COMSOL CONFERENCE 2016 MUNICH

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

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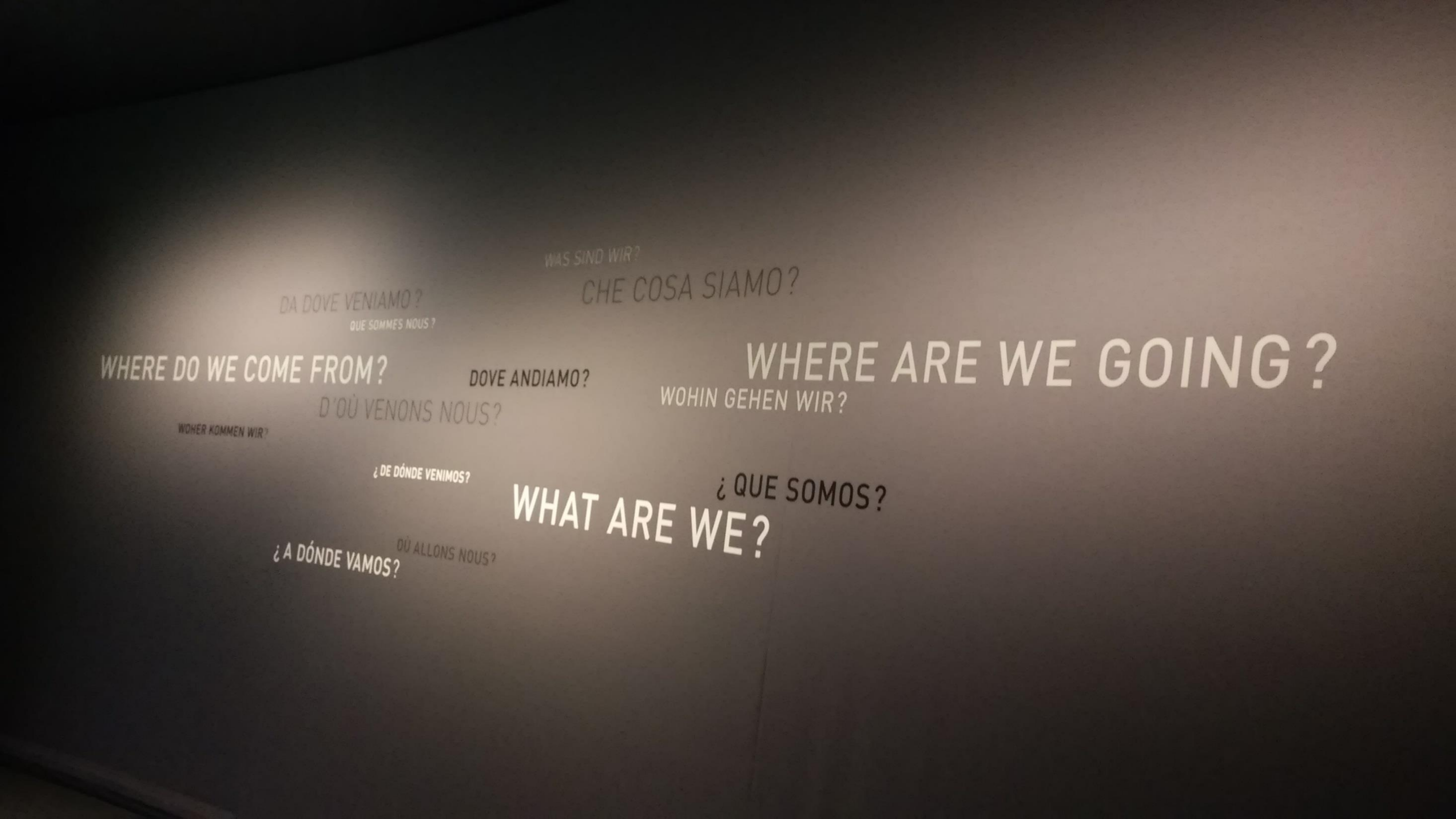
THE STEAM

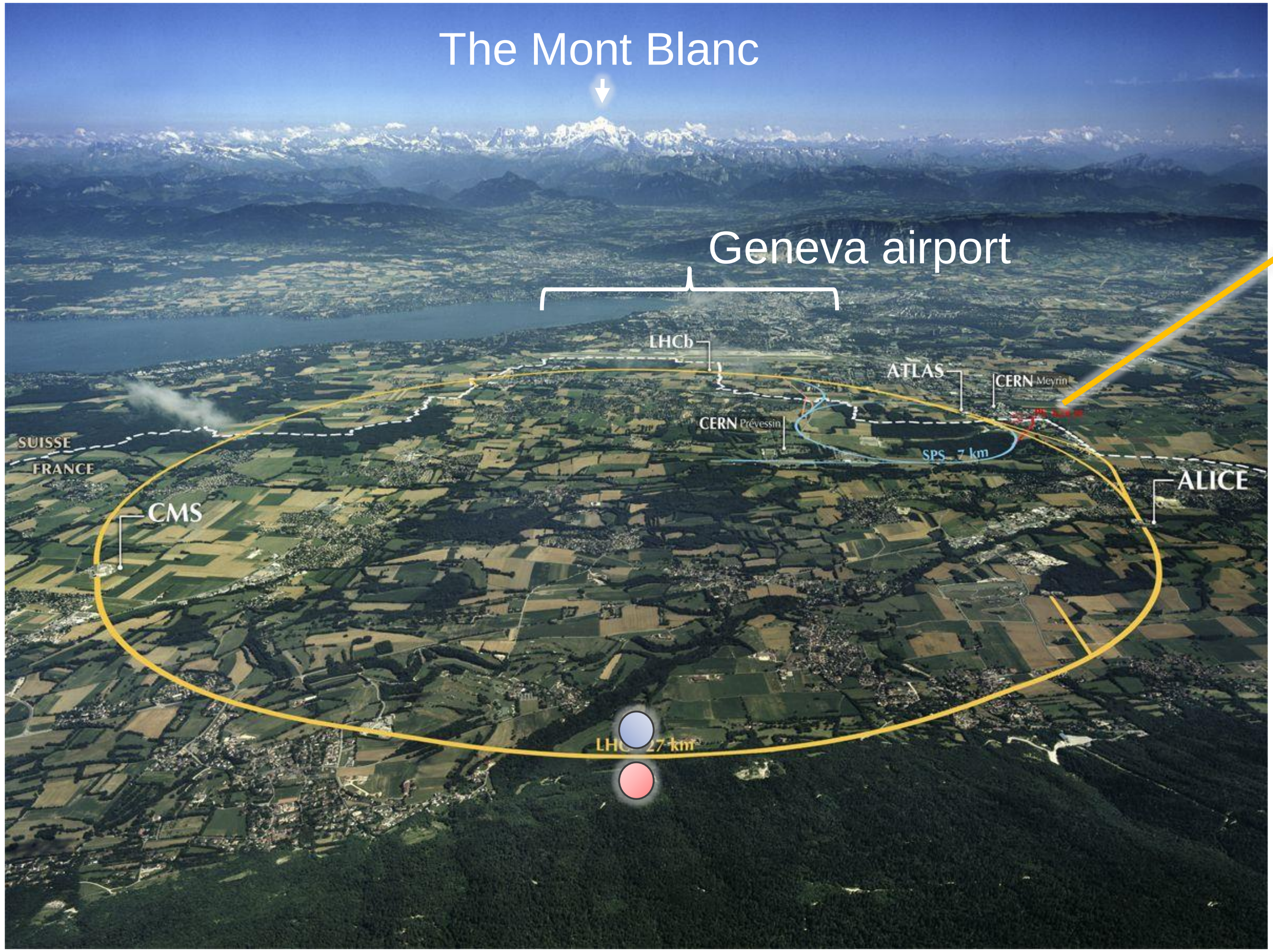
1) CERN 2) Lodz University of Technology 3) TECHNISCHE UNIVERSITÄT DARMSTADT

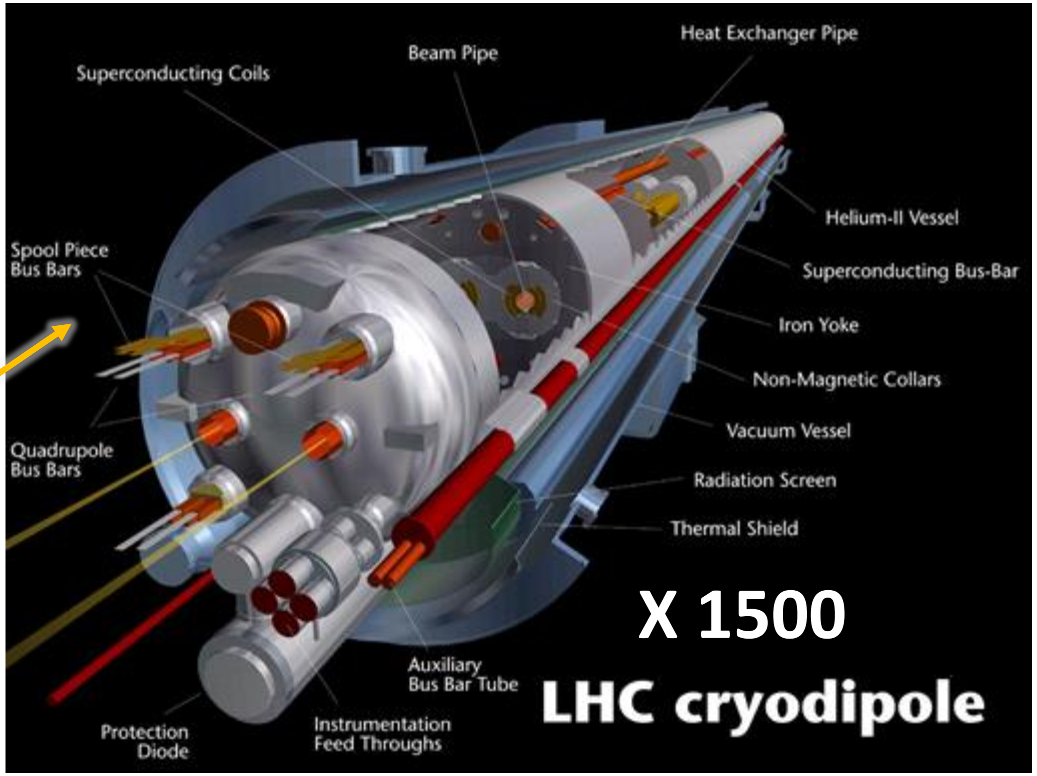
Special thanks to Dr. Friedel and COMSOL Switzerland

lorenzo.borot @ cern.ch


WAS SIND WIR?
CHE COSA SIAMO?
DA DOVE VENIAMO?
QUE SOMMES NOUS?
WHERE DO WE COME FROM?
DOVE ANDIAMO?
WHERE ARE WE GOING?
WOHIN GEHEN WIR?
D'OÙ VENONS NOUS?
WOHER KOMMEN WIR?
¿ DE DÓNDE VENIMOS?
¿ QUE SOMOS?
WHAT ARE WE?
OÙ ALLONS NOUS?
¿ A DÓNDE VAMOS?

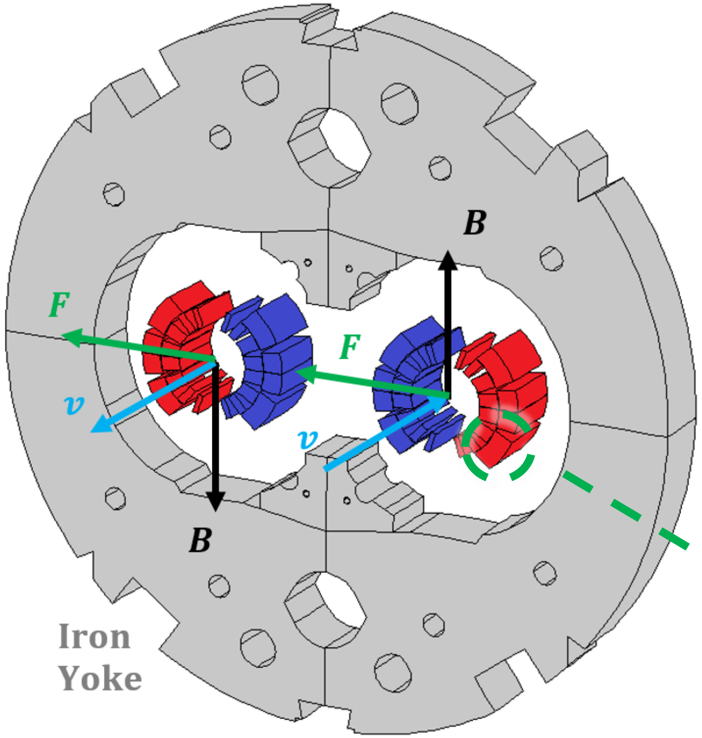
LHC – The Large Hadron Collider

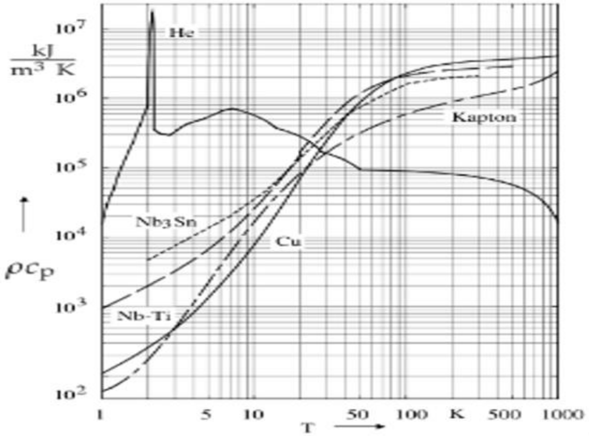


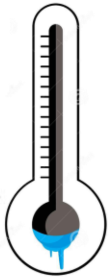


- 15 m
- 30 ton
- 8.33 T
- 1.9 K
- 12 kA

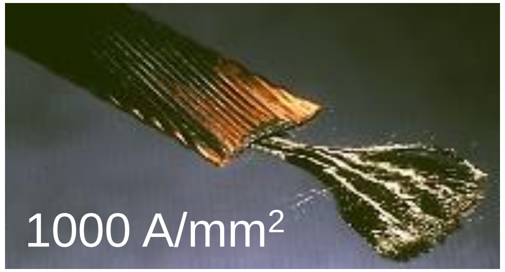
The 8.33 Tesla, Twin-Aperture, LHC Dipole Magnet

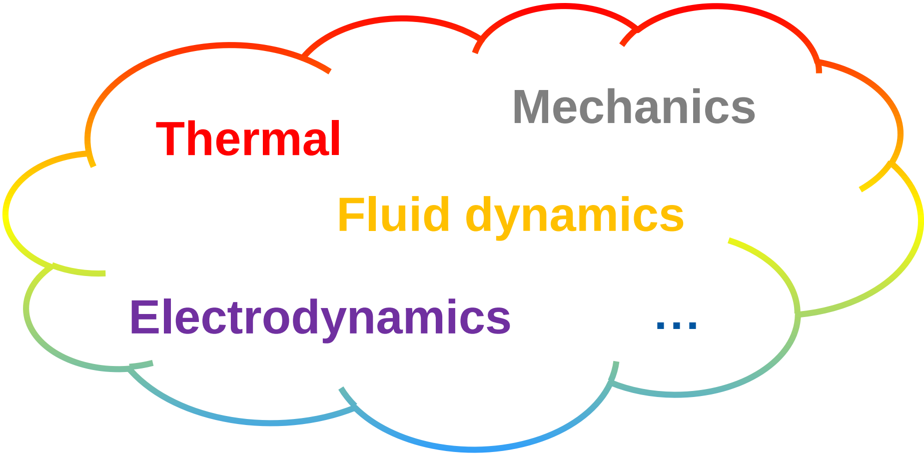






Liquid He @1.9 K





Multi-Physics
Multi-Rate
Multi-Scale

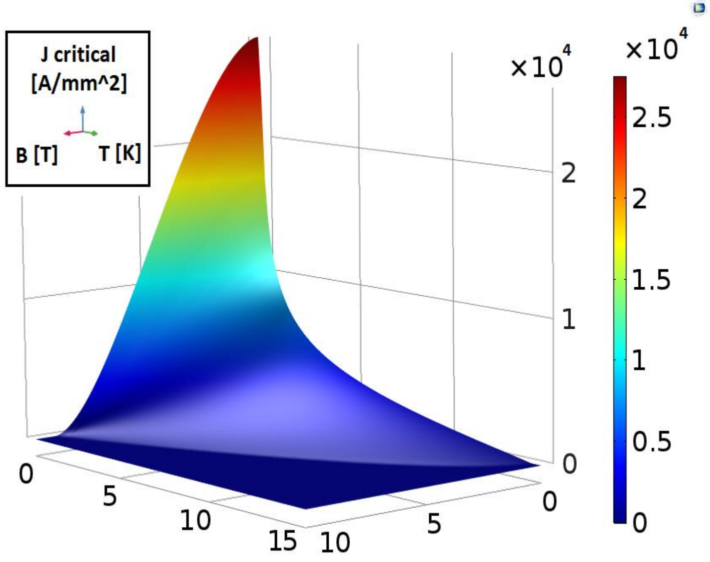
Why Do We Need Simulations

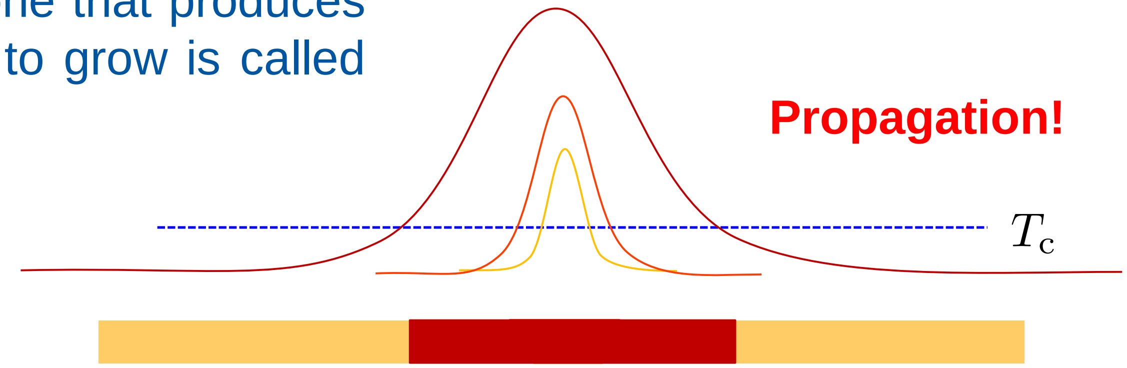
Superconductivity is related to the material's Critical Surface (J [A/mm^2], B [T], T [K]).

If the working point moves beyond the surface, it triggers a local transition from the superconducting to the normal conducing state.

A resistive zone that produces enough heat to grow is called **Quench.**

Quenches cannot be avoided.





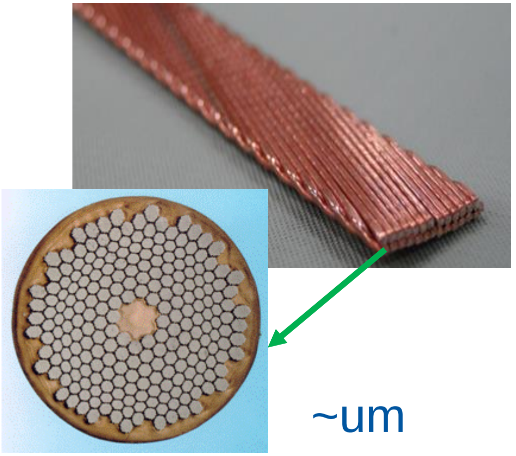
The stored energy in the magnet is released as **Ohmic losses:**

7 MJ

20 tons truck @ 95 km/h

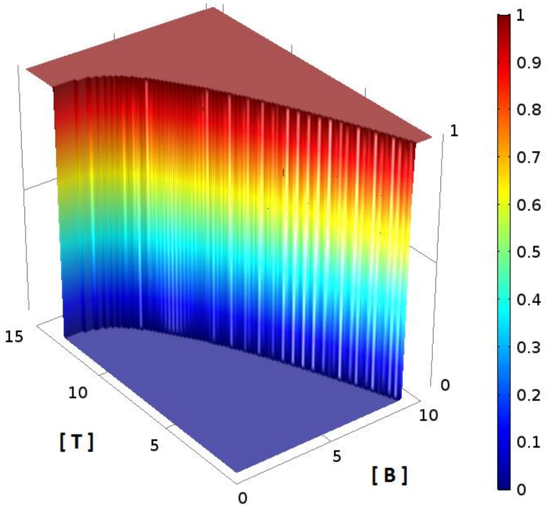
Simulations support the prevention of disruptions!

Modelling: Challenges



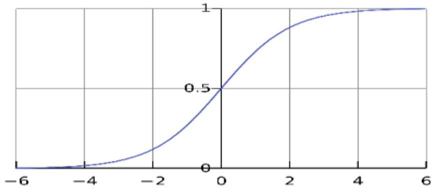
Magnetic formulation

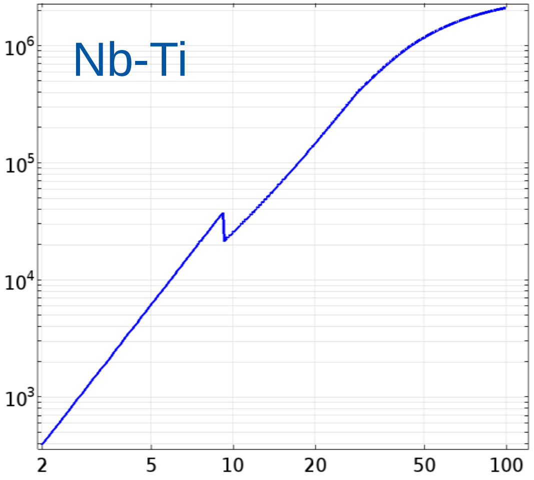
- Complex geometry for both, cable and strand
- Eddy-currents
- Magnetization
- Hysteresis



Quench transition

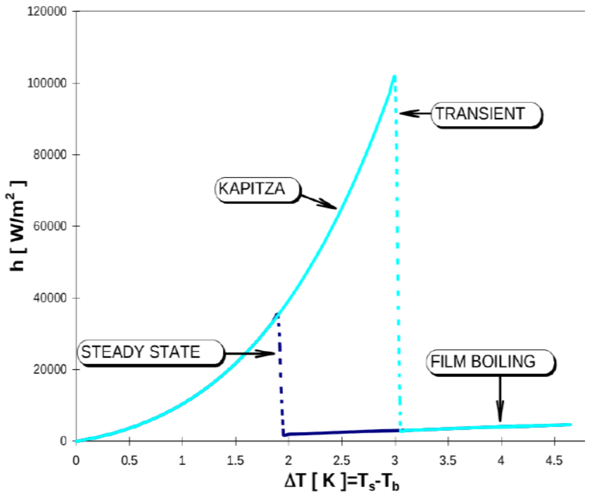
- Discontinuity
- Numerical instability
- Need for smoothing functions (Sigmoids)





Material properties

- Very small heat capacity @ 1.9 K
- Variation of several orders of magnitude within 100 K
- Non-linearity
- Discontinuities

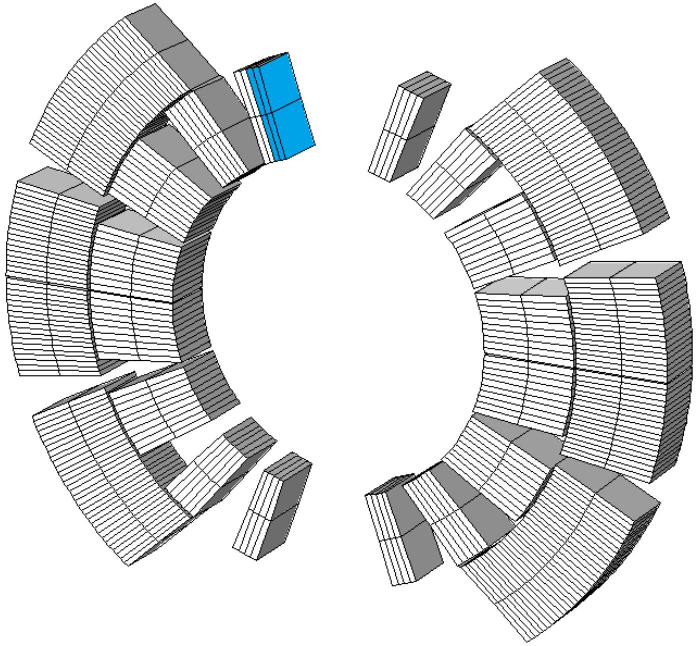


Superfluid Helium

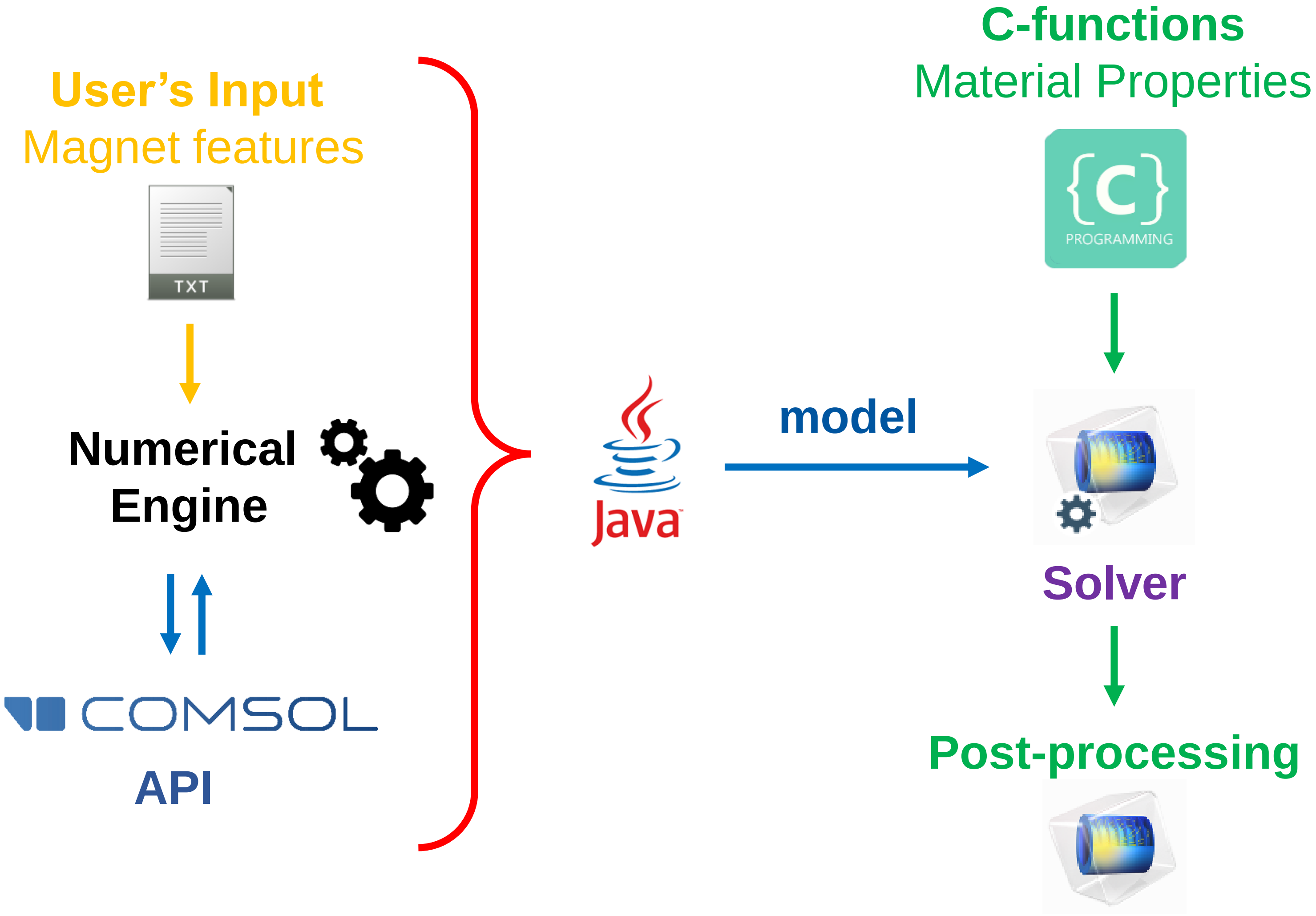
- four different conduction regimes within four Kelvin
- Helium phase transition

- **Not modelled yet (under investigation)**

Modelling - Construction



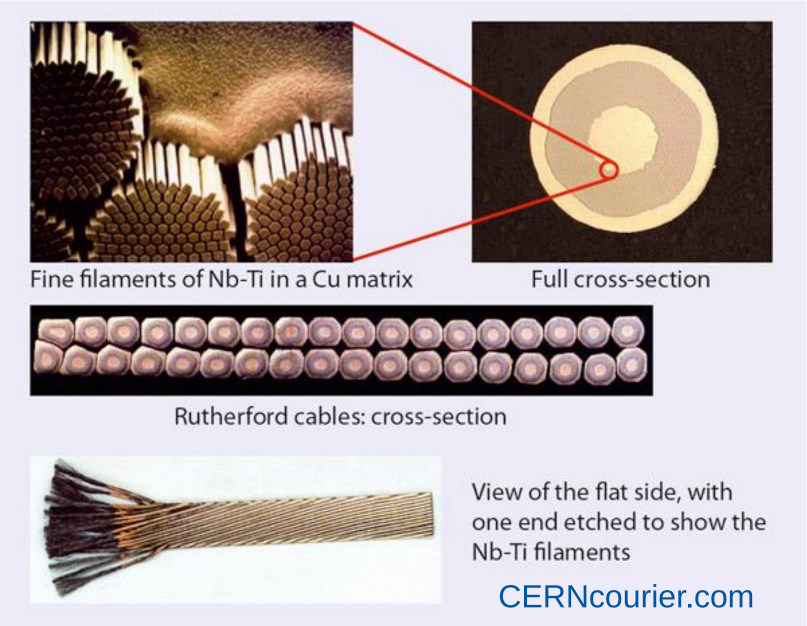
- 320 domains (cable cross sections)
- Domain-dependent equations
- GUI workflow risky, slow, error-prone
- **Automation as solution**



Modelling – Eddy-Currents

How to discretize a superconducting cable?

~100 um



If the eddy-currents paths are known a priori, The equivalent magnetization effect can be directly related to the change of magnetic flux density

Faraday-Lenz + Ampere-Maxwell

Wilson / Verweij equivalent magnetization

- Formulation

$$\mu_0 \mu_r \vec{M}_{eddy} = \tau_{eq} \frac{\partial \vec{B}}{\partial t}$$

- Constitutive law

$$\vec{B} = \mu_0 \mu_r \left(\vec{H} + \vec{M}_{eddy} \right)$$

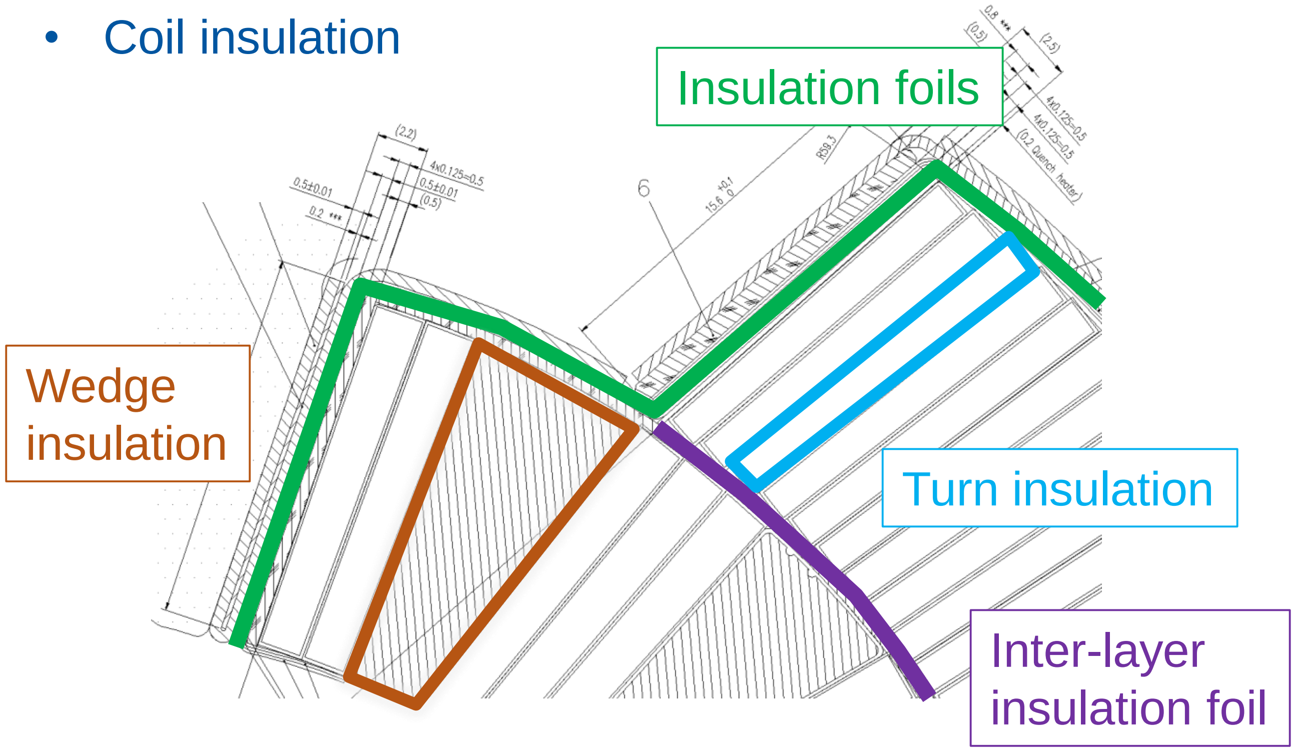
- Ampere-Maxwell Law

$$\sigma \frac{\partial \vec{A}}{\partial t} \longrightarrow \nabla \times \vec{M}_{eddy}$$

Eddy-currents' paths don't have to be resolved anymore!

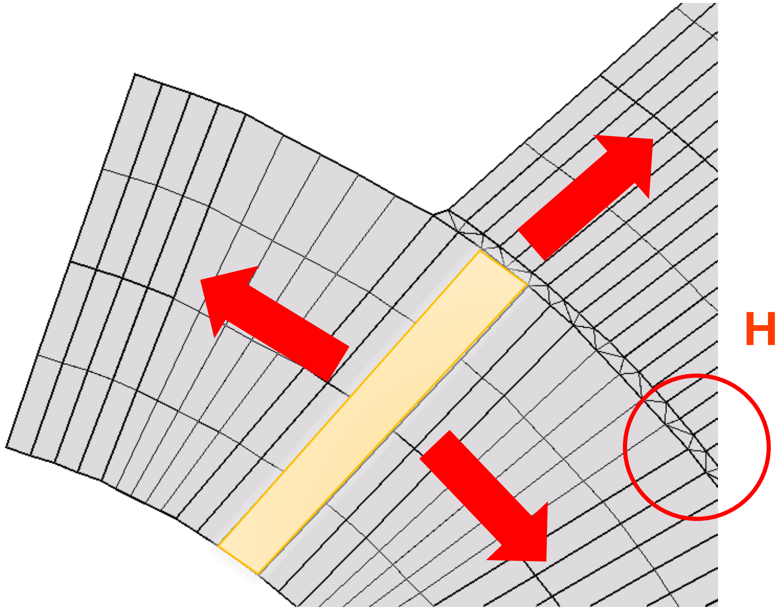
Modelling – Thermal Balance

- Coil insulation



- ➢ Multi-layer insulation, up to 7 layers
- ➢ Multi-material insulation
- ➢ Layer orientation (upside-downside)
- ➢ Interfaces among insulation layers

An accurate insulation modelling is **critical** for the simulation of a quench propagation



How to Mesh?

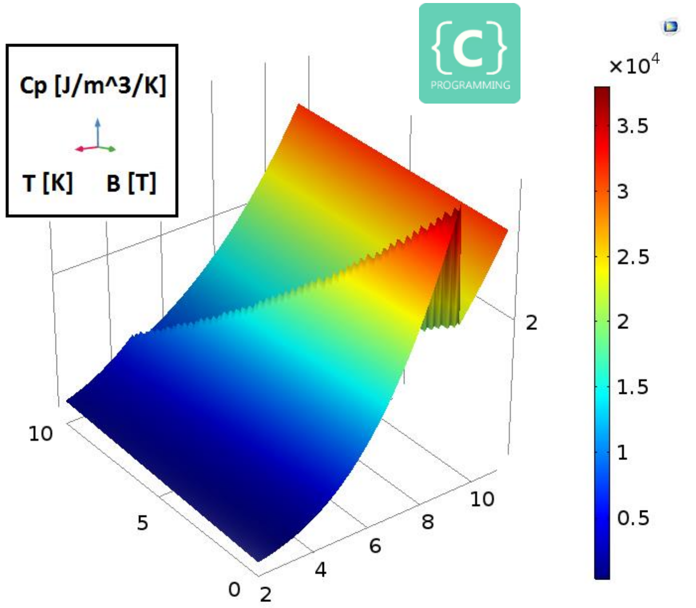
Heat mapping?

Automatic insulation handling?

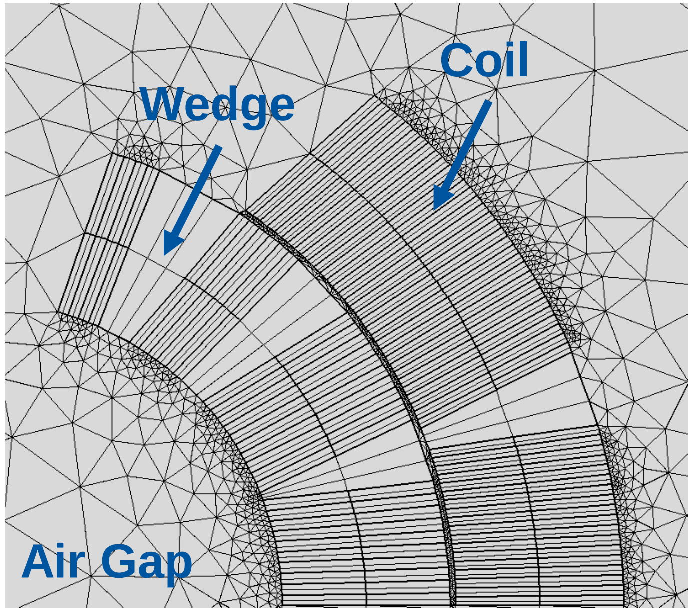
- ➢ Homogenized insulation
- ➢ Combination of 1-D *General layers* and 2-D explicit domains
- ➢ Manual, error-prone insulation assignment

Modelling - Details

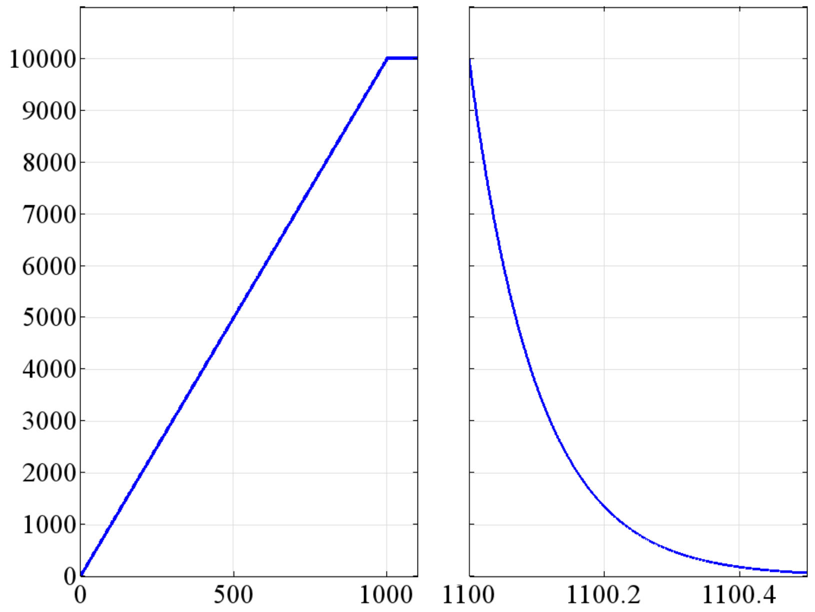
Definitions:
Wide use of external C-functions, performant and flexible enough for the non-linear material properties



Mesh:
Combination of structured and unstructured elements, to minimize the number of nodes

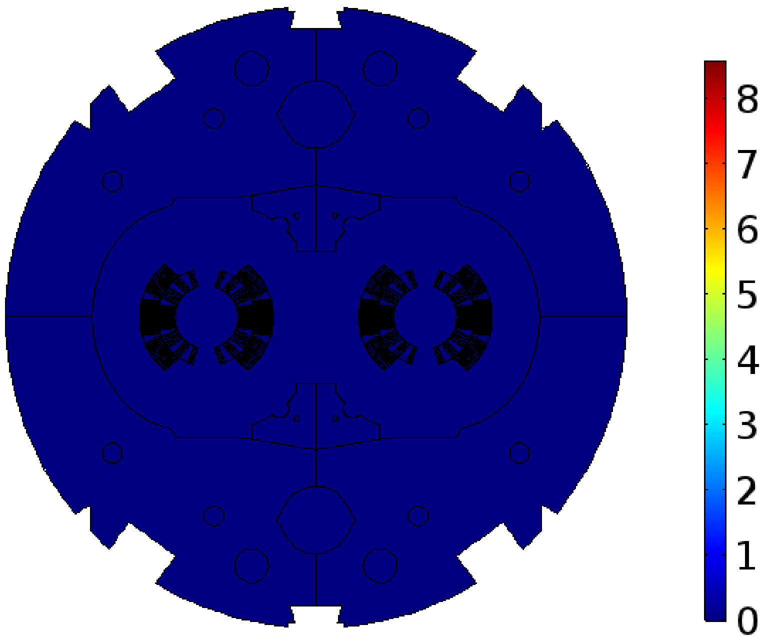


Time dependent study:
Two concatenated studies, linear ramp-up and exponential decay of the magnet's current

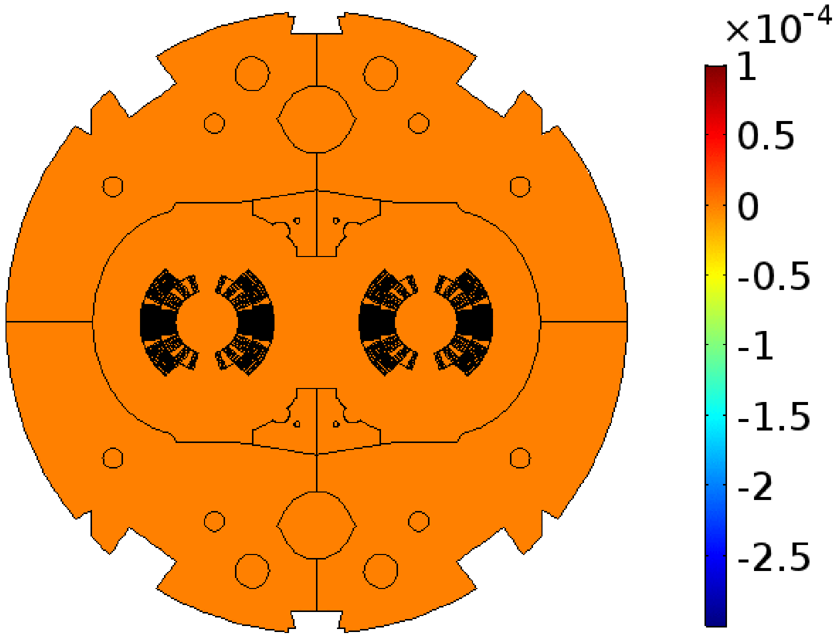


Results – Magnetic field

Magnetic flux density [T]



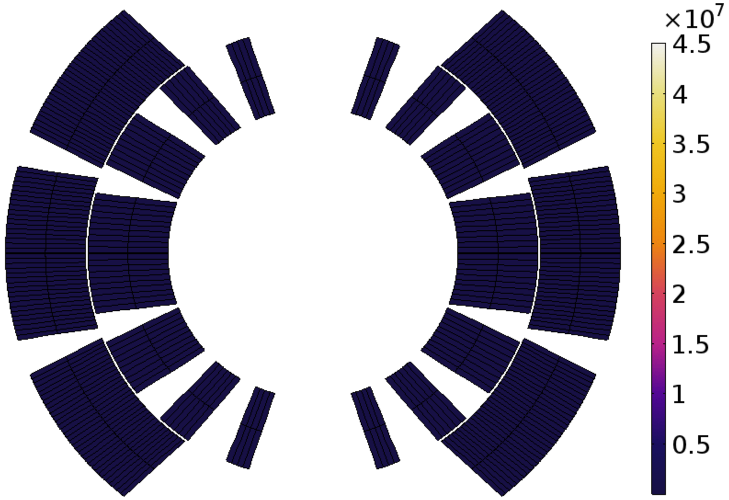
Eddy-currents equivalent magnetization [A/m]



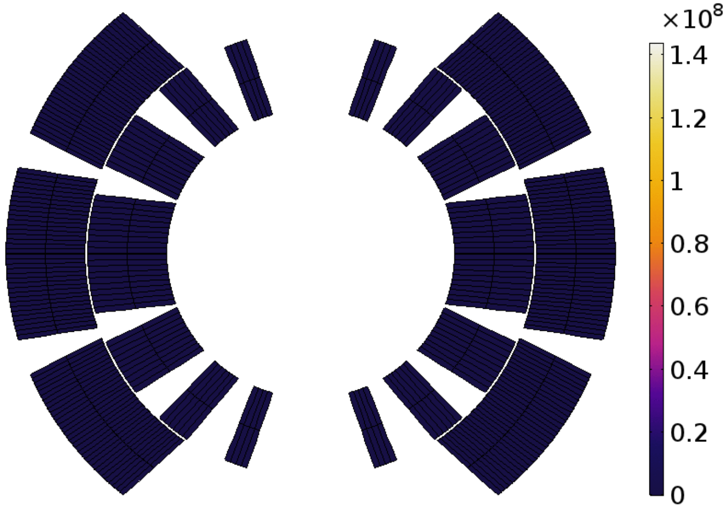
- Linear current ramp-up: of 100 A/s, up to 11.85 kA

Results – Heat Balance

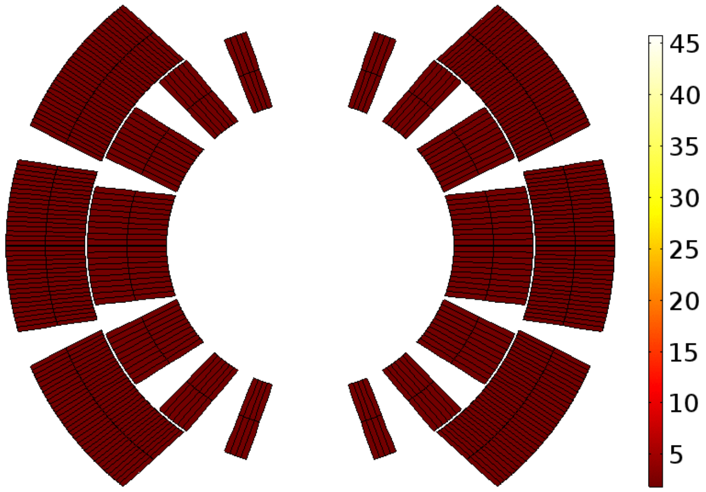
Eddy-currents losses [W/m^3]



Ohmic losses [W/m^3]



Temperature [K]

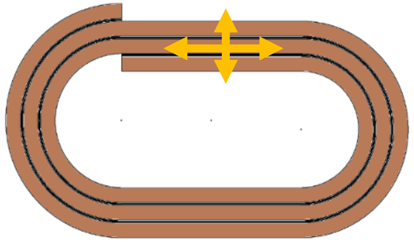


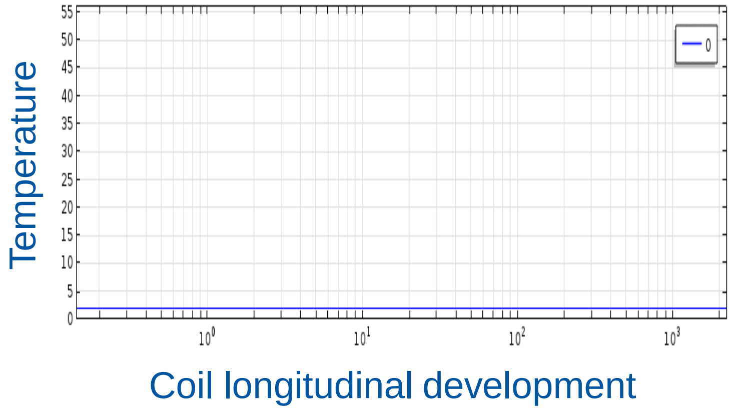
Conclusions and Outlook

- ✓ The complexity of the model construction is handled via a dedicated Java workflow, based on the COMSOL API.
- ✓ An equivalent magnetization model accounts for the eddy-currents in the magnet's coil.
- ✓ Highly non-linear material properties are managed via external C-functions.
- ✓ Structured-unstructured mesh coupling allows to drastically reduce the number of nodes.

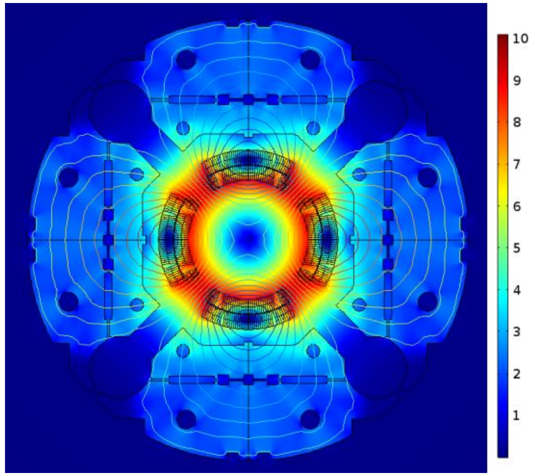
The electro-thermal model for the LHC Main Dipole has been developed, and the related time domain transient has been investigated.

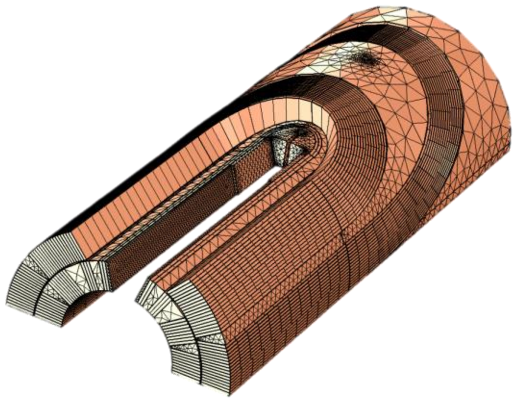
- ➢ 1-D: Quench initiation and propagation, both, longitudinally and from turn to turn





- ➢ 2-D: New magnet designs
- ➢ 3-D: Electro-thermal





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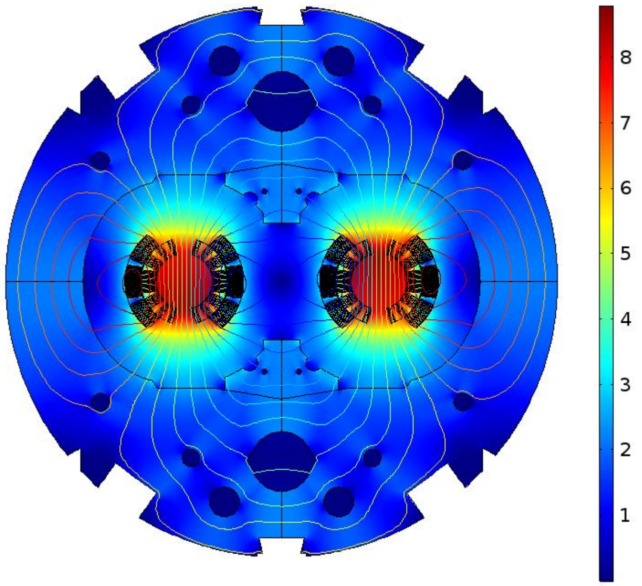
Annexess

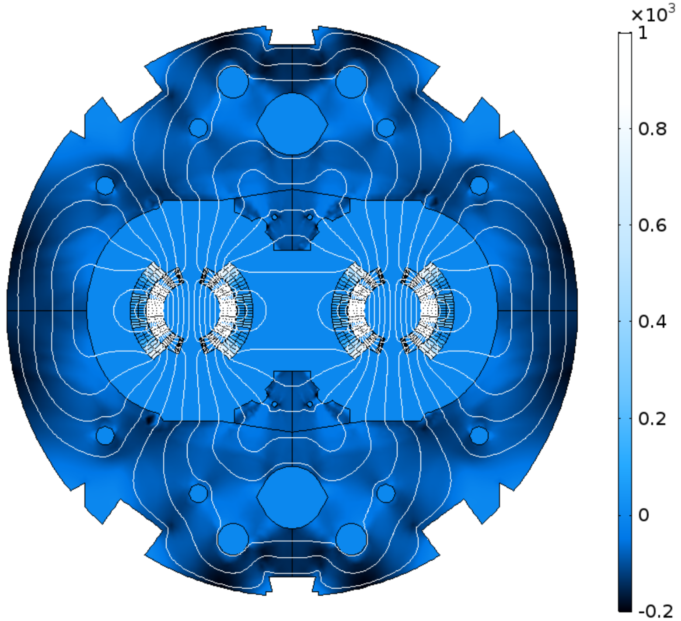
Results – Magnetic field

Magnetic flux density [T]



- nominal current

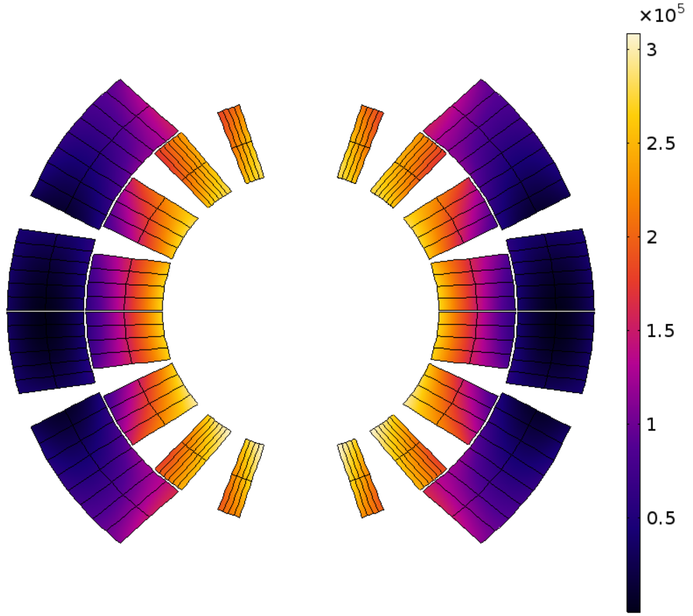
Eddy-currents equivalent magnetization [A/m]



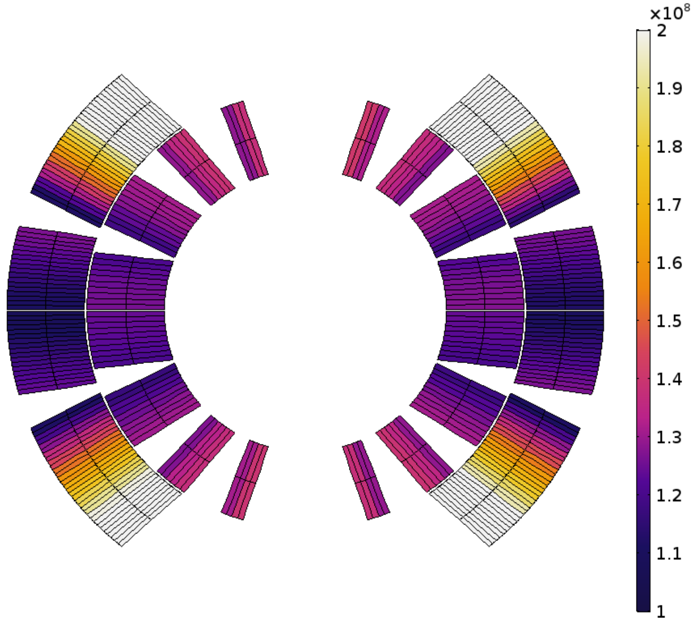
- Linear ramp-up of 100 A/s
- 8 kA

Results – Heat Balance

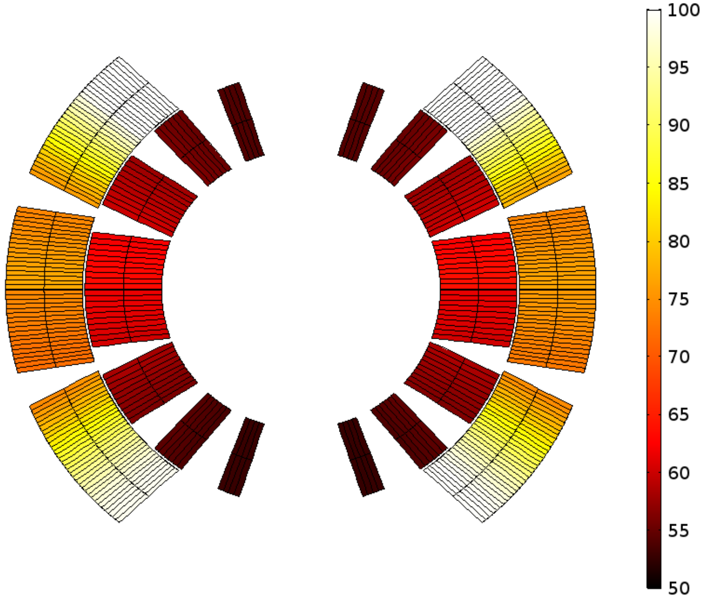
Eddy-currents losses [W/m³]



Ohmic losses [W/m³]



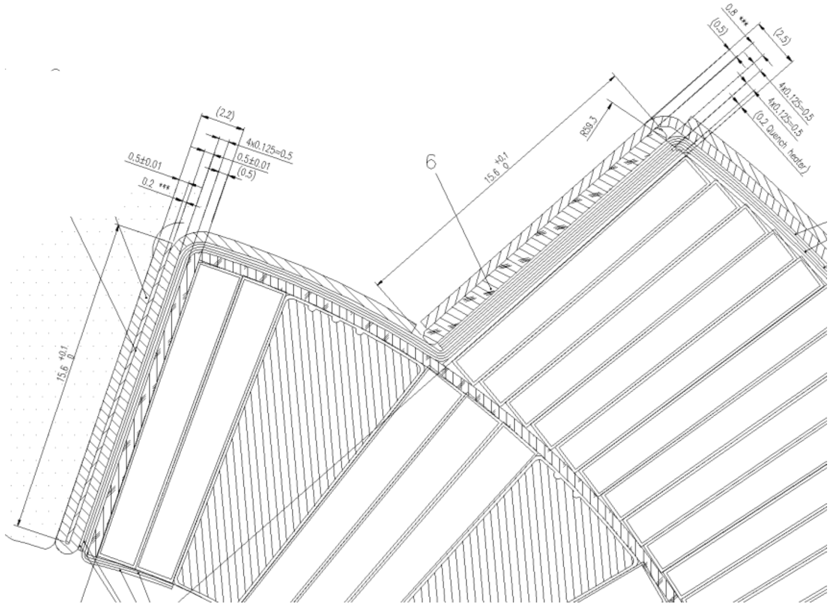
Temperature [K]



- Three orders of magnitude higher than the eddy-currents losses

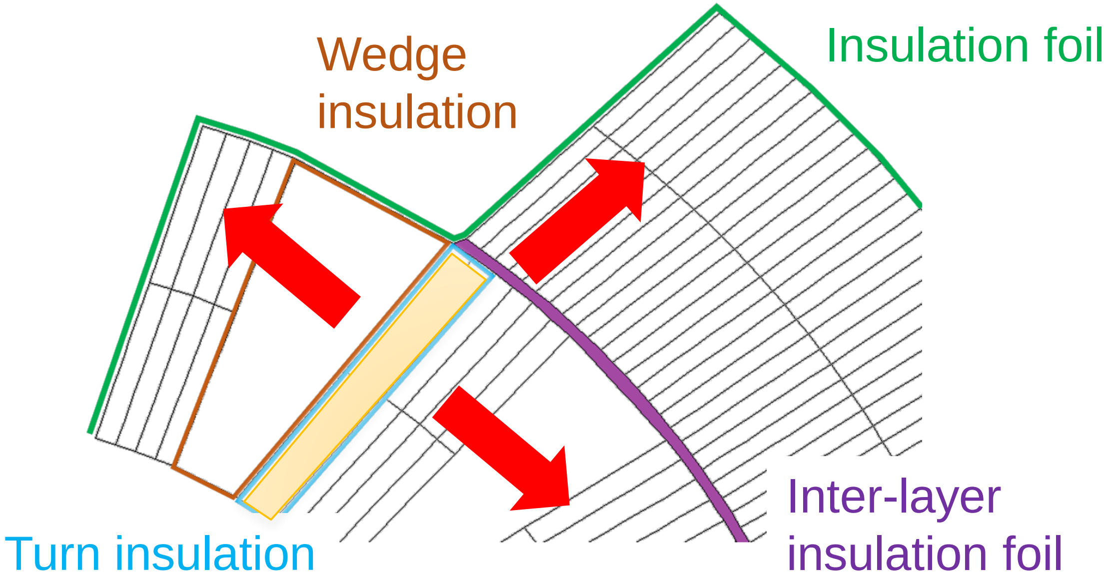
Modelling – Thermal Balance

Coil insulation



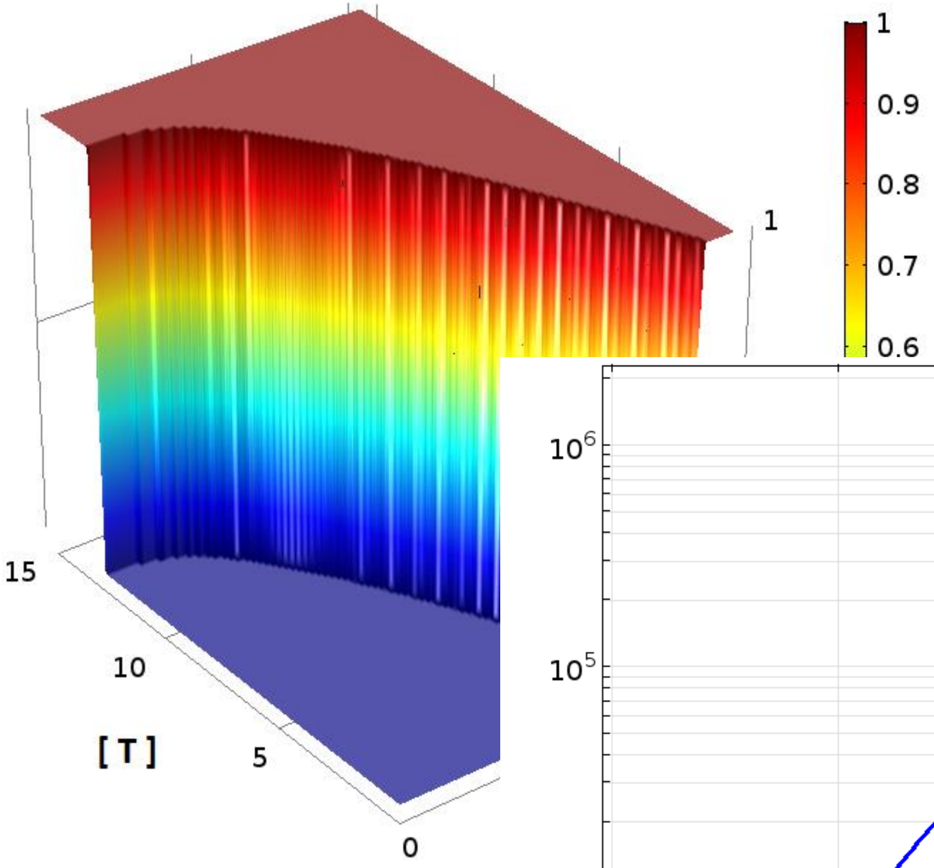
- Multi-layer insulation, up to 7 layers
- Multi-material
- Layer orientation (upside-downside)

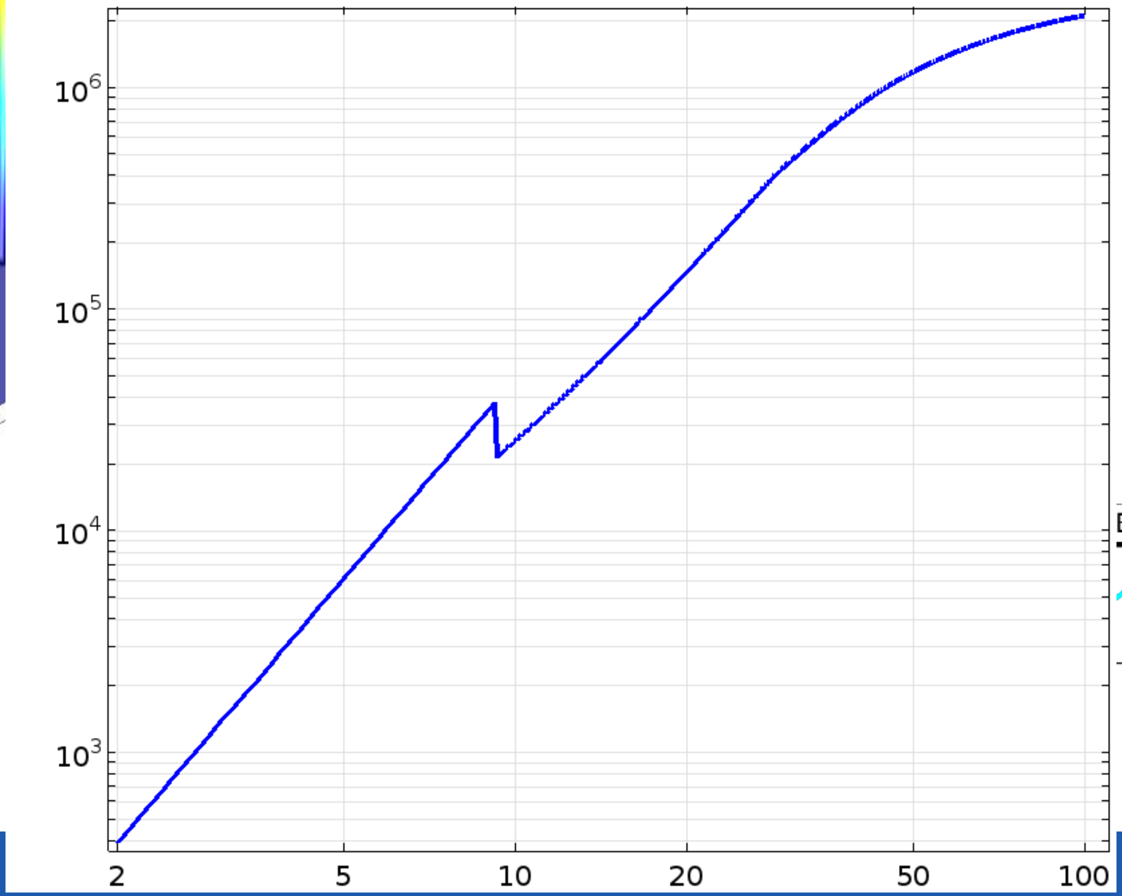
An accurate insulation modelling is **critical** for the simulation of a quench propagation

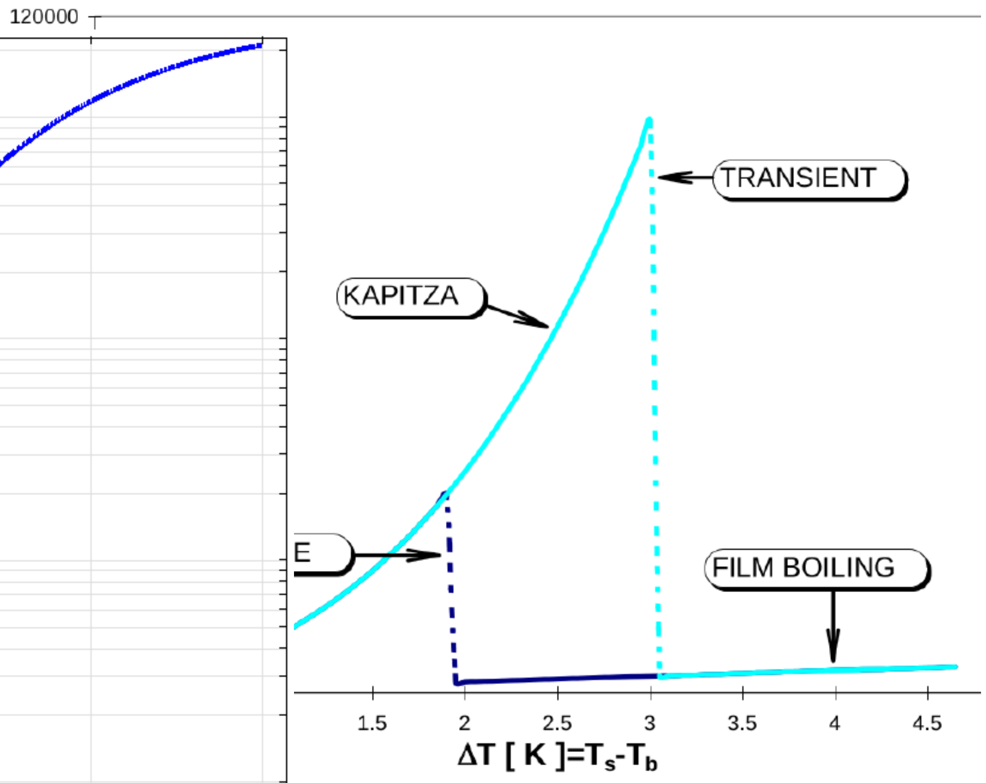


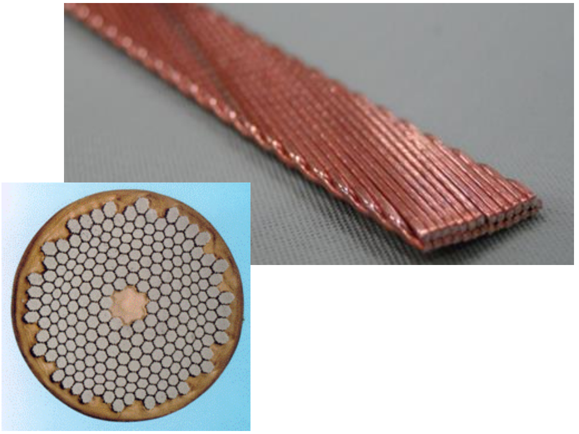
- Homogenized insulation
- Combination of 1-D *General layers* and 2-D explicit domains
- Manual, error prone assignment to boundaries

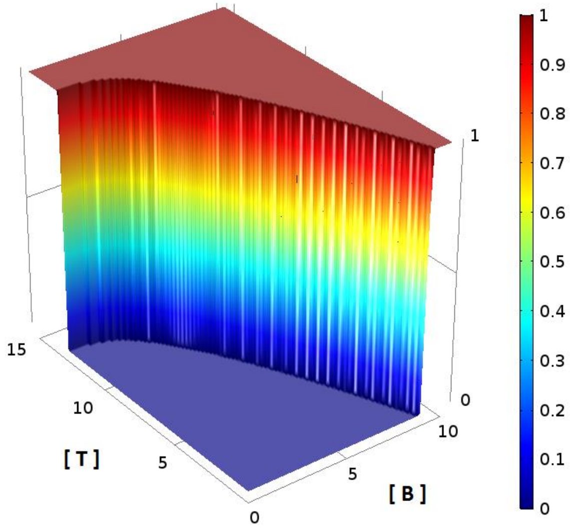
Physics of Superfluid Helium

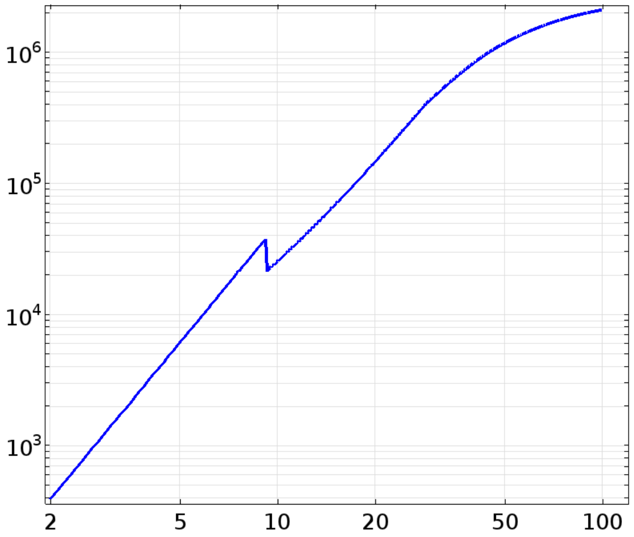


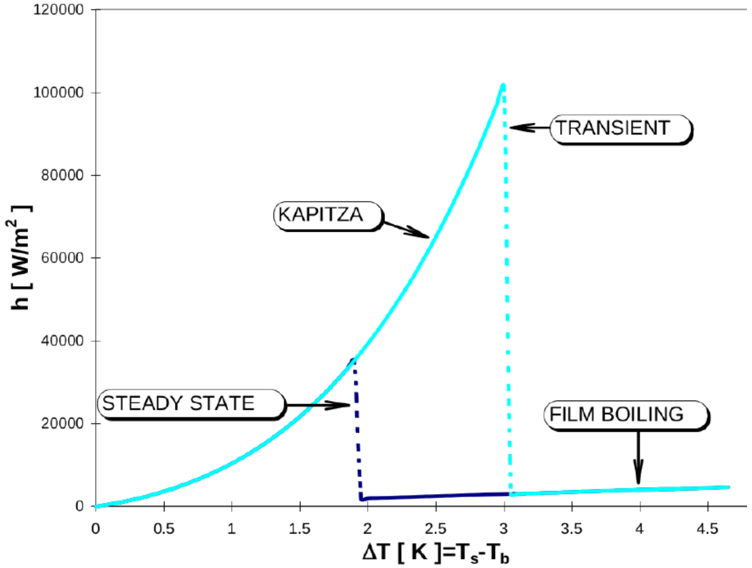







1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
15
10
5
0
[T]
1
0
10
5
[B]


10^6
10^5
10^4
10^3
2
5
10
20
50
100


120000
100000
80000
60000
40000
20000
0
h [W/m^2]
TRANSIENT
KAPITZA
STEADY STATE
FILM BOILING
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
ΔT [K]=T_s-T_b

Some suggestions:

Slide 1: Maybe add STEAM logo
Slide 2: add (or replace the pictures of the detectors) a 3D pictures of a 15 m long dipole, 30 ton, 8 T, 1.9 K, 12 kA
Slide 3: note that this is 2-D, usually sufficient.
Slide 7: a fire is maybe a bit too much…

Maybe spent a few lines on heat transfer to helium (or otherwise put it in the outlook)

The names (wedge, outer, interlayer, halfturn) are not very clear

Slide 9, 10, 11: movies are nicer! **No Time**

Add a slide on difficulties in modelling (SC-n transition, phase transitions helium, very thin insulation layer, very low heat capacity, complicated cable/strand cross section, various dynamic effects such as coupling current and magnetization, hysteresis etc, initial quench propagation is 3D)

Take the occasion to also present the **problems in modelling**, not only show the good results…

Cheers,
Arjan