Heat Transfer Measurements through Thermally Enhanced Insulation Schemes for Nb-Ti Superconducting Magnets operating in He-II

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Superconducting magnets submitted to large heat loads, as the low-β quadrupoles for the LHC luminosity upgrade, need the development of new concepts of cable electrical insulation featuring a He-II porous wrapping scheme.
This paper reports and discusses recent results of dedicated heat transfer measurements performed on different variants of such schemes, with emphasis on the heat transfer enhancements achievable with respect to the state-of-the-art insulation used for the main LHC magnets.

INTRODUCTION

Superconducting magnets for future applications, as for the interaction regions of particle colliders or for fast cycled accelerators, will be very demanding from the thermal standpoint requiring to deal with large heat loads. In order to overcome the current limitations it is necessary to improve the cable insulation, that constitutes the bottleneck of the magnet cooling potential.

In the frame of the R&D of the new Nb-Ti inner triplets for the LHC upgrade [1], an innovative cable insulation scheme was developed [2]. This Enhanced Insulation (EI) relies on a wrapping pattern improving the heat transfer to the He-II bath, while ensuring the necessary electrical protection [3]. Hence it will allow maintaining the magnet in the superconducting state under the large heat deposition associated to the achievable luminosity, higher than in the current exploitation of the accelerator [4].

This paper reports the results of heat transfer measurements performed on a variant of EI scheme, based on the same concept but with different geometrical parameters. The improvement with respect to the state-of-the-art insulation scheme used in the LHC magnets is confirmed, as well as the weak thermal coupling between adjacent cables. The driving heat transfer mechanisms are discussed, depending on the cable temperature.

INSULATION SCHEME

The EI features a different wrapping scheme from that of the LHC magnets [5], aiming at increasing the He-II heat transfer through the micro-channels located between the insulation tapes with respect to the solid conduction across the insulation bulk. The scheme is made of three polyimide tapes, as shown in Figure 1.

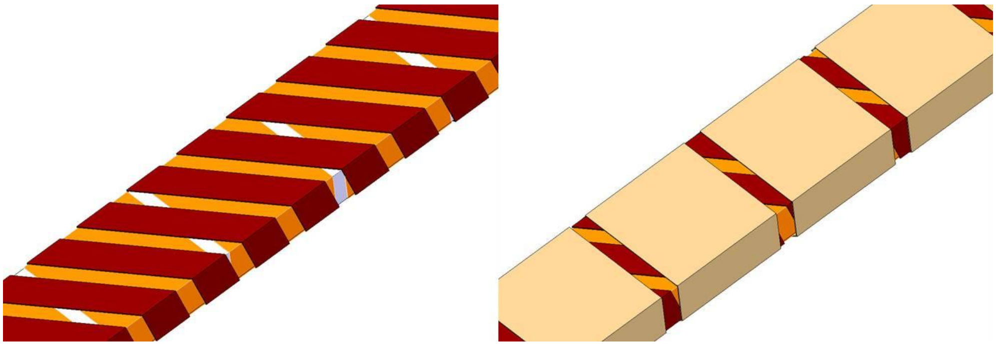

Figure 1 Scheme of the Enhanced Insulation: the 1st and 2nd tapes are shown on the left, whereas all the tapes are shown on the right.

Compared to the three tapes of the LHC insulation scheme, the role of the second tape in the EI is not to provide electrical insulation (together with the 1st one), but spacing between the other tapes thus increasing the micro-channels network. The electrical insulation function is taken over by the third tape, 50 % overlapped with the 1st one, along with the mechanical stability function. Indeed, in both schemes the last tape ensures the cohesion between coil turns thanks to a thermally activated adhesive film on its external part. Furthermore, all the tapes in the EI are wound with spacing.

Table 1 reports the geometrical parameters of the last tested variant of the Enhanced Insulation (EI3), as well as of the previously tested one (EI4) and of the insulation of the LHC main bending (MB) dipoles. EI3 and EI4 are different versions of EI selected among the four versions electrically and mechanically tested so far [3]. They only differ for the thickness of the second tape.

Table 1 Geometric parameters of the considered insulation schemes

Insulation scheme	**1st tape (polyimide)**	**2nd tape (polyimide)**	**3rd tape (adhesive polyimide)**
MB	11 mm wide, no gap 50 μm thick	11 mm wide, no gap 50 μm thick, 50 % overlap with 1st tape	9 mm wide, 2 mm gap 69 μm thick, cross wrapped with 1st & 2nd tape
EI4	9 mm wide, 1 mm gap 50 μm thick	3 mm wide, 1.5 mm gap 75 μm thick, cross wrapped with 1st & 3rd tape	9 mm wide, 1 mm gap 69 μm thick, 50 % overlap with 1st tape
EI3	9 mm wide, 1 mm gap 50 μm thick	3 mm wide, 1.5 mm gap 50 μm thick, cross wrapped with 1st & 3rd tape	9 mm wide, 1 mm gap 69 μm thick, 50 % overlap with 1st tape

EXPERIMENTAL SETUP

The heat transfer measurements aim at determining the steady-state cable temperature of a cable stack reproducing a coil as a function of the extracted heat. The experimental method was described in detail in [2]. It is similar to that used during the LHC design phase [6] since the heat is uniformly generated by Joule effect through a resistive cable. It differs from it mainly because it considers the actual structure of cable, i.e. with the interstices among strands filled by He-II, instead of a machined solid plate.

The sample was prepared from a Cu-Ni cable with the geometry of the LHC type 01 cable [5], insulated according to the EI3 scheme. Six insulated cables were staggered to compensate for the cable keystone, thus forming a rectangular stack which then underwent a curing cycle at 130 MPa, to be consistent with the previous samples. The cables were connected to a current supply, and the dissipated power was calculated from the voltage at the cable extremities and the injected current.

One of the central cables was instrumented with $AuFe_{0.07at\%}$-Chromel thermocouple junctions (TCJs). After removing a small square of insulation from the cable's flat side, they were installed in grooves machined in the strands, then sealed using epoxy resin. Although only one cable was instrumented, it was possible to evaluate the thermal coupling between cables by heating-up one of the adjacent ones. The relative error of the measured temperature difference between the cable and the bath was evaluated to be less than 3 mK or 3 %, whichever is bigger.

The sample was completed by adding fiberglass plates on the stack sides for thermal and mechanical reasons, and epoxy resin plugs on its extremities to prevent longitudinal parasitic cooling. It was installed in an Al-alloy spring-like holder, allowing to apply a compressive stress on the cables flat side. Note that the stress values indicated in the next Section refer to room temperature. An increase of 5 % should be considered at 1.9 K for the 50 MPa value, whereas there is no significant difference at 10 MPa. Figure 2 shows the sample under compression in its holder. The epoxy plug of the sample at one extremity is visible, as well as the connections of the cables.

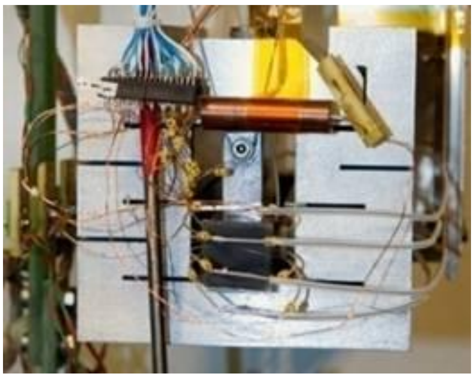

Figure 2 Sample installed in the sample-holder

The sample-holder was installed in a Claudet-bath cryostat, with both small sides of the cables in direct contact with the He-II bath over the central 156 mm. The 0.1 MPa pressurized bath was regulated to the temperature of 1.9 K, stabilized within 0.2 mK, and measured using three Ge temperature sensors with absolute errors less than 10 mK.

RESULTS

The EI3 was tested up to a maximum compressive stress of 50 MPa. It was observed that the effect of stress is more evident at low pressures [2], when the cable is softer, hence the micro-channels undergo a large size reduction. For higher stresses the power extraction does not significantly reduce.

Figure 3 reports the results obtained at the reference stress of 50 MPa, compared to other previously tested insulation schemes [2]. The temperature increases up to a ΔT of 300 mK. The power indicated on the x-axis refers to the central cable, while three central cables were heated up simultaneously. The curve upon which the LHC magnets design was based [6] is also reported, showing a good agreement with our measurements. It must be noted that the setup described in [6] features few differences with respect to ours, mainly the larger conductor dimensions and the use of a machined solid bar instead of a real cable.

With respect to this LHC MB reference case, the EI's allow evacuating about 4-5 times more power. The slight further enhancement provided by the EI3 might be due to the lower peak stress reached during the stress cycle carried out before the installation of the sample in the cryostat. The mechanical effect of the lower peak stress, which was shown in [3], would allow having a larger micro-channels cross-section with respect to the EI4 despite the reduced thickness of the II tape. This enhancement is confirmed at a lower stress of 10 MPa. Modeling of the experimental results is ongoing.

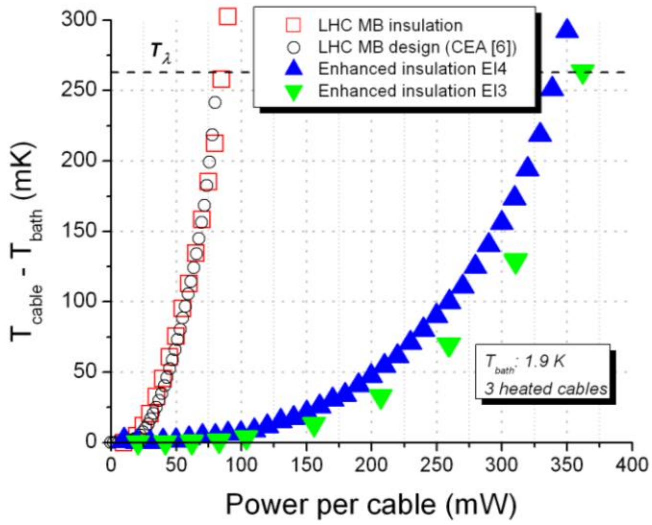

Figure 3 Cable temperature increase vs. power dissipated in the central conductor, in He bath at 1.9 K

Figure 4 shows the results of the MB and EI3 in the case of one heated cable, on the left and on the right respectively. A logarithmic scale was chosen to better highlight the features of the heat transfer laws below and above the λ transition. As long as the He does not overcome the λ transition, the measurements can be reproduced by power laws whose exponent is related to the impact of solid conduction on the overall heat transfer: the higher the exponent is, the more the measurements approach the He-II Gorter-Mellink law. This is the case for the EI3, where the He-II heat transfer is predominant, thus making the solid conduction effect negligible and providing an explanation for the large allowed heat evacuation. The solid conduction effect is never negligible for the MB scheme, because of the less effective micro-channels network. Furthermore, the transition between two regimes characterized by a different exponent is evident in this last case. This transition is associated to the onset of the so-called "mixed regime", already observed in [7], that in our system we believe associated to the point where the solid conduction through the cable small faces is not negligible anymore.

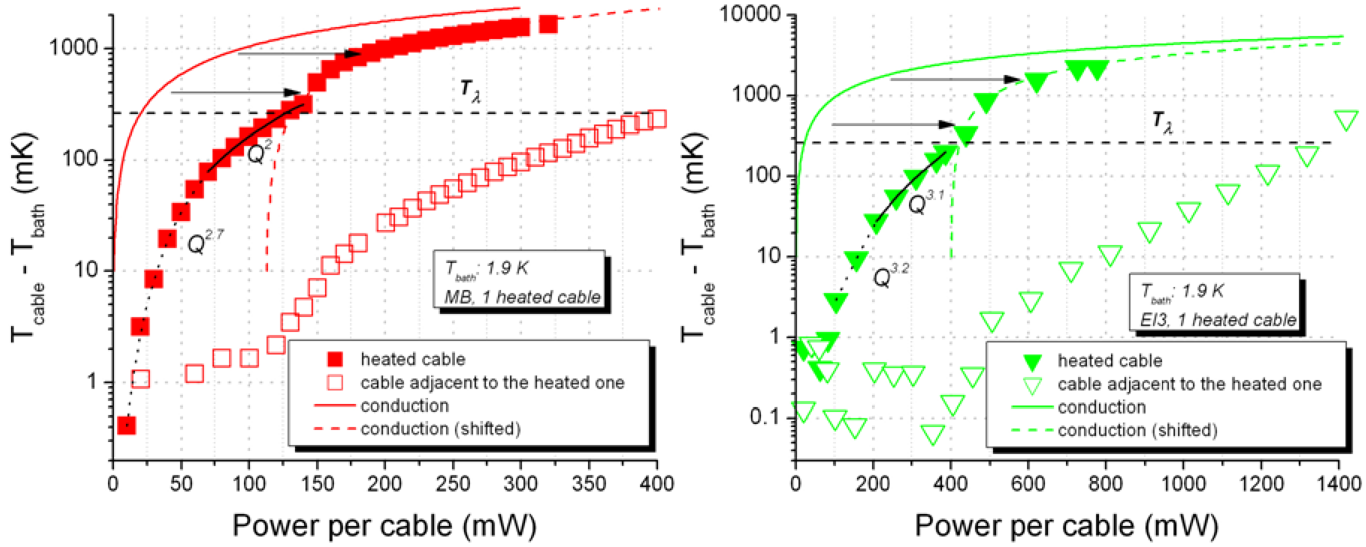

Figure 4 Cable temperature increase vs. power dissipated in the central conductor, in He bath at 1.9 K. MB insulation on the left, EI3 on the right. The conduction curves are shown, as well as the power laws fitting the measurements below 300 mK

The conduction curves are also reported in Figure 4, considered decoupled from the He-II mechanism. They were calculated as the sum of the contribution of the cable small faces towards the 1.9 K bath and of the cable large faces towards the adjacent cables, whose temperature is reported in the Figure as well. The second contribution is more important because of the larger heat transfer surface. If shifted to the point where the abrupt rise in temperature associated to the λ transition occurs, the conduction curves reproduce fairly well the experimental data after this point. The solid conduction mechanism becomes dominant, that is confirmed by the corresponding temperature rise of the adjacent cable. However the He-II mechanism is still present above the λ transition, probably because the only He in the channels undergoing the λ transition is that close to the cable [7].

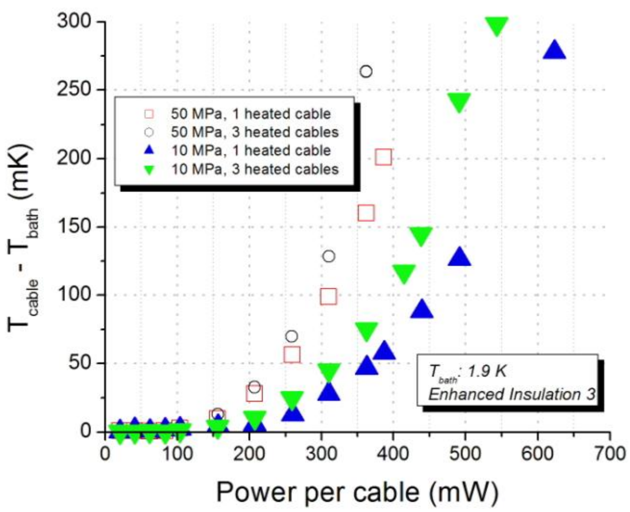

Figure 5 Cable temperature increase vs. power dissipated in the central conductor for EI3, in He bath at 1.9 K. Two stresses and two heating configurations are considered

It is worth noting that the temperature of the heated cable at which the adjacent one starts increasing its temperature is larger for EI3 than for MB. This confirms the already observed weaker thermal coupling of the EI with respect to MB, thanks to the efficient heat transfer between cable and bath.

Figure 5 shows the more efficient heat extraction in case of one heated cable with respect to three, both at an applied stress of 10 and 50 MPa. The higher the applied pressure is the lower is the heat transfer, as expected because of the reduced dimension of the micro-channels. The relative increase of heat transfer when going from three to one heated cable is larger at 10 MPa than at 50 MPa. This means that, if no other cables are heated, the central one can transfer more heat to the bath through the He-II channels located between itself and the adjacent cables, rather than by solid conduction to its adjacent cables.

CONCLUSION

A new variant of He-II porous cable insulation scheme was tested in the frame of the development of the Nb-Ti superconducting magnets for the LHC upgrades. Heat transfer measurements confirmed the improved heat transfer capability of such schemes by at least a factor of four with respect to the LHC insulation schemes. The analysis of the experimental results allowed identifying the dominant heat transport mode of turbulent He-II through the insulation micro-channels. The impact of solid conduction was also shown, depending on the temperature and on the insulation scheme.

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