Quench Heater Technology for HL-LHC Superconducting Accelerator Magnets

C. Scheuerlein, R. De Oliveira, R. Piccin, F. Meuter, F. Glogiewicz, B. Katzer, and T. Thetter

***Abstract*—Quench heaters for the active protection of superconducting magnets are large flexible circuits that are produced in a photolithographic process. The HL-LHC quench heater base material, the circuit production process and the qualification tests are described. For potential future use as interlayer quench heater, a Cu coating with a Ta diffusion barrier has been developed that can resist the high temperatures needed for coil reaction. The application of a coverlay enables dielectric tests at voltages that approach the specified breakdown strength of the polyimide insulation. Potential further improvements of heater performance and robustness are discussed.**

***Index Terms*—Electrolytic Cu deposition, flexible circuit, polyimide, quench heater, quench protection, RRR.**

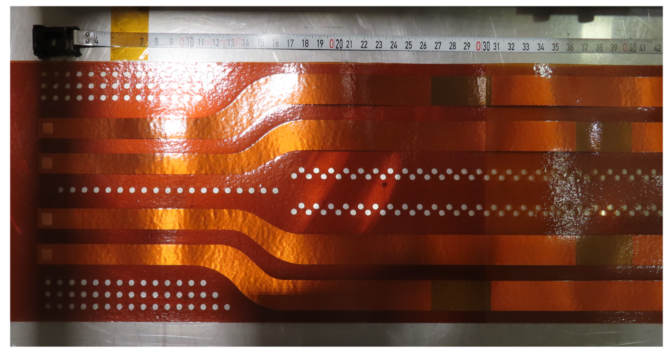

Fig. 1. MQXFB quench heater terminal with coverlay.

I. Introduction

QUENCH heaters are large flexible circuits used for the active protection of superconducting magnets against excessive voltage build-up and coil overheating during a resistive transition [1], [2]. When a quench is detected in a magnet coil, a current pulse is passed through the heater circuits such that a large fraction of the coil becomes normal conducting to distribute the thermal energy over a larger area. This minimises the peak temperature in the coil and prevents coil damage.

For the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) [3] new superconducting Nb_3Sn magnets will be installed. Approximately 500 quench heaters with a total length of about 3000 m are needed for the HL-LHC magnets. The HL-LHC heater circuits need to be partially Cu coated to adapt their resistances [4]. Like the LHC quench heaters [5], the HL-LHC quench heaters are produced using Flexible Printed Circuit (FPC) technology in a photolithographic process. An MQXFB quench heater terminal is shown in Fig. 1.

In the present article we describe the technology used for the manufacturing of the HL-LHC quench heaters, including the base material properties, the Cu coating of the stainless-steel foil and the photolithographic heater circuit etching processes, and we describe the test methods used to assess the heater quality. Cu coating thickness distributions across the entire circuit have been measured, and the heater circuit resistances determined at room temperature (RT), 77 K and at 1.9 K are compared with calculated results. Options for further heater design improvements are discussed.

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II. Quench Heater Laminate Structure

A. Base Material

The HL-LHC quench heaters base material is a commercially available lamination (GTS laminate L960461), consisting of a 50 µm-thick polyimide film (Kaneka Apical 200AV) and a 25-µm thick austenitic stainless steel EN 1.4307 (304 L) hard temper foil. The stainless-steel foil is glued to the polyimide film with a 15 µm thick epoxy adhesive (GTS AS1084).

The thicknesses of the polyimide film and glue, and the polyimide, glue and steel measured together with a micrometre screw are 66.5 ± 3.2 µm and 90.5 ± 1.7 µm, respectively, confirming the nominal thickness values from the supplier.

The Young's modulus and ultimate stress at RT of the Kaneka Apical 200AV polyimide film measured at CERN are $E = 3.3 \pm 0.2$ GPa and $R_m = 170 \pm 26.2$ MPa, respectively, in agreement with the data provided by the manufacturer [6]. The Young's modulus and ultimate stress at RT of the entire GTS laminate are $E = 42.5 \pm 2.0$ GPa and $R_m = 445 \pm 41$ MPa, respectively [7].

To reduce the overall heater circuit electrical resistance, the steel circuits are partially coated with an approximately 10 µm-thick Cu layer, which electrical resistance at cryogenic temperature is small with respect to the stainless-steel resistance. Thus, the quench heater circuit consists of areas with and without Cu layer. This leads to clearly defined heating stations at the positions where the Cu layer is etched away.

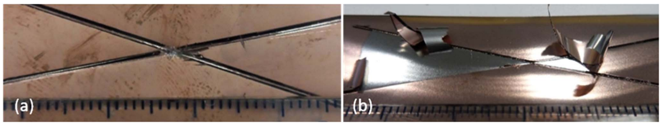

Fig. 2. (a) Electrodeposited. (b) Sputter-deposited Cu coatings tested according to ASTM D6677.

B. Cu Coating Deposition

For the HL-LHC heaters different Cu coating methods have been studied, notably electron beam evaporation [8] and electrolytic deposition. The quality of these coatings has been assessed for instance by ambient temperature electrical resistance measurements, Residual Resistivity Ratio (RRR) measurements and adhesion tests.

A main advantage of the electrolytic Cu deposition process is that it can be performed on the steel-polyimide lamination, whereas during the electron beam evaporation process in vacuum the substrate temperature increased to unacceptably high values causing a degradation of the laminate glue.

The Cu coating of the base material for all HL-LHC quench heaters is performed with a dedicated electrolytic Cu coating line that is operational at the CERN PCB laboratory. This line has coated foils of 16 m. The treatment is continuous, so the maximum possible length is not yet defined.

C. Cu Coating Adhesion

A good adhesion of the Cu coating on the 304L steel surface is crucial for the reliable heater operation. Adhesion tests have been performed according to the standard ASTM D6677 [9], where the test sample is prepared with an "X"-shaped cut in the coating. The sharp edge of the knife is then used to peel off the coating, and depending on the ease of coating detachment the adhesion is rated ranging from 0–10.

A rating system is given, ranging in steps of 2 from 0–10. The coating is rated "0" if the coating can be easily detached and flakes greater than 6.3 mm in length can be peeled off. A rating of "10" is given for a coating that is very difficult to peel from the substrate, and if flakes occur, they are smaller than 0.8 by 0.8 mm. For the quench heaters only Cu coatings rated 10 according to ASTM D6677 are acceptable.

Electrolytically deposited Cu coatings showed very high adherence to the 304L stainless steel surface (Fig. 2(a)). The adherence of sputter deposited Cu coatings [10] was very dependent on the coating process parameters, interlayers and substrate pre-treatment. Fig. 2(b) shows a sputter deposited Cu coating with very low adhesion. Large flakes of coating could be easily peeled from the steel foil.

D. Cu Coating Thickness Distribution

The electrolytic Cu coating process has been optimised to achieve best possible thickness homogeneity across the 15 m long and 0.6 m wide quench heater base material. The Cu coating thickness is derived from the coating surface resistance according to EN 14571 [11], considering the influence of the electrically conductive 304L steel substrate on the Cu coating thickness determination. The Cu coating thickness distribution

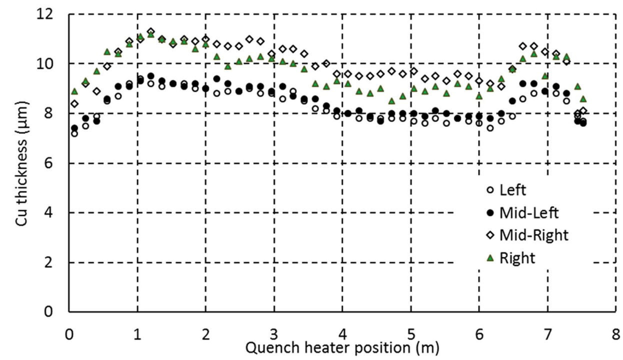

Fig. 3. Typical Cu coating thickness distribution on the four circuits of an MQXFB quench heater.

TABLE I
ELECTRICAL RESISTIVITY OF QUENCH HEATER CIRCUIT MATERIALS

	ρ Cu ($\Omega mm^2/m$)	ρ steel 304L ($\Omega mm^2/m$)
RT	0.017	0.73
77 K	0.004 (RRR=10)	0.53 (RRR=1.372)
1.9 K	0.0017 (RRR=10)	0.53 (RRR=1.372)

has been measured on the base material before heater production and on the finished heaters. During the different chemical etching process typically 1 µm Cu are removed.

A typical Cu coating thickness distribution on the four circuits of an MQXFB quench heater is shown in Fig. 3. The specified Cu coating thickness on the heater circuits is between 5–15 µm.

E. Stainless Steel and Cu Residual Resistivity Ratio (RRR)

At 1.9 K magnet operating temperature the heater resistance is dominated by the resistance of the non-Cu coated heater stations. For the stainless steel EN 1.4307 foil of the heater base material an RRR $= 1.372 \pm 0.025$ has been measured at the CERN Cryolab with samples extracted from the GTS lamination. The same resistivity values can be used for resistance calculations at 77 K, since cooling to temperatures below 77 K has only a very small effect on the resistivity of stainless steel [12].

The function of the Cu coating is to reduce the circuit resistance outside the uncoated heating stations at cryogenic temperature. To achieve this goal, the RRR of the Cu coating [13] needs to be sufficiently high so that the thin Cu coating can work as an efficient low resistance parallel current path.

For the Cu RRR determination resistance measurements of Cu coated steel foil were performed at RT in air and in liquid helium at 4.2 K. The RT electrical resistivity of the stainless-steel substrate is about 40 times higher than the Cu RT electrical resistivity (Table I), and the relatively small influence on the Cu RRR measurement due to current flow through the steel substrate has been neglected. For the HL-LHC heaters a Cu RRR$>$10 is specified.

F. Cu Coating Compatible With Nb_3Sn Coil Reaction Heat Treatment

For magnet protection it could be advantageous to place a quench heater between the two layers of a coil. If both layers are produced without splice and heat treated together, the heater

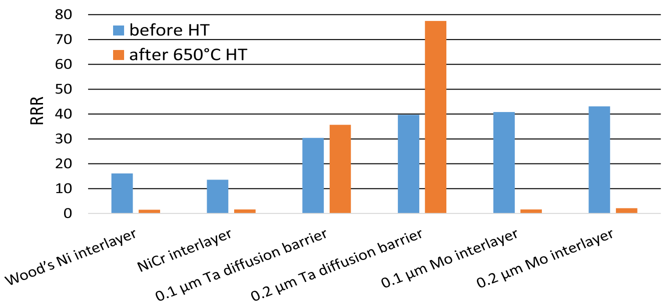

Fig. 4. RRR of Cu coatings before and after the 650 °C-50 h HT.

would need to withstand the Nb_3Sn coil reaction heat treatment with a peak temperature of typically 650 °C.

As a first step for the development of such an interlayer heater, in the context of the 11 T dipole project a Cu coating with a diffusion barrier that prevents Ni diffusion from the steel substrate into to the Cu coating was developed.

The comparison of RRR results before and after the 650 °C heat treatment confirms that the RRR of Cu coatings produced by electrolytic deposition with a Wood's Ni or with NiCr interlayer is strongly degraded by the heat treatment due to Ni diffusion into the Cu.

Two potential barrier materials, notably Tantalum and Molybdenum, have been tested. The barrier layers have been deposited by sputtering [10]. As can be seen in Fig. 4, a 0.1 µm thick Ta interlayer is an effective diffusion barrier with which the Cu coating can keep a good RRR after the 650 °C heat-treatment. A 0.2 µm thick Ta interlayer further reduces interdiffusion of impurities, and the Cu annealing during the 650 °C heat-treatment improves the RRR [14]. The Mo interlayer is not effective to prevent Ni diffusion.

A reliable quench heater insulation system compatible with the 650 °C coil reaction heat-treatment remains to be developed.

III. Quench Heater Manufacturing

The quench heater circuits are chemically etched from the base material using flexible printed circuit production technology. The printed electrical circuit comprising the uncoated stainless-steel heating stations and the Cu coated stainless-steel strips joining them, is created in two sequential photolithographic steps.

By each photolithographic steps we intend the five following steps: 1/lamination of a photoresist on the foil, 2/UV exposure of a pattern trough a mask, 3/development of the desired image, 4/chemical etching of the metallic layer, 5/ stripping of the remaining photoresist. All these steps are done with horizontal continuous machines.

To create the heating stations, the first photolithographic step is done using a mask which is protecting the foil area around the stainless-steel pattern. The open area is then etched with nitric acid to remove the Cu and Ni layer. The nitric acid has no impact on the stainless-steel layer.

The second photolithographic step will use a mask which is entirely protecting the electrical circuits, comprising the Cu coated strips and the stainless-steel heating stations. At this stage the chemical used to etch the metallic Cu/Ni/SS stack in one step is ferric chloride, this chemical etches sequentially these three metals.

After these two steps and applying a final cleaning, the quench heater is ready. Depending on the application a final protection layer (coverlay) can be deposited.

TABLE II
Electrical Resistivity of Quench Heater Circuit Materials

	circuit dimensions (mm)		
	MQXFA	MQXFB	11T
Total circuit length	4506	7500	10812
Uncoated steel length	1040	1800	3300
Cu coated steel length	3466	5700	7512
Circuit width	20	20	19/24

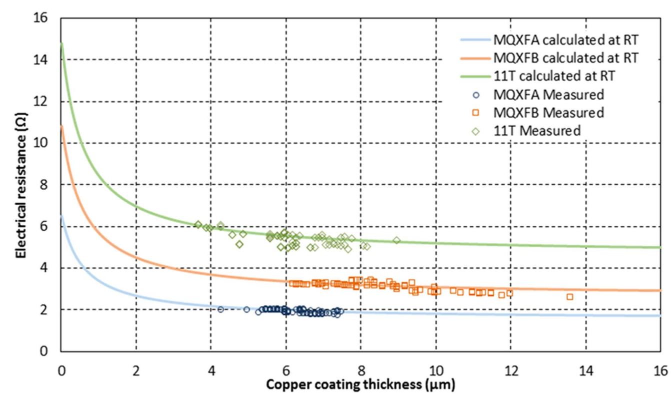

Fig. 5. RT circuit resistance as a function of the Cu coating thickness.

IV. Quench Heater Circuit Resistance

The heater circuit resistances are systematically measured during reception tests at RT. Four-point electrical resistance measurements have been performed with a MEGGER DLRO 10 Digital Low Resistance Ohmmeter with a test current of 10 mA, with an estimated uncertainty of $\pm$ 10 mΩ.

The nominal dimensions of the MQXFA, MQXFB and 11 T dipole quench heater circuits that have been used for the calculation of the theoretical circuit resistance are summarised in Table II.

In Fig. 5 for three heater types the resistances calculated from the nominal circuit dimensions in Table II and the electrical resistivity values presented in Table I are plotted as a function of the average Cu coating thickness. In the same plot the measured resistances are plotted as a function of the average Cu coating thickness determined for the same heaters. The average resistance of the 66 tested 11 T dipole circuits is $R_{11T\text{-}RT} = 5.39 \pm 0.30$ Ω. The average resistances of the 108 MQXFA and the 88 MQXFB circuits tested are $R_{MQXFA\text{-}RT} = 1.95 \pm 0.09$ Ω and $R_{MQXFB\text{-}RT} = 3.12 \pm 0.19$ Ω, respectively.

At RT the variation of the circuit resistances is mainly caused by the Cu coating thickness variations on the laminate base material. The resistance of a completely uncoated 11 T dipole stainless-steel circuit would be 14.5 Ω, and with an infinitely thick Cu coating outside the heating stations the resistance would be 4.62 Ω (the specified Cu thickness is 5 to 15 µm).

For selected heaters the 77 K resistance was measured as well. The average RT to 77 K circuit resistance ratio of the six 11 T dipole heater circuits that were tested is 1.54 ± 0.03. Further cooling to 1.9 K slightly reduces the circuit resistance, and the RT to 1.9 K resistance ratio measured for 24 circuits is in average 1.59 ± 0.06.

V. Terminal-Wire Solder Connections

In the HL-LHC magnets the quench heater circuits are connected to the magnet cryostat vacuum feedthroughs via AXON HH1819 AWG 18 (Ø = 1.024 mm) wires, with an approximate RT resistance of 18 mΩ per m length, and an RRR = 100.

The wires are insulated by wrapped and sealed polyimide tape held together by small amounts of FEP glue. The tensile force at rupture of the insulated wire measured at CERN is 224 ± 10 N (at RT). The heater wires are joined with the Cu coating of the heater circuit terminals by soft soldering, using Sn60Pb40 solder and MOB 39 flux.

The mechanical strength of the solder connections has been tested at RT and in liquid nitrogen at 77 K. Under uniaxial tensile loading the joint can withstand a tensile force of 225 ± 8 N and of 310 ± 33 N at RT and at 77 K, respectively. The joint strength is limited by the strength of the connecting wire, and the solder joint and the Cu coatings remained intact during all RT and 77 K tensile tests [7].

VI. Heater to Coil Insulation System

The insulating polymer film between the quench heater circuit and the magnet coil is required to have good dielectric properties to prevent short circuits between coil and heater. On the other hand, the thermal conductivity of the film and adhesive should be as high as possible.

For breakdown strength measurements of heater insulation samples have been produced from the GTS base material where the steel foil was etched away such that 50 mm × 50 mm steel foil was surrounded by > 100 mm polyimide in order to avoid surface discharges. A Ø = 20 mm high-voltage electrode in contact with the steel foil and a flat grounding electrode were used for the alternating current (AC) breakdown voltage measurements with a voltage rise speed of 611 V/s.

The average AC breakdown voltage measured on four samples is 13.1 ± 0.05 kV/$\sqrt{2}$, and all breakdowns took place below the steel foil through the 50 μm thick film and the 15 μm thick epoxy adhesive.

For comparison, the breakdown voltage stated in the Kaneka Apical 200AV data sheet is 12.6 kV (according to ASTM D149). The minimum specified breakdown voltage is 10 kV.

Flexible heater circuits are commonly encapsulated with a polyimide coverlay. For the second generation MQXFB heaters a coverlay Krempel AKAFLEX KDF 0 50 25 (50 μm polyimide + 25 μm epoxy adhesive) is applied at the CERN PCB laboratory with a static laminator at a pressure of 30 bar and a peak temperature of 170 °C.

Before application of the coverlay the quench heater DC breakdown test voltage was limited to about 4 kV DC in air, because at higher voltages surface discharges occur. After encapsulation of the heaters with a 50 μm thick polyimide film, surface discharges are avoided, and the DC breakdown test voltage could be increased to 8 kV. The minimum distance between the circuit and the polyimide insulation periphery and holes is 7 mm.

VII. Discussion and Conclusion

The well-functioning of quench heaters is crucial for the safe operation of superconducting magnets whose natural quench propagation speed would be insufficient to avoid overheating and excessive voltages. The robustness of the quench heater circuit to coil insulation system and of the heater wire joints are of particular importance.

Partial Cu coating of the steel circuits is needed to adapt the circuit resistance to existing heater power supplies, and to enable quench heater wire joints by soft soldering. The quality of the Cu coating, in particular the thickness distribution and the required excellent adhesion to the steel substrate have been found critical in the HL-LHC quench heater production, and different coating methods have been compared. Electron beam evaporated Cu coatings can provide the required adhesive strength and RRR. However, the laminate temperature increase during this vacuum coating process can cause degradation of the adhesive used to glue the steel foil to the polyimide film.

The electrolytic Cu coating with Ni interlayer adheres well on the steel substrate, and it has the required 4.2 K resistivity. A dedicated coating line was procured with which all HL-LHC heater base material is Cu coated at the CERN PCB laboratory.

The insulation system between heater circuit and the magnet coils must meet the conflicting requirements for highest possible dielectric strength and highest possible heat conductivity. The insulation also needs to resist the mechanical constraints to which the quench heaters are submitted during magnet assembly, thermal cycles, and operation. A redundant insulation system is desirable for high robustness of the heater to coil insulation. The glue between polyimide film and steel foil contributes to the thermal resistance, but only the polyimide film is considered a reliable dielectric barrier.

The application of a coverlay makes the heaters more robust, and it enables dielectric tests at voltages that approach the specified breakdown strength of the polyimide insulation.

To improve heater performance for future magnets quench heaters made with alternative polyimide films with improved breakdown voltage, and heater insulation systems with improved thermal conduction between heater circuit and coil will be produced and tested. The highest breakdown voltage stated for a commercially available 50 μm-thick polyimide film is about 19 kV, thus with such a film the breakdown voltage could be improved by roughly 50%. Thermal conduction can be improved by using an insulating film with improved thermal conduction and/or by reducing the thickness of the glue between circuit and insulating film.

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