Heat Transfer through the Electrical Insulation of Nb₃Sn cables

Pier Paolo Granieri, Lina Hincapié, Rob van Weelderen

Abstract—For the LHC upgrade projects, CERN will rely on the Nb₃Sn technology to build high field dipole and quadrupole superconducting magnets. In the frame of this R&D program, cooling studies are carried out to determine the heat extraction from this new type of accelerator magnets and the relevant quench limits.

In this paper we present and discuss experimental results of heat transfer through the electrical insulation of Nb₃Sn cables. A cable-stack was prepared using fiberglass sleeves and CTD-101K impregnation resin. Two different measurement methods were compared, consisting of instrumenting the sample before or after the vacuum impregnation. The tests were performed both in 1.9 K superfluid and 4.2 K liquid helium baths, using different heating configurations. We also present results of the numerical model developed to reproduce the experimental results.

Index Terms—Electrical insulation, heat transfer, LHC upgrade, Nb₃Sn, superconducting high field magnets.

I. INTRODUCTION

THE Large Hadron Collider (LHC) [1] has operated for a few years and produced new physics, while working at about half its nominal beam energy [2]. The full energy will be reached after consolidation of the defective splices of the magnet interconnections, taking place in 2013/2014 [3]. In the meantime, CERN has defined a plan to upgrade the LHC, starting with a Luminosity upgrade, High Luminosity LHC (HL-LHC) from around 2020, possibly followed by an Energy upgrade, High Energy LHC (HE-LHC), around 2030. This plan consists of several projects requiring the development of new superconducting accelerator magnets beyond 10 T [4]: FRESCA2 [5], the 11 T dipole [6], MQXF [7] and a 20 T dipole for HE-LHC [8].

These magnets are based on the Nb₃Sn technology, which allows reaching the required magnetic fields. All the aforementioned studies run under the project called *High Luminosity LHC*. In this frame we investigated the thermal behavior of Nb₃Sn coils. This is of interest for the magnet design, especially when having to cope with large heat loads [7], as well as to determine its quench limits [9] [10].

In this paper we present experimental results of heat transfer

through the electrical insulation of the cable of the MQXF low- β quadrupole foreseen for HL-LHC. After summarizing the features of the electrical insulation of Nb₃Sn cables in section II, we describe in section III the experimental setup and two different instrumentation methods we installed for comparison. Section IV reports the results, obtained in a 1.9 K and a 4.2 K helium bath, corresponding to the different cooling options envisaged [11]. In section V we further analyze the experimental results to determine the thermal conductivity of the insulation. In section VI we present the results of a simple numerical model allowing the reproduction of the sample's thermal behavior.

II. ELECTRICAL INSULATION OF Nb₃Sn CABLE

The insulation of Nb₃Sn coils manufactured with the most common *Wind & React* technique is made of a mineral fiber cloth wrapped around the cable before the winding and the subsequent heat treatment at around 700 °C to form the Nb₃Sn compound. Following the heat treatment, the coil is vacuum impregnated with epoxy resin.

The fiber cloth, which must withstand high temperature without downgrading the mechanical properties, has different purposes: it helps in controlling inter-turn distances and thus final coil size, it facilitates an even distribution of resin and reduces crack propagations. As for the epoxy resin, it enhances the turn-to-turn breakdown voltage and confers a rigid shape to the coils, in order to ease handling and assembly and to protect the brittle material [12]. Furthermore, it can limit the stress concentration at the crossovers between strands of the two-layer Rutherford-type cable [13].

The different types of fiber cloth used are the boron-free S or S2-glass in the USA and R-glass in Europe, and the E-glass which contains boron and therefore shows degradation after exposure to neutron radiation. Glass-fibers are coated with organic materials (“sizing”), indispensable for weaving but leaving electrically conducting carbon residues during the heat treatment to form Nb₃Sn. For this reason the fiber is “de-sized” (removal of the sizing compound) and later “re-sized” to restore its lubricant properties.

The fiber cloth can be in the form of tape, sleeve or braid, possibly combined with mica/glass sheet [14]. The most used impregnation resins are: CTD-101K, MY-750 with Jeffamine-400 hardener, Araldite F with HY-905 hardener [15].

III. EXPERIMENTAL SETUP AND INSTRUMENTATION METHODS

The experimental setup is a cable-stack representative of a coil, as in [16]. We used cables made of resistive strands in

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order to generate Joule heating, uniformly over the cable cross-section by supplying a few dozens of Ampères. The cable temperature was measured with $\text{AuFe}_{0.07\text{at}\%}$ -Chromel thermocouple junctions (TCJs) built in-house.

The test sample was prepared from six pieces of $\text{CuNi}_{10\text{wt}\%}$ cables with the same geometry as the LHC Cable 01 [1]. Each cable piece was insulated with a S2-glass fiberglass sleeve, which did not undergo any de-sizing process. The six insulated cable pieces were alternately stacked to compensate the keystone angle, thus forming a rectangular stack. In order to bond the fiberglass insulation and the cable into a monolith of accurate dimensions, the stack was vacuum impregnated using the epoxy resin CTD-101K. The dimensions of the impregnation mold determine the final stack dimensions, as well as the insulation thickness. They were defined in order to have an insulation thickness of 150 μm on all the cable faces. Since our sample was built from resistive cables, the usual Nb_3Sn heat treatment at about 700 $^\circ\text{C}$ was not carried out. The materials used and the geometrical parameters of the sample are reported in Tables I and II.

Five adjacent cable pieces were connected at their extremities to a current supply, the sixth one being necessary only for geometrical reasons. The heat generated in the cables was calculated, with an error smaller than 0.1 %, using the measurement of the voltage at the cable extremities and of the injected current. Different heating configurations were studied; heating 1, 3 or 5 conductors, while measuring the temperature of the central one. This allowed studying the impact of a localized heat deposition versus a distributed one.

The sample preparation was completed by adding 5 mm thick fiberglass plates above and below the stack to reduce the heat flow through the large faces of the cables, and epoxy resin plugs on its extremities to prevent longitudinal cooling. No mechanical pressure was applied on the sample during the tests. Indeed, unlike the case of He-porous cable insulations, where the applied mechanical pressure influences the heat extraction [16], there is no pressure dependence for impregnated insulations. The sample (Fig. 1) was installed in a saturated bath cryostat, with both small sides of the cables in direct contact with the He bath over the central 140 mm.

The next subsections describe the two instrumentation methods for the temperature measurement that were implemented and compared. In both cases the relative error of

the measured temperature difference between the cable and the He bath was evaluated to be less than 3%. The bath was regulated to the temperature of either 1.9 K or 4.2 K, stabilized within 0.2 mK or 10 mK, respectively, and measured using two Cernox temperature sensors with absolute errors smaller than 10 mK.

A. Instrumentation before impregnation

The first instrumentation method, less invasive than the other one, is more complex. It consists of inserting the TCJs in one of the central cables (the third from the top) before insulating it. The TCJs and their wires were located in grooves machined into the strands. Some of the TCJs were placed in the cable axis, i.e. at equal distance from the two small faces of the cable, and some closer to the small faces. The wires were guided along the grooves towards the thick edge of the cable and through the insulation outwards.

One of the main difficulties of this method is the removal of the sample from the mold after the impregnation without damaging the sensor wires. The very brittle TCJs wires needed to be extremely well protected, thus complicating the process.

B. Instrumentation after impregnation

The second instrumentation method is simpler and commonly used [17] [18], although more invasive. It was implemented in the other central cable (the fourth from the top) of the same sample, where three holes were drilled perpendicularly to the cable small face (horizontal direction in Fig. 1), after impregnation. The holes had a diameter of 1 mm and a depth of half the cable width. They hosted three TCJs and each was filled using a different filler: the same epoxy resin CTD-101K used for the stack impregnation, the DP-190 epoxy which is widely used for cryogenic measurements, and the Apiezon N cryogenic high vacuum grease.

IV. HEAT TRANSFER RESULTS

The measurements aim at correlating the steady-state temperature difference between cable and bath to the power generated in the cable, which equals the heat flowing out of the cable. The temperature difference is referred to as temperature increase. The power indicated on the x-axis of the following plots is generated in the central cable where the temperature is measured, while either none, one or two adjacent cables on both sides were heated electrically in series.

A. Sample instrumented before impregnation

Fig. 2 and 3 report the experimental results obtained with

Fig. 1. Sample instrumented before impregnation.

TABLE I

MATERIALS OF THE SAMPLE COMPONENTS

Component	Sub-component	Material
Cable	strands	Cu-10wt%Ni
Insulation	fiberglass sleeve impregnation resin	S2-glass CTD-101K

TABLE II

SAMPLE GEOMETRICAL PARAMETERS

Cable	strand diameter	(mm)	1.065
	number of strands	(-)	28
	mid-thickness	(mm)	1.9
	width	(mm)	15.1
Insulation	thickness	(μm)	150
Stack	heat transfer length	(mm)	140

sensors installed before impregnation, at a bath temperature of 1.9 and 4.2 K, respectively. At a fixed power, the temperature increases when passing from 1 to 3 to 5 heated cables because of the different boundary conditions of the instrumented cable. The temperature is higher in the cable center than in the edge because of the larger distance to the bath.

All the curves feature the typical shape of pure conduction curves, because of the impregnated structure of the stack. This is different from the insulation of Nb-Ti cables, conducting more heat at small temperatures [9] thanks to its porosity to He II [19]. On the other hand, Nb₃Sn coils can exploit a larger temperature margin than Nb-Ti coils thanks to the higher critical surface. The smaller temperature differences in the 4.2 K bath w.r.t. the 1.9 K case at the same heating power result from the thermal conductivity of the insulation increasing with temperature.

B. Sample instrumented after impregnation

Fig. 4 and 5 report the experimental results obtained with temperature sensors installed after impregnation, at a bath temperature of 1.9 K and 4.2 K, respectively. They are compared to the results obtained with the other technique,

Fig. 2. Measured temperature difference between cable and bath as a function of the power generated in the central conductor, in a He bath at 1.9 K. The temperature sensors were installed before impregnation, in the cable center and edge. The lines are a guide to the eye.

Fig. 3. Measured temperature difference between cable and bath as a function of the power generated in the central conductor, in a He bath at 4.2 K. The temperature sensors were installed before impregnation, in the cable center and edge. The lines are a guide to the eye.

showing a maximum difference of 15%, probably due to the thermal conductivity of the filler materials. In particular, the DP-190 epoxy features a smaller thermal conductivity than most epoxies [20], which can be the cause of the higher temperature observed for the corresponding TCJ. Also the TCJ whose hole was filled with the impregnation resin CTD-101K features a higher temperature than the TCJ installed before impregnation. We believe it was influenced by the hole filled with DP-190, located at a longitudinal distance of only 5 mm.

In the 1.9 K bath, the TCJ whose hole was filled with Apiezon N features a power shift below a temperature difference of 300 mK. This clearly originates from a He II leak. Such behavior was expected, because of the not leak-tight nature of the vacuum grease, whereas no leaks are discernible in the 4.2 K bath. Though at a much smaller scale, the same sign of a He II leak is observed with the other TCJs installed after impregnation. This can be due to the instrumentation, to insulation cracks or to an imperfect impregnation. The latter two imperfections might constitute an issue in case of a quench of a coil. The overheating of the helium penetrated inside the coil might lead to a pressure increase, therefore to mechanical damages.

Fig. 4. Measured temperature difference between cable center and bath as a function of the power generated in the central conductor, in a He bath at 1.9 K. Comparison between the temperature sensors installed after vs. before impregnation. The lines are a guide to the eye.

Fig. 5. Measured temperature difference between cable center and bath as a function of the power generated in the central conductor, in a He bath at 4.2 K. Comparison between the temperature sensors installed after vs. before impregnation. The lines are a guide to the eye.

Fig. 6. Thermal conductivity of the S2-glass + CTD101K insulation derived from the experimental results (red symbols), extended to higher temperatures using a logarithmic fit. Values for other materials are reported for comparison ([20] [21] [22] [23]).

V. THERMAL CONDUCTIVITY OF THE INSULATION

In case of 5 heated cables we can assume that the heat from the instrumented cable is mostly extracted perpendicularly to the cable small faces, because of the negligible heat transfer towards the adjacent cables. Using Fourier's law, we computed the thermal conductivity of the insulation composite material of known thickness (150 μm) and surface (1.9 mm x 2 x 140 mm). We considered the temperature of the cable edge, measured with sensors installed before impregnation. The very high He II thermal conductivity allows to assume the insulation surface temperature on the cold side to be equal to the bath temperature.

The results, plotted in comparison to other materials in Fig. 6, refer to temperatures from 2 to 4 K. In order to build a model of the experiment, values of thermal conductivity are needed also at higher temperatures. Among the different fits that were tried to extend the conductivity curve above 4 K, the best agreement between tests and model (shown in the next section) was found with a logarithmic fit. The derived thermal conductivity is about 60 to 80% of the one of G10 [21], smaller than that of E-glass fiber and DGEFB epoxy resin [22] and pre-impregnated tape IVA [20], but larger than that of DP-190 epoxy [20] and polyimide [23].

VI. MODELING

We developed a simple 2-D model using COMSOL Multiphysics [24]. The non-insulated cable is simulated by a

Fig. 7. Computed temperature distribution in the stack cross-section. The heat deposit rate is 200 mW/cm² in 1 cable (left) and in 5 cables (right).

Fig. 8. Temperature difference between cable center and bath as a function of the power generated in the central conductor, in a He bath at 1.9 K. Comparison between test and model.

rectangular domain for which we assumed a homogenized thermal conductivity equal to the weighted average of Cu-10wt%Ni and epoxy [21]. The latter contribution was found to be negligible. The thermal conductivity of the cable insulation is the one derived in the previous section, whereas for the fiberglass plates we assumed that of G10 [21]. Heat transport in the 1.9 K bath is described by the He II Gorter-Mellink law. We neglected the thermal boundary resistance at the strand-epoxy and insulation-bath (Kapitza) interfaces.

Fig. 7 shows the temperature distribution in the stack cross-section, for the cases of one (left) or five (right) heated cables. The temperature gradients develop in the left and right fourth of the cable, whereas the temperature in its central part is constant. The model reproduces the measured temperature differences well, as Fig. 8 shows. For the different heating configurations, as well as for the different sensor locations (cable center and edge), the difference is smaller than 10%.

VII. CONCLUSION

We performed stack measurements of the heat transfer through the electrical insulation of Nb₃Sn cables for the MQXF low- β quadrupole foreseen for HL-LHC. Two different instrumentation techniques were compared, showing that it is admissible to instrument the sample after impregnation, possibly filling the holes hosting the temperature sensors using the same resin as for impregnation.

The thermal conductivity of the insulation was determined to be about 60 to 80% of that of G10. Using the derived values, the results of all the different heating configurations can be reproduced with a simple model. Hence knowledge of the thermal conductivity of the insulation composite material is sufficient to reproduce the coil thermal behavior.

The approach described in this paper is suitable to investigate also other types of Nb₃Sn coils, as well as High Temperature Superconductor (HTS) coils.

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