Possibilities of Finite Element Modelling for a Better Understanding of Heat Transfer in Rutherford-Type Cables

The use of COMSOL Multiphysics as an analysis tool for purely thermal sytems and coupled electro-thermal systems.

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Abstract

The results obtained with Finite Element models help to better understand the heat transfer mechanism in complex structures, like Nb-Ti Rutherford type cables. With FE models, it is possible to implement the real geometry with different levels of precision, giving the possibility to take into consideration the properties on interfaces between copper, helium and kapton, as well as phase changes in helium and the strongly non-linear behavior of HeII.

Intro

To better understand the stability behavior of superconducting cables, experiments as well as simulations are required in the steady-state as well as the transient regime.

A simulation tool should be able to take into consideration very specific situations, but also should be flexible enough to cover several possibilities: i.e. cables vs strands, impregnated vs non-impregnated, $T_{\mathrm{operational}}$ at arbitrary temperature i.e. 1.9 vs 4.5 K, steady-state vs transient

COMSOL Multiphysics

Commercially available software packages have some known advantages and disadvantages:

Con:

Expensive, **black-box**, **not specific enough**, limited support

Pro:

Easy to use, widely applicable, **stable**, no-debugging required for 'standard' simulations

COMSOL Multiphysics is available at CERN on a campus license and gives the user the possibility to implement governing equations

Coupling

COMSOL Multiphysics can be used for thermal calculations and for arbitrary coupled systems, like electro-thermal simulation of superconductors.

Coupling of different physical fields can be introduced on complex geometries (1D, 2D, 3D). The newest version(s) make(s) use of a ‘model tree’, which allows the user to go back to previous modeling steps, making it possible to change parameters easily.

Developed models

Several models have been developed since 2008 by some students* supported and partly supervised by me and by myself:

- Quench propagation in busbars and stability behavior in defective 13kA joints [1]
- **Steady state heat transfer through cable insulation** [2,3]
- Temperature distribution over coils; several types of ground insulation [4]

* Many thanks to Robin Berkelaar, Daniel Molnar and Tom Wolterink

[1] Molnar D., Verweij A., Bielert E. Electro-thermal FEM simulations of the 13 kA LHC joints, Cryogenics, 53 (2013), 119-127

[2] Bielert E., Verweij A., Ten Kate, H. Finite Element Modeling in 3D of the Impact of Superfluid Helium Filled Micro-channels on the Heat Transfer through LHC Type Cable Insulation, IEEE Trans. Appl. Supercond., 22-3 (2012)

[3] Bielert E., Ten Kate H., Verweij A., A structured approach to analyze the influence of channel dimensions on heat extraction via superfluid helium, Physics Procedia, submitted for publication (2014)

[4] Bielert E., Kirby G., Ten Kate H., Verweij A., New 2D thermal model applied to an LHC inner triplet quadrupole magnet. Proc 23rd int cryo eng conf. Wroclaw (2011), 1065–70.

Modeling steps

The modeling steps which need to be followed, are very natural:

- Definitions (parameters)
- Geometry (1D, 2D, 3D)
- Materials (from library or uploaded by user)
- Physics (coupled if required, governing equations as well as boundary and initial conditions)
- Mesh (several mesh element shapes and sizes possible)
- Studies (transient or steady state, parametric sweeps etc.)
- Post-processing

Easy use of the software, no specific knowledge of numerical algorithms or meshing is required and easy geometry building.

Cable insulation: geometry

What **is** considered for the present steady state calculations:

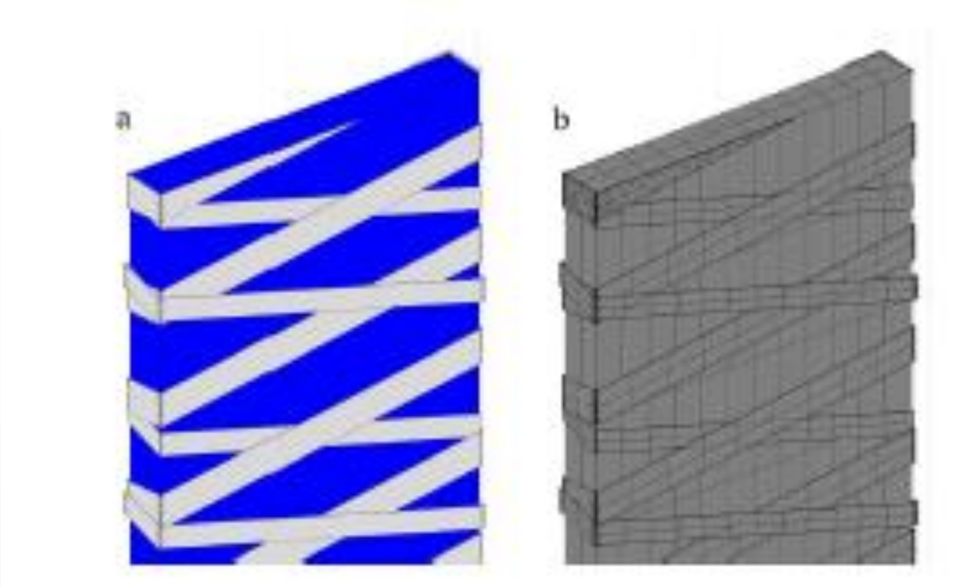
- Size of helium channels
- Thickness of Kapton
- Contact between Kapton and cable and Kapton and helium

FEM software makes it easy to implement the geometry!

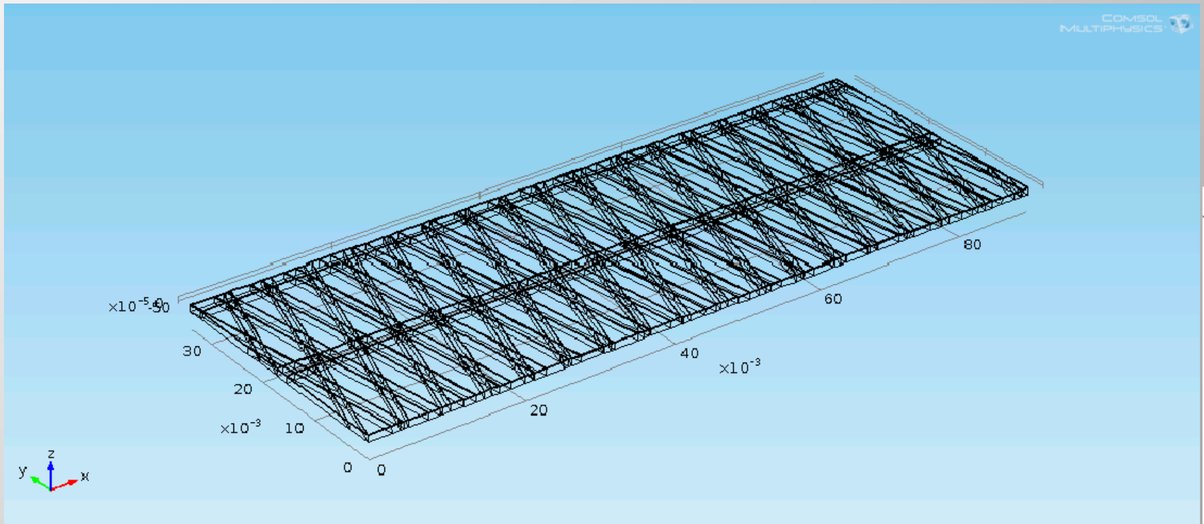
Since the cable insulation acts as the main thermal resistance between cable and helium bath, the cable is considered as a block:

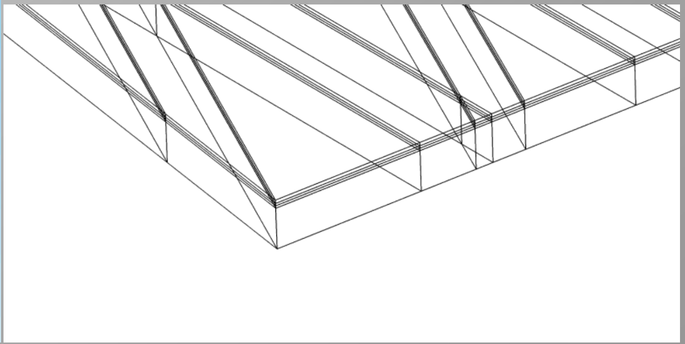
- Correct averaged material properties of cable
- Homogeneous heating of cable

Cable insulation: geometry, overview



Real 3D or 2.5D, giving more flexibility to change geometrical parameters

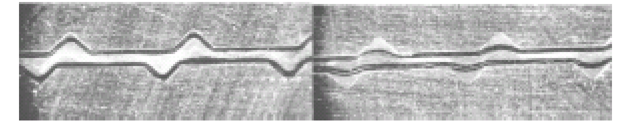




Cable insulation: geometry, improvements

What **should be** considered for the future calculations:

- Creep of Kapton inside channels and strands
- Wetted cable (strand) surface
- Void fraction



From Cryogenics 39 (1999) 921-931 Meuris, Baudouy, Leroy and Szeless

- Anisotropic material properties (averaging taking into consideration the direction of twist and internal voids and channels)
- Inhomogeneous heating inside the cable

The first three points can be analyzed with microscope, tomography and/or a mechanical FEM model, the last two points can be taken into consideration with a more detailed geometry or profound analysis before these parameters are used as an input.

Cable insulation: materials

Only the (effective) thermal conductivity is required for ss…

Cu/SC/helium ratio if opted for average material properties

Additional for transients:

Heat capacity (latent heat!)

Density

RRR (since it has an influence on the thermal conductivity…)

Additional for coupled systems:

Electrical conductivity (or resistivity)

Several databases are available, inputs can vary with about 20%.

Cable insulation: physics

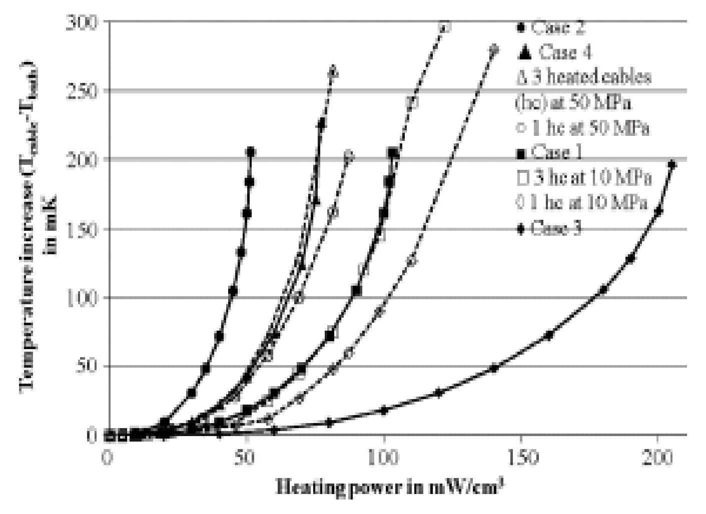
Governing equations:

Standard Fourier law:

$q=-k\nabla T$ with $k(\boldsymbol{T},RRR,B)$

Gorter-Mellink equation:

$q^{m}=-1/f\ \mathrm{d}T/\mathrm{d}x$ with m=3, $f(\boldsymbol{T},p)$, 1D->3D



From [2], good match with 26% channel size reduction

Boundary conditions:

Kapitza resistance

Boiling curve (natural convection, nucleate- and film boiling)

Contact resistance between solids (depending on pressure!)

Fixed temperature

Ideas to answer some unanswered questions

Phase transitions: important or not for steady state?

Implementation by boundary resistance and without phase change, since the layer of HeI or helium gas is very thin. ΔT over this thin layer should be enough such that Critical Heat Flux (CHF) is not reached in helium volume, since this causes convergence problems and requires a very fine boundary mesh...

In which direction does most of the heat flow in a cable pack? Via the small face towards the bath or via the large face towards the next cable? Or in between the cables towards the bath?

$T1$

$k_{\text{artificial}}$ very large

Sample of unknown k due to complex geometry

$k_{\text{artificial}}$ very large

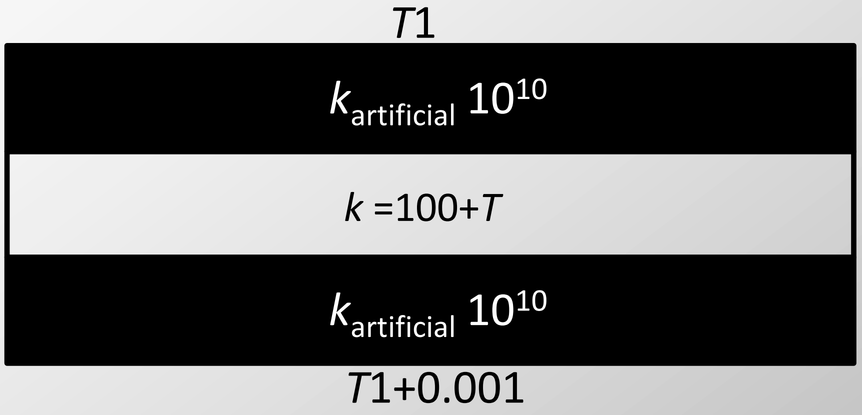
$T1+\mathrm{d}T$

q calculated

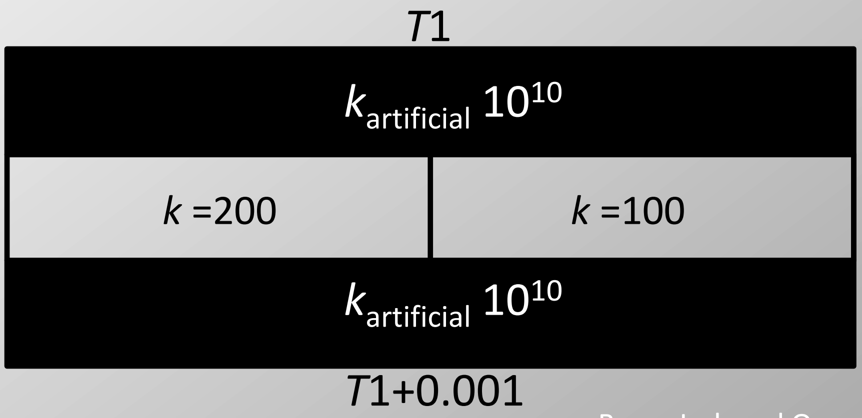
Examples

Only valid if:

The largest resistance occurs in the analyzed geometry, and if the heat source occurs over several unit lengths.

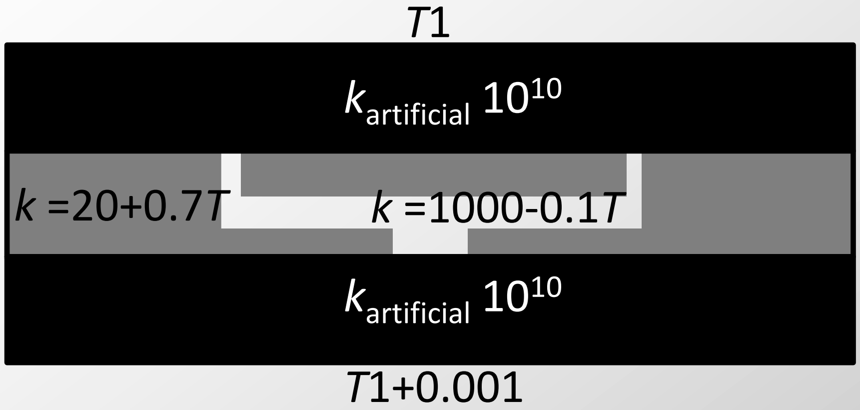


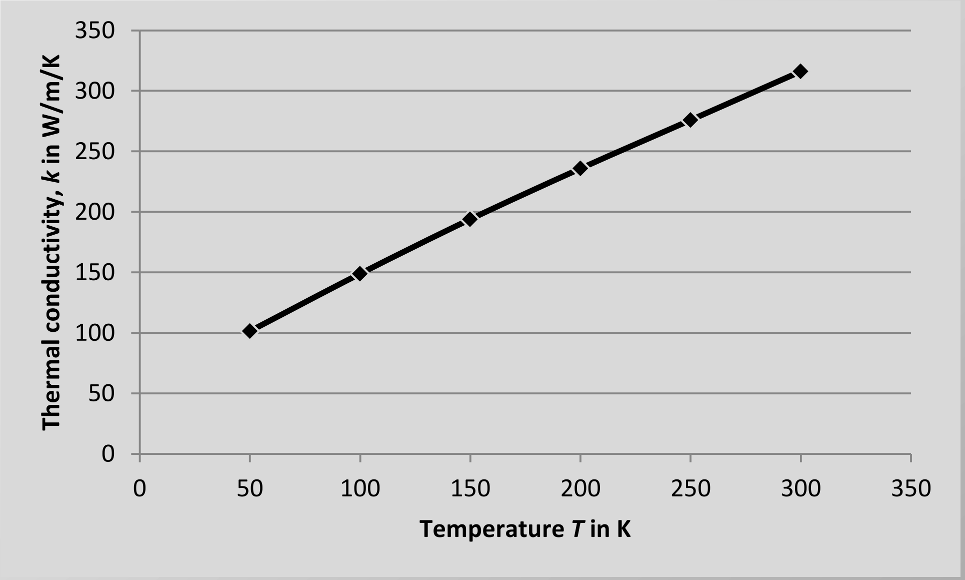
T1	q	k
50	1.5002	150.02
100	2.00033	200.033
150	2.50151	250.151
200	2.99917	299.917
250	3.4967	349.67
300	3.99656	399.656



T1	q	k
293.15	1.499999	149.999

Examples





T1	q	k
50	1.01395	101.395
100	1.48831	148.831
150	1.93864	193.864
200	2.3578	235.78
250	2.75872	275.872
300	3.16094	316.094

Conclusion

The present model allows to vary the width and thickness of cable insulation and therefore the network of helium channels in between the solid material.

Only predefined sizes of insulation and channels are implemented at the moment. Mechanical models should give a direct input for the size of the helium channels and the creep of Kapton in between strands. An additional (one way) coupled mechanical module can be an outcome.

For transient models, the amount of helium inside the cable, in between strands is important and therefore, OR the exact geometry of the Rutherford-type cable should be implemented OR, if allowed (more discussion needed!) a correct averaging of material properties is required.