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*Large Hadron Collider Project***LHC Project Report 85****Electrical Insulation of Superconducting Cables and Coils in LHC Magnets**

B. Szeless

Abstract

The electrical insulation system comprising composites and organic films for the prototype superconducting dipole magnets for the Large Hadron Collider currently under construction at CERN is presented. The electrical and mechanical aspects of the different components are described and some choices and options are discussed. The mechanical and electrical stresses on the insulation during the production process, storage at room temperature and at operational temperature (below 2 K) and when powered are important due to the dimensions of the cable and due to the forces on the cables and on the coil.

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Switzerland

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ELECTRICAL INSULATION OF SUPERCONDUCTING CABLES AND COILS IN LHC MAGNETS

B. Szeless

CERN - European Laboratory for Particle Physics, CH-1211 Geneva 23, Switzerland

The electrical insulation system comprising composites and organic films for the prototype superconducting dipole magnets for the Large Hadron Collider currently under construction at CERN is presented. The electrical and mechanical aspects of the different components are described and some choices and options are discussed. The mechanical and electrical stresses on the insulation during the production process, storage at room temperature and at operational temperature (below 2 K) and when powered are important due to the dimensions of the cable and due to the forces on the cable and on the coil.

INTRODUCTION

The Large Hadron Collider (LHC) is a 7+7 TeV proton accelerator-collider currently under design at CERN and to be installed in the existing 27 km long circular LEP tunnel [1]. Its superconducting magnets which use NbTi alloy cables operate at superfluid helium temperature and are installed in cryostats with thermal intercepts working at about 5 and 70 K. The nonmetallic construction elements in these cryomagnets are electrical insulation of cable and coils, parts of thermal insulation in the cryostat [2,3] and low heatinleak structural support elements for the magnet in its cryostat [4]. The different components of the electrical insulation and their arrangement in a dipole are shown in Fig. 1. The list comprises cable insulation, copper spacer insulation, "fish bones", quench heaters with their insulation, ground insulation and pole separations, the coil endspacers and ground insulation of the cold bore, beam pipe. A brief description with specific requirements for each item at assembly, warm, cold, and working condition is given.

Fig. 1. Cable and ground insulation arrangement

Fig. 2. Electrical Insulation for NbTi cable

CABLE AND COIL INSULATION

The cable insulation which by definition should take as little space as possible [5,6] consists of an inner (or several inner) and an outer wrap each with distinctive mechanical and electrical functions, Fig 2. The first wrap has to provide a safe electrical insulation; the second wrap provides, apart of electrical insulation, protection of the inner wrap, adhesion to the next turn

of the wound coil, and some space for helium channels between the cable turns. The required properties for the cable insulation at different stages over the life time of a magnet are listed in the table. Several of them are to some extent contradictory like integrity of the electrical properties and permeability to helium.

	300 K winding	~ 465 K curing	300 K assembly + storage	2 K working condition
Tensile and shear strength	X			
Abrasion resistance	X	X	X	
Compressive yield strength		X	X	X
Radiation resistance				X
Dielectrical strength	(X)		(X)	X
Permeability to helium II				X
Bonding		X	X	
Ageing			X	X

Required properties for Cable Insulation at different stages

The insulation tapes which form the wraps are wound with controlled tension around the cleaned cable, a continuous voltage test assures insulation quality. The insulated cable is wound under tension around a cylindrical mandrel and the end spacers to form a semi-circular coil, one pole layer. Due to the small bending radii and the big cable dimensions the insulation suffers shear and in the coil bends additionally tensile stress due to increasing cable width. The degree of mechanical solicitation for a given insulation is largely determined by cable and coil characteristics, Fig. 3. During winding the integrity of the cable insulation is continually monitored between cable and mandrel.

CABLE:

PARAMETERS WHICH INFLUENCE THE SOLICITATION OF THE INSULATION MATERIALS DURING WINDING:

- CABLE SIZE IN PARTICULAR HEIGHT
- RADIUS OF CABLE EDGES
- CABLE PITCH
- FILLING FACTOR
- SOLDERED/UNSOLDERED
- CLEANLINESS, FREE OF METAL CHIPS

LHC

SSC

COIL:

- MANDREL RADIUS 4.5
- BENDING RADIUS 28
- FORCES ON CABLE DURING WINDING 30-60K_g
- QUALITY OF WINDING TOOLING

Fig. 3. Cable and coil parameters acting on cable insulation (dim. in mm)

To activate the adhesion and to form a compact coil it is cured on its mandrel in a mould under azimuthal pressures of 60 to 100 MPa after winding. At this stage the narrow edges of the cable are also exposed to radial pressure from the mould and the mandrel. The result of such a curing process probably badly done and over stressed can look like Fig. 4 where the prepreg used as outer wrap has disappeared exposing locally the inner insulation wrap.

Fig. 4. Cross section of cured coil arc
(polyimide and glass fibre prepreg)

The curing temperature, is a function of curing time, heating power and thermal inertia of the mould. It is 130 to 160°C for various prepreps and at least 185°C for the polyimide adhesives. Possible thermal effects on the cable quality notably the deterioration of critical current are under investigation.

Thickness tolerances of the insulation tapes and of the cables have a strong influence on the apparent Youngs Modulus of the coil for a given mould volume and curing pressure. The Young Modulus of the coil arc is a function of the cable and insulation moduli and the degree of the compaction, Fig. 5. In the model and prototype magnets a shimming between the coil and the enclosing collars takes care of the possible coil size variations to get the right coil dimension for a given prestress. For the series production the aim is a strict dimensional reproducibility of the coil dimensions.

Fig. 5. Youngs Modulus and Thickness tolerance

Once the coil is cured its geometry and electrical integrity are controlled. After that the outer coil is soldered onto the inner coil, and then assembled into the collars under a press, to give the defined radial precompression onto the coil structure. From this moment onward the cable insulation system is exposed continually to compression forces. Cables which themselves are made up of twisted layers of strands touch each other only on a fraction of their common surface, as shown by the prints, with and without insulation from two cables under pressure, Fig. 6. The effective contact surface between cables being much smaller than the overall area the point loads are much higher than the mean pressures exercised on the insulation during curing and collaring. The insulation material yields in some points but so do the cable strands to some extent according to tests performed at CERN. Long term creep with ~ 100 MPa constant pressure was observed on 24 layer cable stacks Fig. 7. As the volume in a real coil is constant the pressure will drop with some creep and thus creep will diminish tending to an equilibrium. Furthermore, creep will decrease drastically once the magnet is cold. To reduce the initial creep before locking the collars, mechanical cycling can be done under the press during collaring.

Fig. 6. Prints of cable without and with insulation

Fig. 7. Creep measured on a stack of 24 cables

The radiation resistance both for warm and cold conditions was checked and seems satisfactory compared to the predicted beam losses [7,8] Fig. 8.

Fig. 8. LHC dose rate for 10 years nominal intensity, annual loss rate $1,65 \times 10^{11}$ protons m^{-1}

For the satisfactory functioning of superconducting magnets at 1.9 K at a given beam loss level inside the coils the cooling between cable and helium bath must be assured by the superfluid helium, so some physical path between cable and outside through the insulation must be created. Thus the permeability to helium becomes an important issue for the layout of the cable insulation. Comparative tests have been and are still being carried out at CEA, Saclay [9], Fig. 9.

Sample Number	First wrap 50% overlap	Second wrap	S mm	t μm
A6 ¹⁾	Kapton 100 HN 25 μm x 12 mm	Glass fibre prepreg 125 μ x 12 mm	2	70
A16 ²⁾	Kapton 120XCI-1 33 μ x 9.5 mm	Kapton 140XRCI-2 38 μ x 9.5 mm	50% overl.	105
A15	Kapton 100HN 25 μm x 12 mm	2 x Kapton 140XRCI-2 2 x 38 μ x 12 mm	2	100
A18	Kapton 100HN 25 μm x 12 mm	Alternating glass fibre prepreg 125 μ x 12 mm	0	109
A19	Kapton 100HN 25 μm x 12 mm	dry glass-Kevlar 120 μ x 10 mm	0	125
A20	Kapton 50HN 12.5 μm x 12 mm	Alternating Kapton 140XRCI-2 dry glass-Kevlar	0	120

1) HERA type insulation system

2) SSC type insulation system

S = Spacing second wrap
t = Total thickness after curing

Fig. 9. Temperature rise of central conductor for different insulation systems

The first model magnets [10,11] and prototype dipole magnets [12] were built with one or two layers of 25 μm dry polyimide film tape as first wrap and glass fibre prepreg or some with mixed glass-fibre-aramide fibre prepreps in the second wrap. This material is now replaced by a thicker ($\sim 65 \mu\text{m}$) polyimide tape with a polyimide adhesive coating on the outside.

The insulation of the copper spacers separating blocks of cables inside the coils have a similar insulation structure as the cables.

The coil end spacers keeping the cables in shape and supporting them at the coil ends, need particular attention due to their complex form and diversity, Fig. 10. The geometry of these spacers represents an inherent problem, their geometry can strictly be correct either for winding stage of the coil or for the finished cured and compressed coil. Ideally an endspacer should be correct and resistant enough to withstand the winding forces but during curing it should soften and deform with the coil and harden again at its final shape. The magnet model program used several types of endspacers with different geometries and materials like, cast metallic spacers insulated with Al_2O_3 insulation or CNC machined G11 spacers both with lateral slots to allow for deformation when curing. The updated design uses G11 or polyetherimide endspacers charged with glassfibre (ULTEM®), moulded or machined [13, 14].

Fig. 10. Coil endspacers of a dipole inner layer coil

The top and bottom poles are separated by polyimide foils in the horizontal plane to give an additional voltage protection in the case of a quench.

FISH BONES, QUENCH HEATERS AND GROUND INSULATION

The so called "fish bones" are 0.5 mm thick G11 spacers with channels and are placed between the inner and the outer coil to allow for some electrical and mechanical insulation between the coils and the helium circulation for the outer coil. They consist of two 0.2 mm thick pre-cut glassfibre epoxy laminates glued and shaped to half cylinders (Fig. 11).

Fig. 11. Fish bones, 0,2 mm precut laminate, superposed and shaped

A "quench heater" is made of 30 μm thick stainless steel strips sandwiched between 125 μm polyimide films to form a preassembled unit which includes the connection cables. These quench heaters are placed onto the outer coil to heat it up and thus to protect the magnet in the case of a quench [15].

The "ground insulation" of the coils comprises 4 to 6 foils of 125 μm thick polyimide, preshaped and preassembled in batches. Glassfibre prepreg as mechanical back up and to keep its shape can also be added. Several layers have to be staggered in the overlap regions where more than one insulation layer is always required. The pressures during mounting and in working conditions are lower than on the cables but still lead to some plastic deformation on the quench heaters and on the ground insulation sheets.

The cold bore containing the beam pipe, is insulated from and centred to the inside of the coil by wraps of a 125 μm polyimide foil with preshaped bumps being elastic enough to allow assembly and take up some tolerances. The insulation wrap is preassembled onto the pipe, tested and then introduced into the magnet bore. Once the magnet is finished the integrity of both the ground insulations and the quench heaters are retested.

ELECTRICAL TESTING

On the first series of models and magnets a thorough and continuous testing program was performed to assure electrical integrity of the magnets at all production phases (Fig. 1).

1. Cable insulation was tested continuously on the tape wrapping machine at 1 KV at 500 Hz between rollers, brushes or through a bed of metallic beads. In the case of a short circuit the machine was stopped and the fault was repaired by adding an insulation tape locally.

2. During coil winding the resistance between the cable and the winding mandrel was continually monitored.

3. Cured coil is tested first without and then with pressure by applying a discharge of about 70 V/turn, the insulation resistance is then measured.

4. The assembled poles and the assembled dipoles are again tested without pressure and then assembled in their collars.

5. During final assembly of the iron yoke and of the shrinking cylinder a discharge test and a dielectrical test of dipole coils against ground, and of quench heaters against dipole coils are once again performed.

For the series production some rationalisation of these tests will have to take place to end up with only a few but significant final acceptance tests.

MATERIALS AND ALTERNATIVES FOR CABLE INSULATION

Inner wrap materials were tested, at least on samples:

- Polyimide tapes [16]:

- KAPTON® H, LT, CI and RCI type: dry tape, Al_2O_3 charged, tape with polyimide adhesive and with charge and polyimide adhesive.

- APICAL®, dry tape.

- UPILEX® R and S, amorphous and cristallinic structures.

- Polyetheretherketon (PEEK): cristallinic and amorphous grades [17]:

- LITREX® and STABAR®

- Polyimide underlayed with thin dry glass tissues

- Polyarylate: ISARYL® [18]

Outer wrap:

- Glass fibre preregs: [19] here many parameters were investigated:
 - Epoxy content and epoxy flow.
 - Filament size, yarn size and sizing.
 - Different weaving types.
 - Tape width cut and woven ribbons.
 - Wrapping tension.
- Glass fibre aramide fibre prepreg.
- Glass fibre and aramide fibre rowings [20].
- Preregs underlayered with polyimide foils.
- Polyimide with polyimide or epoxy adhesive.
- Crimped NOMEX® with adhesive.

SAMPLE TESTING

The sample testing took systematically place on:

- Tape samples:
 - Tensile strength
 - Tear strength
 - Bonding (where appropriate)
- Tape on short cable sample:
 - Abrasion test
 - Bonding test around mandrel
- On cable stack and short coil arcs:
 - Insulation thickness under pressure
 - Bonding quality
 - Youngs Modulus
 - High voltage test under pressure
 - Creep at room temperature (some samples)
- On real coil in magnets

DISCUSSION

The very first concern was to find for the given cable sizes, geometries, winding forces and pressures insulation systems which were mechanically strong enough to remain intact over the whole production and assembly process.

Then, as described above all other parameters like radiation hardness, permeability to helium etc. were checked.

The glass fibre prepreg in the second layer has some disadvantages against the polyimide tapes, at comparable mechanical strength. The cable positions using prepreg seem to give less precise coil geometries than those with adhesive polyimide tapes, the epoxy when liquid acts probably as a sort of sliding surface of one cable layer to the next. Furthermore the permeability to helium is reduced when using the same inner wrap arrangement but having prepreg instead of polyimide as an outer wrap.

The today's choice for the new series of magnets is one inner wrap of 50 μm (rather than two of 25 μm) and the outer wrap of some 68 μm with adhesive, both wraps being of polyimide.

The polyimide foils compared to PEEK foils showed higher compressive strength, thus less creep. PEEK on the other hand is more easily formable and maintains its shape. So it can be useful for forming pieces for part or all of the ground insulation.

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