**Finite Element Modeling in 3D of the Impact of
Superfluid Helium Filled Micro-channels on the Heat Transfer
through LHC Type Cable Insulation**

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Index Terms—Cable insulation, Finite Element Method, heat transfer, superconducting accelerator magnets

I. INTRODUCTION

SUPERCONDUCTING accelerator magnets making use of Nb-Ti technology nominally operate at about 1-2 K below the critical surface. The next generation accelerator magnets for interaction regions, however, will be exposed to a much enhanced energy deposition due to the debris of collisions in the detectors [1,2]. Also fast cycling magnets are subject to high heat loads. In order to guarantee stable magnet operation, the temperature of the cables in the magnet windings should be kept well below the current sharing temperature and thus the heat extraction from the cables has to be improved. In cases where use is made of the high effective thermal conductivity of superfluid helium this implies to stay below the transition temperature of 2.17 K. Thermal barriers introduced in the magnet design for electrical or mechanical reasons have to be minimized. However, because of the same criteria, the window for thermal improvements is rather small. The packing factors of collar and yoke, for example, have to be about 95% for mechanical reasons, but obviously a more open structure is superior from a thermal point of view [3]. The ground insulation is another, usually thick, thermal barrier

that needs to be improved thermally, without compromising the electric design [4]. Dielectric materials are unfortunately also good thermal insulators. Besides the ground insulation, the cable insulation is the main thermal resistance between the superconductor and the heat sink. Many years are spent to better understand heat transfer through the cable insulation [5]-[8]. An enhanced cable insulation has been proposed [7] and subjected to several tests [8]-[9]. Also an analytic and a numerical model have been made to calculate the heat transfer [10]-[11]. Here a new and much more detailed 3D FEM model is presented and used to demonstrate the beneficial features of the enhanced insulation by comparison to measured data [9].

II. STATE OF THE ART AND ENHANCED CABLE INSULATION

In the analyses of the cable insulation the present LHC insulation scheme (MB) is compared to the Enhanced Insulation scheme (EI) [7], see Fig. 1. The present insulation comprises three layers with an overlapping first and second layer, where in principle no helium in between the cables, but without a path to the strands. The new insulation consists of three layers as well, but each layer incorporates helium channels due to spacing of the polyimide (Kapton) ribbons. In both cases, dielectric protection is guaranteed [12] and mechanical protection is provided by the outer layer. Here the focus is on the complex network of the EI insulation scheme.

Fig. 1. Cable insulation schemes [7]: a) State of the art cable insulation for the LHC main dipoles (MB) and b) Enhanced insulation scheme (EI).

A heat transfer experiment on the Enhanced Insulation has been done using a dummy cable made of Cu₁₀Ni with the correct key stone angle and surface grooves, representing the real LHC inner layer cable [13]. A stack of such cables is made and a large transversal pressure is applied, also determining the contact surface of the insulation and cable. Voids inside the dummy cable do not exist as they are solid, but they are only relevant in transient conditions. Depending on which insulation is applied, the surface grooves can be partially filled with insulation, altering the network of micro-channels, see Fig. 2. [6]. The thickness of the insulation layer

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depends on the transversally applied pressure. The effective cooling channel cross-section is decreased by some 31% at 130 MPa and 29% at 80 MPa [12]. Consequently a higher pressure will decrease the tolerable heat deposition to reach the same temperature. From about 50 MPa, the pressure dependence flattens out [8].

Fig. 2. Photographs of cable insulation, reprinted from [6] with permission from Elsevier: a) The insulation fills the surface grooves and b) The insulation leaves the surface grooves open.

The 3D simulations discussed here concern a simplified representation of the stack experiment using a rectangular geometry without surface grooves. The model characteristics are listed in Table I. Three additional cases are analyzed: twice the thickness (unrealistic but interesting for new designs), half the thickness and a case where the insulation is 26% thinner, roughly corresponding to an applied pressure of 50 MPa.

TABLE I MODEL CHARACTERISTICS [9]

Description	Value	Comment
Cable size ($l \times h \times w$) in mm	$90 \times 1.9 \times 15.1$	Rectangular, simplification
Kapton tape width in mm	9, 3, 9	1 st - 3 rd overlap 50%
Channel width in mm	1, 1.5, 1	
Insulation layer thickness or channel height in μm	50, 50, 69	Enhanced Insulation scheme 3 (EI3). Nominal values, Case 1
	25, 25, 34	2 $\times$ reduced, Case 2
	100, 100, 138	2 $\times$ increased, Case 3
	37, 37, 51	26% reduced, Case 4

In all cases a complex network of superfluid helium filled micro-channels exists not only at the cable thin edge, but also in the layer of insulation between two cables. The joint behavior of the small and wide cable surfaces is not evident and requires a three dimensional model. A zero-dimensional network approach has been proposed before, where some of the unknowns need experimental validation [7]. The limiting factor is that it is extremely difficult to measure temperatures and heat fluxes in micro-channels. The unknowns can also be estimated from the 3D FE model proposed here.

III. NUMERICAL HEAT TRANSFER MODEL

The simulations are performed with COMSOL Multiphysics [14], a commercial code with a built-in mesher and solving algorithms, whose settings can be steered by the user. Required user input is the geometry of the object, the physical relations valid in the bulk materials and at the interfaces between domains of different materials, and the

initial - and boundary conditions of the dependent variable. The coefficients of the implemented equations are material properties which in the case of superconducting magnets are temperature- and magnetic-field dependent. In addition, the properties of liquids are dependent on applied pressure, also true for the heat conductivity function of superfluid helium.

Superfluid helium is implemented as a solid with an effective thermal conductivity [4]. This is possible since the assumption is made that the heat transfer can be described using the Gorter-Mellink equation for turbulent heat transport in Tisza's two-fluid model [15]. The micro-channels filled with superfluid helium have lengths of about a factor of 10 larger than the widths and about a factor of 100 larger than the heights. The assumption is made that the Kapton insulation itself is not conducting any heat. The channels are thus treated as being the only possible thermal route towards the heat sink and therefore temperature gradients occur only over the length of the channels. The boundary conditions on the channel sides are thus adiabatic. Under these assumptions, the cooling channels in the novel Enhanced Insulation can be seen as a network of one-dimensional channels. The one-dimensional approach justifies the use of the Gorter-Mellink law [16], which replaces the standard Fourier conduction law. The temperature dependent thermal conductivity of Kapton ($\sim 6 \times 10^{-3}$ W/mK at 1.9 K) is also of interest but only above the lambda transition temperature. The thermal resistance of the helium channels is about a factor 10 smaller than the thermal resistance of the Kapton (200 K/W versus 2000 K/W), even though the path length through the Kapton is in the range of the thickness of the insulation ($\sim 169 \mu\text{m}$) whereas the length of the channels is about the width of the cable (~ 15.1 mm). Especially for low heat flux, the heat extraction via the micro-channels is superior to the thermal conduction through the Kapton. This also implies that below the lambda temperature adjacent cables are largely thermally decoupled. Above 2.17 K, thermal conduction through the Kapton becomes more important [9] and a much stronger coupling occurs. For simplicity, the thermal conductivity of the cable is taken as 1 kW/mK, a value comparable to copper at 1.9 K.

The new model is validated by comparison to the sophisticated 3D numerical model (SUPER-3D) –which besides temperature distributions and heat fluxes also simulates the velocity fields of the normal and superfluid components in the two-fluid model– and experimental results [17]. Fig. 3 shows Critical Heat Fluxes (CHF), the maximum heat flux where the helium stays superfluid, calculated with COMSOL for relatively simple ducts with various contractions and measured CHF's redrawn from [17]. The results indicate that the calculated temperature profiles match the experimentally obtained data very well. Although this validation takes place on a different size scale, the heat transfer regime is similar. The turbulent Gorter-Mellink equation can be used since the involved heat flux densities are in the same range. Consequently the new model is suitable to describe the heat transfer through the cable insulation.

Fig. 3. Critical Heat Flux (CHF) versus contraction open ratio in a 3D channel. Model (continuous lines) compared to experiments (dotted lines) for different bath temperatures.

The behavior at the interfaces between the different parts is important as well for the correct analysis of the problem. As a first approach, all interfaces are set such that the temperature distribution is continuous over the interfaces. The impact of the Kapitza conductance is therefore not yet analyzed. Introduction of the Kapitza conduction will increase the temperature of the cable, therefore it can be used as a tuning parameter of the model. From an engineering point of view it is only interesting to know what the temperature increase of a cable is when subjected to a certain heat deposition. Since the temperature rises quickly once in the micro-channels the lambda temperature is reached [9], the focus here is on the temperature range between 1.9 and 2.17 K.

IV. IMPLEMENTATION IN THE SOFTWARE

Fig. 4 shows schematically how the insulation layer with micro-channels is implemented in the software and how the mesh looks like. The differences in characteristic scale of length are very large. The simulated geometry is 90 mm long due to the twist pitches in cable and insulation (the scheme is repetitive over this length) and the thickness of one insulation layer is about 50 μm . This results in an aspect ratio of 1800. A simple free mesh of tetrahedral elements would result in an impractical large amount of degrees of freedom (DOF), implying very long calculation times. In the worst case a failure of construction of a useful mesh or ‘out of memory’ errors will occur. The solution to limit the DOF is a meshing scheme by which a free triangular or mapped mesh across the surface of the thin layers is extracted in the direction of the insulation thickness, see Fig. 4.

Because of the complex structure of the insulation an assembly is used to facilitate mesh implementation and give the possibility to introduce thin thermal resistive layers. In general, the temperature field is not continuous across boundaries. Kapitza conductance can only be modeled this way, since the physical layer where the temperature jump occurs in reality is much thinner than the insulation layers. The mesh consists of 306 prisms and 2926 hexahedrals, resulting in a total of 44,408 DOF. When using the direct

UMFPACK solver, the calculation time is less than 5 minutes on a desktop computer.

Fig. 4. Implementation of the cable insulation a) Geometrical model of the helium channels along a unit length of the sample. b) The applied mesh.

V. COMPARISON TO EXPERIMENTS

Measurements on the cable indicate that for a slight increase in temperature, the temperature distribution in the metallic cable is uniform. However, close to the lambda transition, just below 2.17 K, significant gradients do occur in the cable [18]. This may indicate a spatially distributed transition. The simulations indeed show that some parts of the cable are better cooled. Clearly not all channels have the same length between cable surface and helium bath. The longer channels reach the lambda temperature faster than the shorter ones. The thermal path length towards the bath varies with the position on the cable surface (see Fig. 4). Once the lambda temperature of 2.17 K is reached, a thin layer of normal liquid helium will seal the channel and the heat transfer mechanism at the solid-helium interface has changed. The preferable heat transfer path shifts towards the shorter channels and finally to the Kapton insulation [9].

The model simulates only one cable. The wide surface outer boundaries are assumed to be adiabatic, which means that the simulations represent a stack experiment where all cables are heated simultaneously. Therefore the results give a too high temperature increase. The neglected Kapitza conductance gives a correction in the opposite direction. In Fig. 5, the simulated results are compared to the stack measurements. Notice that a scaling factor is applied such that the units on the horizontal axis are mW/cm^3 instead of W/cable , as used in [9]. The Cases 1-4 from Table I, are indicated with the solid lines. The measurements from [9], at 10 and 50 MPa transverse pressure, and with one or three cables heated, are represented by the dotted lines. Since the coupling between a heated cable and an adjacent cable is stronger than between a heated cable and its neighbor, the simulated results are best compared with the measured case of three heated cables. Case 1, where the nominal insulation parameters are used fits the situation at 10 MPa. At a pressure of 10 MPa the insulation is only compressed slightly, which means that a good agreement is found. Case 4, where the effective channel cross-section is reduced with 26% should be compared to the situation where three cables are heated at 50 MPa. Again an excellent agreement is found.

Fig. 5. Temperature increase of the cable versus deposited heat. Model (continuous lines) compared to experiments (dotted lines) [9].

Because the thermal conductivity of the cable itself is high, and the first channel is in direct contact with the solid surface over its total length, the temperature in the first layer of channels is almost equal to the cable temperature. It is important to realize that the temperature gradient in the channels occurs along the length of the channels in the second and third layer. As can already be expected from the Gorter-Mellink power law, a decrease of the cross-sectional area of the channels has a strong influence on the heat extraction capabilities. Note that indeed a factor of 2 difference in channel cross-section, results in a factor of 8 difference in temperature at the same heating power. The sensitivity to the first layer thickness is negligible and therefore the thickness of the first insulation layer can be reduced from a thermal point of view, without significantly reducing the extraction capabilities of the insulation. To keep the total insulation thickness the same, the third insulation layer can be made thicker thereby increasing the extraction capabilities.

In accelerator magnets, usually the thin edges of the cables in the inner coil layer are in direct contact with the helium in the annulus between the coil windings and the beam pipe. The thin edges of the cable at the other side, however, are often in contact with a quench heater. This means that only one side of the inner layer in the winding pack is effectively cooled. The second layer has even less direct paths to the helium bath. This practical case can be modeled by assuming an increased bath temperature. Results for this case with effective cooling only on one side of the cable stack are shown in Fig. 6. For comparison it shows the nominal case of cooling at both sides as well. Additionally, three cases where a slightly higher bath temperature is assumed, with cooling on both thin edged sides, are displayed in Fig. 6. Depending on the spatial distribution of the heat deposition in the magnet windings only small parts of the insulation are allowed to be blocked. When the channels are for instance blocked over 20% of a unit of length, local adiabatic boundary conditions are assumed here. All the deposited energy still needs to be extracted. This happens via the neighboring non-blocked micro-channels. These channels are therefore subjected to a 20% increased heat flux. When losses are in the range between 5×10^4 and 6×10^4 W/m³, this will cause a too large temperature increase, turning the superfluid into normal liquid. A commonly accepted quench design limit for Nb-Ti accelerator magnets is 4.3 mW/cm³ or 4.3×10^3 W/m³ [2], thus far below the critical value found for

the new enhanced insulation with open superfluid helium filled micro-channels.

Fig. 6. Temperature increase of the cable versus deposited heat. Practical situations of a slightly higher applied bath temperature are compared to the situation with a nominal bath temperature of 1.9 K. The continuous line with squares represents the nominal situation: Case 1, see Table I which is also compared to the case where one thin edged side of the cable-insulation is blocked and thus leads to a more rapid temperature increase.

VI. CONCLUSION

It is demonstrated that below the He II – He I transition temperature of 2.17 K, the thermal behavior of the Enhanced Insulation featuring a complex network of micro-channels filled with superfluid helium can be described well with the new 3D model. Although, for example a network model [10] is able to describe the same thermal behavior in a slightly different way, it is not able to implement a geometric Gorter-Mellink model as straightforward as in the new 3D FEM model described here. Especially the implementation of the geometry occurs in a very natural way in this new model.

Adjacent cables in coil windings using the new insulation are thermally decoupled from a heated one when the temperature of the helium inside the micro-channels stays below the lambda temperature. The channels representing a very high effective thermal conductivity act as thermal shorts. Because of the large aspect ratio of the cable itself, still some small fraction of the heat is flowing towards the adjacent cable.

Further work of interest is to make a mechanical simulation model which is able to quantify the reduction of the micro-channel cross-section as a function of the applied pressure. The coupling to adjacent cables and especially the transition at the lambda temperature are of fundamental interest, although not relevant from an engineering point of view, since the temperatures increase quickly when the cooling with superfluid helium is not exploited.

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