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A structured approach to analyze the influence of channel dimensions on heat extraction via superfluid helium

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Abstract

For the luminosity upgrade of the LHC at CERN, the final focusing quadrupole magnets will be exposed to an increased energy deposition in their coil windings. To have a higher heat transfer rate between cable and superfluid helium bath, the cable insulation has been subject of many studies. Improved cable insulation designs, making use of several layers of Kapton tape wound around Rutherford type cables, allow helium to penetrate via micro-channels, which are left open between adjacent Kapton tape sections. To better understand the thermal behaviour at operating temperatures below and some degrees above the helium lambda transition, besides experimental work, several numerical models have been developed to study the influence of the cable insulation. Here we present a new numerical model based on an earlier presented FEM model, which makes use of coupling variables such that the user can easily and quickly change the parameters of interest, giving the possibility to analyse new ideas effectively.

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Keywords: LHC; luminosity upgrade; cable insulation; numerical model; FEM; COMSOL Multiphysics

1. Introduction

Present superconducting accelerator magnets in operation, like the main dipole and quadrupole magnets in the LHC, make use of Nb-Ti technology. The nominal operating temperature is about 1 to 2 K below the current sharing

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temperature of the superconducting material. Since the next generation of accelerator magnets for the interaction regions will be exposed to much higher levels of energy deposition, the thermal design needs extra attention for to ensure stable magnet operation, Baglin et al (2008). The temperature of the cables in the magnet windings should be kept well below the current sharing temperature and therefore, enhanced heat extraction from the cables to the heat exchanger pipe is required. Optimal use of the very high effective thermal conductivity of superfluid helium (He II) is only possible when the temperature of the helium stays below the lambda transition temperature. If the cable surface, which is in contact with He II exceeds this temperature, an insulating layer of normal liquid helium, or even helium gas, is created; hindering the possibility to extract heat effectively from the cable to the He II (burn-out). Thermal resistances, introduced in the magnet design for mechanical or electrical reasons, should be minimized and all design parameters should be considered in parallel. Due to the large currents and accompanying Lorentz forces, the electrical and mechanical designs are of utmost importance and consequently limit the possibilities for thermal design improvements. The packing factor of collar and yoke is an example where thermal- and mechanical design are opposed: to have an as-large-as-possible radially outward oriented channels filled with He II, solid material has to be removed, and therefore the allowed forces are obviously smaller.

The main two thermal barriers between the cables and the 2 K heat exchanger are, however, the usually thick ground insulation around each coil, and the cable insulation around each individual cable. Dielectric materials used for electric insulation are also good thermal insulators. To improve the thermal performance of the cable insulation for use in future accelerator magnets, new insulation schemes have been proposed over a period of several years, La China and Tommasini (2008). Lots of effort by several groups during many years have led to a better understanding of the heat transfer properties of superconducting cable insulation immersed in a helium bath, Meuris et al. (1999), Granieri and Richter (2011) and Kimura et al. (1999). Analytic as well as numerical models have been developed to describe and predict the thermal behaviour, Bocian (2013) and Granieri (2012). However, none of them allowed the user to vary the parameters in a structured way, giving the possibility to analyse different solutions effectively. The main reason for these missing analyses is that setting up and varying the various free parameters is very laborious with the existing models. Here we present a new FEM model, developed with COMSOL Multiphysics V4.4, based on an earlier presented numerical model, Bielert et al. (2012). This new model makes use of coupling variables such that the user can easily and quickly change the geometrical parameters of interest, giving the possibility to analyse new ideas and different designs effectively. Furthermore, integration of the heat flow over the different boundaries gives the preferred direction of the heat transfer and thus indicates where design improvements can and should be made.

Nomenclature

T_λ	lambda transition temperature between He I and He II, 2.17 K at atmospheric pressure
KWi	width of the Kapton tape in each layer, where "i" stands for the layer counted from the cable side
CWi	width of the channels between the Kapton, where "i" stands for the layer counted from the cable side
Di	thickness of the Kapton tape in each layer, where "i" stands for the layer counted from the cable side

2. Sophisticated FEM model with coupling variables

2.1. Basic ideas

The development of a sophisticated FEM model comes naturally if the impact of different geometrical designs on heat transfer properties is of interest. The model as described in this paper is comparable to the network model described by Bocian (2013). It is claimed that the network model's main advantage is that there are no free tuning parameters. By implementing the proper geometry and the correct material properties the heat transfer is calculated. For the steady state only the thermal conductivity is required, while for transients, of course, the specific heat and density of the materials are needed as well. The model described here has the same advantage and in addition, does not require estimations for the geometry: it is implemented following the exact nominal dimensions of the design.

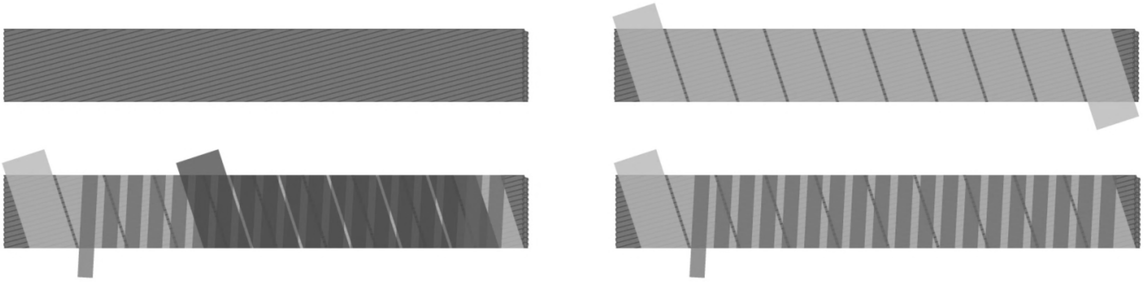

Fig. 1. Overview of the three Kapton insulation layers. Clockwise, starting from top left: bare cable, 1st layer, 1st and 2nd layer and all three layers.

2.2. Geometrical parameters

The cable insulation represents a thermal resistance between the cable and the helium bath. The cable itself is mainly made out of copper and is twisted with a transposition pitch of 115 mm, Bruening et al. (2004). This means that within the cable, the diffusion of heat is very high in all directions and therefore the temperature of the cable is homogeneous, as long as the cooling is fairly homogeneous as well. As soon as the heat flux in the longest channels filled with He II reaches the critical heat flux, Doi et al. (2008), the cooling is not evenly distributed anymore and temperature differences within the cable are expected, which are confirmed by measurements, Richter (2011). As a simplification to the real cable, a rectangular block with the same size is used in the model. Furthermore, only nominal values for the designs of the insulation are modelled, see Fig. 1 and Table 1. In a real magnet, the coil is compressed under large pressures, Bruening et al. (2004). A mechanical FEM model gives an idea of the reduction in channel cross-section as a function of pressure Lorin et al. (2012). Here only the qualitative behavior and impact of changes in the nominal design are discussed.

Table 1. Geometrical characteristics.

Description	Value			Comment
	Layer 1	Layer 2	Layer 3	
Cable size (*l*×*h*×*w*) in mm	90 × 1.9 × 15.1			Rectangular block: simplification to keystoned Rutherford type cable
Kapton tape width (KW) in mm	9	3	9	Layer 1 and 3 have 50% overlap
Channel width (CW) in mm	1	1.5	1	
Angle relative to cable longitudinal direction in degree	73	82	73	Due to the finite thickness of the insulation, the angle is slightly larger for layer 3 compared to layer 1
Kapton thickness (D) in µm	50	50	69	Enhanced Insulation Scheme 3 (EI3) nominal values
	50	75	69	Enhanced Insulation Scheme 4 (EI4) nominal values

2.3. Model implementation

Since the insulation has a very complex geometry, it is difficult to assign the correct physical properties to all the domains and boundaries in the FEM model. Especially since the contact surface properties between copper, Kapton and helium are very important, and because the insulation layers are very thin. Here we propose two different practical solutions. The first solution makes use of the possibility to hide entities and objects in the Graphical User Interface of the software. Therefore, domains and interfaces which were not visible become directly clickable in the graphics window and the correct physical properties can thus be assigned easily by the user. Hidden objects are of course still taken into consideration in the calculations. The second solution is to place different domains arbitrarily in space, while mathematically connecting them via coupling variables. This gives the user the possibility to easily assign the correct material – and physical properties to all parts of the geometry as well. For the first solution, the position of the layers needs to be relative to each other, such that if, for example, the thickness of the layers changes, the correct relative position is guaranteed. For the second solution this is not necessary, as long as the thickness is not increased to a size larger than the distance between the subdomains. The two solutions are explained by a very simple example shown in Fig. 2. On the left hand side of the figure, there are nine sub-blocks forming one large block. For the user, it is difficult to assign properties to the boundaries between the sub-blocks, as well as to domains which are not directly viewable from none of the sides (the center sub-block). The domains and boundaries can either be selected by hand (clicking on the geometry) or by choosing the corresponding ID number. In the case of a regular geometry, the ID numbering scheme which is followed internally by the software is fairly straightforward, but for complex 3D geometry, the ID numbering scheme is hard to follow and therefore it becomes almost impossible to assign the correct properties to all model parts. In the middle, the same geometry with hidden subdomains is shown, allowing the user to select the required subdomains and boundaries. On the right hand side, the sub-blocks are moved away from each other, put at (arbitrary) different positions in space. This frees all subdomains and boundaries between the subdomains. For the user, it is now fairly easy to select the required part of the model and assign the correct physics to it. However, since the subdomains are physically not in contact with each other anymore, the software has to be "tricked". By introducing coupling variables (boundary similarities), the continuity of physical quantities over the boundaries, which are in reality connected to each other, can be guaranteed.

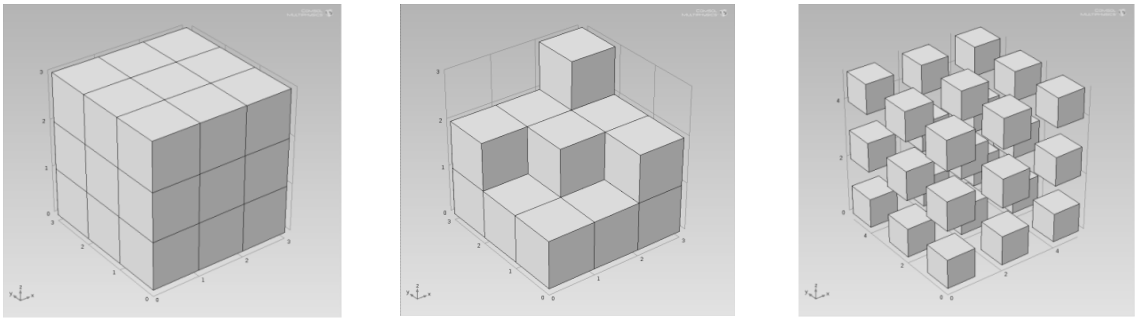

Fig. 2. Two possibilities to correctly assign physical properties on subdomains and boundaries: either by hiding subdomains such that otherwise unreachable areas become visible (middle) or by expanding the geometry by putting subdomains at arbitrary positions in space and coupling them mathematically by introducing coupling variables (boundary similarities).

2.4. Material properties and interfaces

Although the geometry itself is complex, there are only two materials involved: polyimide and helium. The most important material property of both materials is the thermal conductivity. Since the helium bath in the final focusing quadrupole magnets for the LHC is kept at a temperature below T_{λ}, one can only speak about the effective thermal conductivity: heat flow is not following the linear Fourier law, but rather the strongly nonlinear (theoretically cubic) Gorter-Mellink relation, Gorter and Mellink (1949). Since a static bath is used and no temperature differences occur in the bulk of the helium due to the very large effective thermal conductivity, (natural) convection is negligible and is ignored for the calculations mentioned here. Although the heat transfer through HeII is potentially much larger than through Kapton, their respective sizes make the problem complex: the surface of the Kapton is much larger and the thickness is much thinner compared to the cross-sectional surface and the length of the helium channels. The two heat transfer mechanisms are competing with each other. Depending on the heat source distribution within a magnet, heat is transferred directly to the helium bath via the cable's small face, or to the next cable via the cable's large face. In the case the helium is kept at a temperature above T_{λ} it is clear that the main path of heat extraction is via the largest surfaces, since there is no thermal "short" via superfluid helium and the thermal conductivity of normal liquid helium and Kapton are of the same order.

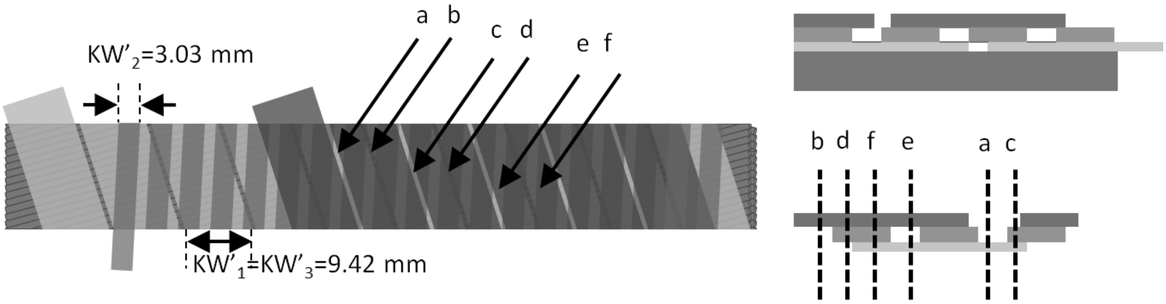

Fig. 3. Details of the cable insulation and implementation in the numerical model. Left: sizes and several areas with different total thickness of insulation. Right: side view of the three layers, with interfaces between helium and Kapton. The lines labeled (a)-(f) correspond to the following situations: (a) only first layer, (b) only third layer, (c) first two layers, (d) last two layers, (e) first and last layer and (f) all three layers.

Material properties are taken from commercially available databases and from literature, NIST database and HEPAK (1999). On the surfaces between Kapton and helium, a temperature dependent Kapitza resistance is present as well. Contact resistance between different layers of Kapton is assumed to be negligible; the temperature profile over these interfaces is continuous.

3. Final model compared with experimental results

3.1. Modeling steps

To obtain temperature distributions, the following steps need to be followed. First the geometry is drawn, then the physics is applied, a mesh is built, the calculation is performed and post-processing should reveal the required results. Three of these five steps are shown in Fig. 4. During the first step it is important to already consider how a proper mesh is built. Since the thickness of the insulation is much smaller than the length of the total sample, it is very convenient to use a swept mesh in the direction of the insulation thickness. Then, over the surface of the insulation, a coarse mesh can be used, strongly limiting the total number of mesh elements, which avoids memory problems during the calculation. The mesh consists of 31,804 prism shaped elements, resulting in about 200,000 Degrees of Freedom (DOF). The calculation time is about 2 minutes per iteration, a parametric sweep where only one input parameter (for example channel width) is changed therefore takes about half an hour. The use of coupling variables guarantees that the temperature profiles are continuous over the artificially introduced boundaries.

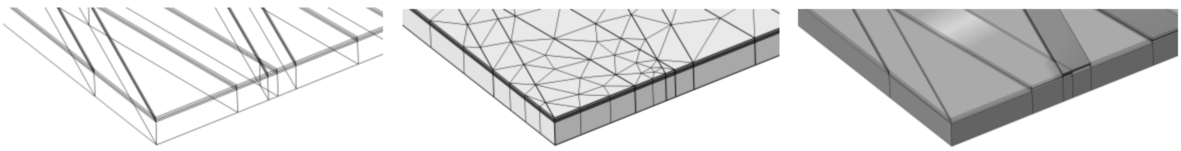

Fig. 4. Modeling steps. On the left a small selection of the total geometry is shown (one of the left end corners), in the middle the applied mesh and on the right, the obtained temperature distribution.

3.2. Comparison to previous model and experimental results

A less sophisticated 3D model was previously validated with experimental data, Bielert et al. (2012). We therefore compare the results of this newly developed model with both the experimental results and the other model. The results are shown in Fig. 5. To be able to compare the models, the simplest configuration of this newly developed model is used. Results of parametric sweeps of different geometries, physical properties and bath

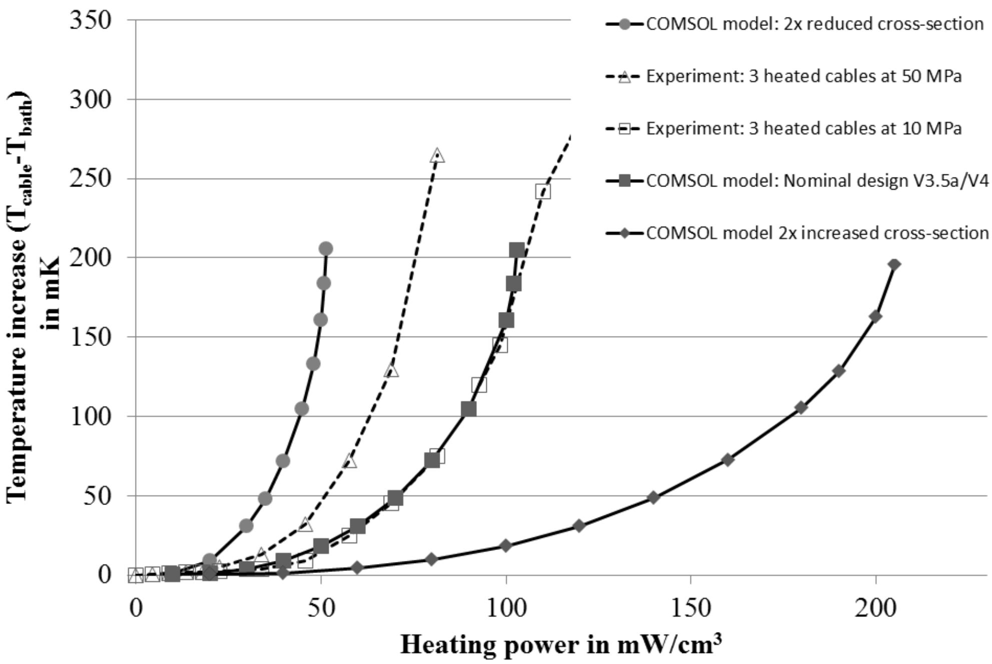

Fig. 5. Validation of the newly developed FEM model, which makes use of coupling variables. The results as obtained with the new model exactly correspond to the results of a previously developed model (V3.5a and V4). The new model can be used more easily to perform parametric sweeps, such that comparisons to experimental data can be performed more adequate.

temperatures will be published in a separate report Bielert (2014). As expected, both models give exactly the same result. As was discussed by Lorin et al. (2012) and which needs to be repeated here, is that the mechanical deformation of the insulation is very important for the final results. Since the cross-sectional area of the channels is decreased when pressure is applied, the heat extraction capabilities are reduced. Since this behavior is strongly non-linear, separate analyses are required, as discussed by Granieri (2012).

4. Conclusion

It is demonstrated that complex geometries can be implemented in a COMSOL model in a more straighforward way, by making use of coupling variables. By implementing the model as described above, it is possible to perform parametric sweeps in a simple and straightforward way. Comparison between different designs are facilitated, once the base model has been created.

The model was tested and is validated for a single design for the moment. Comparison to experimental data and a previously developed model, show that this new tool is useful. From the model it also becomes clear that most of the heat is extracted via the channels in the second layer, towards the thin edges of the cable.

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