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A NEW CABLE INSULATION SCHEME
IMPROVING HEAT TRANSFER TO SUPERFLUID HELIUM
IN Nb-Ti SUPERCONDUCTING ACCELERATOR MAGNETS

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A new cable insulation scheme improving heat transfer to superfluid helium in Nb-Ti superconducting accelerator magnets

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Abstract

The next applications of superconducting magnets for interaction regions of particle colliders or for fast cycled accelerators require dealing with large heat fluxes generated or deposited in the coils. Last year [1] we had investigated the theoretical potential for a large improvement of heat transfer of state of the art Nb-Ti cable insulations in superfluid helium, such as the one used for the LHC superconducting magnets. In this paper we present and discuss new experimental results, confirming that a factor of four increase of the allowed heat flux from coil to coolant can be obtained with the new insulation topology while keeping a sound margin in the dielectric performance.

INTRODUCTION

Superconducting magnets require, as any electrical device, active parts be dielectrically insulated from each other and from ground. Though the conductor resistance is null in the superconducting status, during transients, i.e during magnet energization or during a quench, the voltage difference between adjacent cable turns and between coil and ground can rise to levels approaching or even exceeding the kV range. The large energy stored in superconducting magnets makes the event of an electrical short circuit a potential hazard not only for the safety of the magnet itself but in certain cases for the whole accelerator.

Every turn of the coil has thus to be dielectrically insulated from the adjacent turns as well as from the metallic components of the magnet.

In case of the main LHC superconducting magnets, all wound with Nb-Ti cables, the insulation is composed of helicoidally wound polyimide tapes (figure 1).
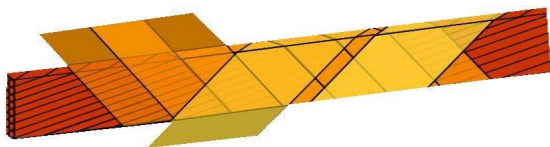

Figure 1:All-polyimide insulation of LHC main magnets.

The inter-turn voltage arising in case of a quench is in the worst case of about 100 V, corresponding to an electric field lower than 500 V/mm, well below the dielectric strength of the bulk polyimide tapes. The issue is thus to avoid the mechanical punch-through the insulation and provide a sufficiently long surface path, leading to a design with a first insulation layer composed by two 50% overlapped tapes.

A second, outer, layer is intended to protect the first layer and to provide cohesion between coil turns. It consists of a single polyimide tape with, on the outer face, a thin coat of polyimide adhesive activated by thermal treatment; the tape is wound with spacing to create gaps for helium to reach the inner layer.

This insulation scheme proved to be sufficiently robust during the manufacture and testing of the main LHC superconducting dipoles and quadrupoles. The spaces provided by the outer layer tape and the one-sided adhesive coating allow increasing the heat transfer through the insulation compared to a "sealed" insulation, as the one considered for the SSC superconducting magnets.

As a comparison, in figure 2, we plot the temperature increase of a cable insulated according to a SSC type and to a LHC type insulation with respect to the heating power generated in the cable. The data are extracted from [2]. The original data in the horizontal axis are here represented as power generated in an inner layer cable turn per meter of length. As shown in the photo embedded in figure 2, we also consider that the heat is evacuated only through the inner edge of the cable and not by both inner and outer edges. As the experiment reported in [2] was done on a sample allowing the heat transfer from both cable edges, we divided the original power data by a factor of two. The vertical axis represents the relevant cable temperature increase when the sample is immersed in a superfluid helium bath at 1.9 K.
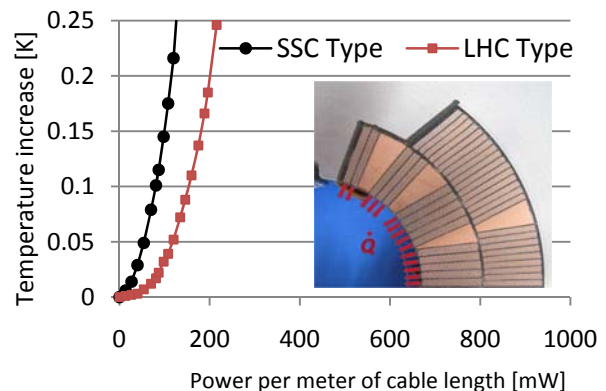

Figure 2: Temperature increase of an insulated cable transferring heat into a superfluid helium bath at 1.9 K through its inner edge. Data scaled from [2].

IMPROVING THE HEAT TRANSFER

The heat transfer from the cable to the superfluid helium bath can be schematized into two different components: one through the open spaces constituting micro-channels between the insulation tapes, the other by solid conduction across the insulation bulk. The study

reported in [1] shows that, thanks to the high thermal conductivity of superfluid helium, the transfer through these micro-channels can be extremely efficient until the lambda transition. With respect to the present insulation scheme used for the main LHC magnets there is then a large margin for improving the heat transfer by increasing the size of the helium channels.

The proposed scheme avoids a direct overlap wrapping by separating the first and last tapes by a series of polyimide strips wound counter-wise, as shown in fig. 3.
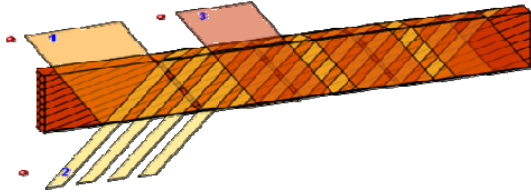

Figure 3: Enhanced all-polyimide insulation.

In such a configuration three distinct layers are wound with spacing, with the first and third layer having what we may call a "spaced overlap" providing at the same time cooling channels and dielectric insulation.

HEAT TRANSFER MEASUREMENTS

The measurements reported in this section are based on experience that we gained in similar measurement [3] on a segment of an LHC production coil, modified by the use of a sample made of resistive cable as in [4].

Sample Preparation

The test sample was prepared from a cable made of 28 resistive $CuNi_{10 \, wt.\%}$ strands with the same geometry as the LHC Cable 01, insulated according to the enhanced insulation scheme described in the previous chapter. Six cables were superimposed alternatively with the thick or the thin edge to one side to form a rectangular stack (Figure 4), and cured according to the standard bonding cycle of the LHC main superconducting magnets, consisting of a pressure cycle up to 80 MPa at a temperature of 190°C.

The active part of the sample, where the transfer of heat was measured, was 150 mm long.

Five adjacent cables were connected at their extremities to a current supply. Heat in the sample was generated by Joule heating in the resistive strands, uniformly over their volume. Voltage was measured at the cable extremities to monitor the heating power.

The central cable, i.e. the 3rd one of these five adjacent cables, was instrumented with an array of eight arc-welded $AuFe_{0.07at\%}$ Chromel thermocouple junctions (TCJs) following the same technique as in [3], with the variant that the TCJs were installed in small pits of Ø 0.6 mm drilled in strands.

The thermocouple wires were then drawn along groves among the cable strands towards the thick edge of the cable and through its insulation outwards. A 3-mm-thick fiberglass plate was added on each side of the stack.

Both extremities of the sample were thermally insulated by epoxy resin rectangular plugs to prevent parasitic cooling of the sample from its extremities, which biased our heat transfer measurement in [3].

The sample was installed in a spring-like holder. Pressure of 30 MPa was applied on the wide side of the cables. Small sides of the cables were exposed to the HeII bath on both sides of the stack.

The sample in its holder was installed in a Claudet-bath cryostat as in [3].

Results

The transfer of heat through the insulation was evaluated by measuring the difference ΔT_{HT} between the temperature of the sample and the temperature of the HeII
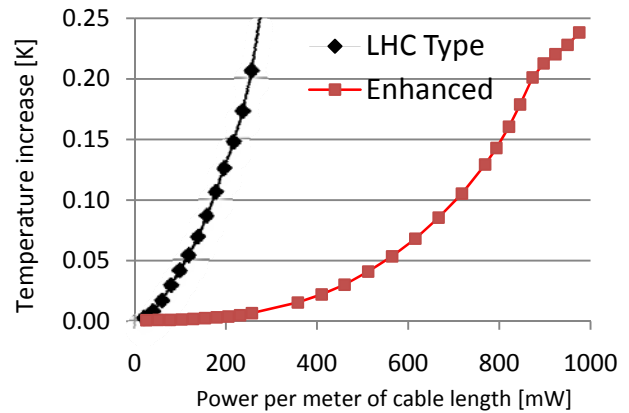

Figure 5: Temperature increase of an insulated cable transferring heat into a superfluid helium bath at 1.9 K through its inner coil edge.

bath for given constant heating power applied to five cables.

The temperature of the HeII bath, stabilized within 0.2 mK, was measured by three Ge temperature sensors with absolute error less than 10 mK. Relative error of the temperature difference ΔT_{HT} was less than 7 %. The heating power P_{heat} was calculated from measured current and voltage with an error smaller than 0.1 %.

The test results shown in figure 5 have been plotted following the same criteria used for figure 2.

The power generated in the cable sample has been scaled to a unitary length of one meter and divided by two to consider heat transfer from a single cable edge.

For reference, a sample made according to the "LHC type" insulation has also been measured at CERN. The relevant results, which are close to those presented in figure 2, obtained by a different laboratory with a different experimental set-up, are shown in figure 5.

The results show that the enhanced insulation scheme, before reaching the lambda point at which superfluid helium channels start getting saturated, can draw about four times the power which can be evacuated using the standard LHC type insulation.

In average, in the hypothesis that heat is evacuated only from one cable edge, each meter of cable turn can transfer almost 1 W to the superfluid helium bath.

DIELECTRIC STRENGTH

The required interturn breakdown voltage shall be sufficiently higher than the 100 V reported previously multiplied by a factor taking into account possible gaseous environment plus test margins.

The verification of the dielectric strength of the enhanced cable insulation is still preliminary, because the exact layout is being trimmed to optimize the wrapping of the tapes around the cable and thereafter coil winding in a semi-industrial environment.

Dielectric strength tests were carried out on samples composed by two insulated LHC inner layer cable sections, 250 mm long. This pair was first submitted to the standard bonding cycle as described in the previous chapter, consisting in a pressure cycle up to 80 MPa at a temperature of 190°C. The two extremities of the sample were thereafter separated by an insulating foil and the central section, over a length of 160 mm, was submitted to a dielectric strength test under a pressure of 50 MPa. Discharge values ranged from 8 kV to 30 kV depending on the layout and thickness of different alternative insulations.

DEPENDENCY ON APPLIED PRESSURE

The proposed insulation scheme is based on free channels made available for helium. As the heat transfer tests described in the previous chapters were executed under a moderate pressure (of the order of 30 MPa), we designed a test set-up (figure 6) to measure the apparent geometrical porosity of the insulation as a function on the applied pressure.
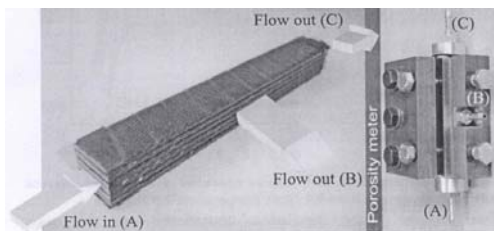

Figure 6: set-up for measuring apparent porosity to air.

A cured insulated 6 layers stack is encapsulated in a sealed mould. Air is injected under pressure through the cable strands and evacuated from the stack sides, thus through the cable insulation. Samples were made with bare cables, with the standard LHC main dipoles insulation and the "enhanced" insulation, obtaining the data shown in figure 7.

The test results confirm the large improvement in the porosity of the "enhanced" insulation scheme compared to the standard one, and show that the channel geometry remains stable between 10 and 50 MPa. These results are in line to the observation that, above 10 MPa, coils made with such insulations show a relatively high elastic modulus, of the order of 10 GPa, indicating that the morphology of the insulation wraps remains relatively stable.
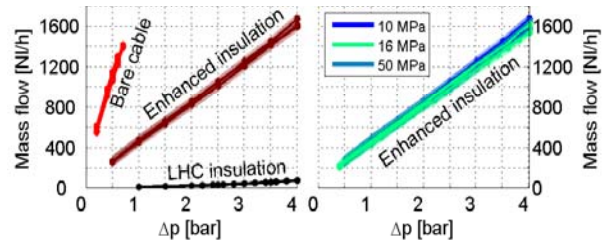

Figure 7: Radial flow in cables with vertical compression of 10 MPa (left plot). Radial flow in cables with enhanced insulation, vertical compression of: 10, 16 and 50 MPa (right plot).

CONCLUSIONS

We presented new experimental data on a new all-polyimide insulation scheme designed to increase heat transfer in Nb-Ti magnets. Such insulation features a remarkable permeability to helium thanks to the newly introduced "spaced overlap" concept. Measurements performed in superfluid helium, when the insulated cables are submitted to a pressure of about 30 MPa, show an improvement in heat transfer by at least a factor of four compared to the standard all polyimide insulation scheme used for the main LHC superconducting magnets. The dielectric strength of the insulation appears well above the required values, providing inter-turn breakdown voltages of the order of 10 kV when the samples are tested in air submitted to a pressure of 50 MPa. The apparent porosity of the insulation does not seem affected by pressure in the interval between 10 and 50 MPa.

Next steps will be the optimization and characterization of the insulation scheme for the industrial manufacture of superconducting coils and the validation of the heat transfer data at higher pressures up to 150 MPa.

ACKNOWLEDGEMENTS

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