due to:

   → Homogenisation of insulation and epoxy resin

   → Coarse insulation layer

   → Helium cooling neglected

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*The analysis was performed on the following calculation unit: Intel(R) Xeon(R) CPU E5-2667 V4 @ 3.20 GHz (2 processors) with RAM 128 GB.

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