THE HIGH CURRENT BUS-BARS OF THE LHC FROM CONCEPTION TO MANUFACTURE

L. Belova, M. Egorychev, BINP, J-L Perinet-Marquet, C. Urpin, CERN, Switzerland

Abstract

The main magnets of the LHC are series-connected electrically in different excitation circuits by means of superconducting bus-bars, carrying a maximum current of 13 kA. These superconducting bus-bars consist of a superconducting cable thermally and electrically coupled to a copper section all along length. The function of the copper section is essentially to provide an alternative path for the magnet current in case the superconducting cable loses its superconductivity and returns to normal state because of a transient system disturbance or normal zone propagation coming from the neighboring magnets. When a superconducting bus-bar quenches to normal state its temperature must always stay below a safe values of about 100°C while the copper is conducting. With regard to that, a quench signal is initiated, which in turn triggers the ramping down of the current from 13000 A to 0. The ramping down rate must not exceed a maximum value to avoid the transition of still superconducting state magnets series-connected with the quenched ones.

This paper concerns the design and the manufacture of the high current superconducting bus-bars needed to interconnect the magnetic elements of the main dipoles of the LHC.

INTRODUCTION

Inside a magnet cold mass, three sets of superconducting bus-bars are present, one set for the dipole excitation, the focussing quadrupoles and the defocussing quadrupoles.

All these sets of bus-bars are immersed in superfluid helium.

BUS-BAR MANUFACTURING PROCESS

The standard bus-bas manufacturing process which involved soldering the superconducting cable onto an already-formed copper section has been abandoned in favor of a bus-bar design that has the advantage of protecting the superconducting.

This method consists in inserting the superconducting cable into a hollow copper section while it is still straight, and after the section has been submitted to all the soldering and machining operations that might be harmful to the superconducting cable. Once the superconducting cable is inserted, the whole assembly undergoes successive bending and twisting operations.

According to a process described below, the gap inside the copper section is then filled with a tin-silver solder to provide both thermal and electrical contact between the superconducting cable and stabilizing copper. Each individual bus-bar is insulated with two layers of polyimide tape and a layer of cured fibreglass epoxy tape. An assembly of the insulated bus-bars inside fibreglass epoxy resin profiles provides a compact set ready to be installed inside the cold mass.

BUS-BAR ELEMENTS

Superconducting Cable

All the high current superconducting bus-bars of the LHC are equipped with the same superconducting cable as used for the outer coil layer of the main dipoles and the quadrupoles.

Copper Sections

There are two different cross-sections of hollow copper profiles: the cross-section A intended for interconnecting the main dipole coils whose ramping down rate does not exceed 120 A/s and cross-section B for interconnecting the main quadrupoles whose maximum ramping down rate is 420 A/s.

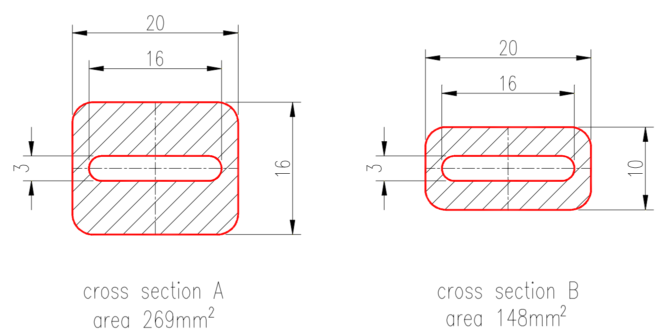


Figure 1: Cross-sections of the hollow-copper profiles.

The hollow-section copper grade is suitable for the various forming, soldering and welding operations necessary for bus-bar manufacture and shows a low residual electrical resistance at low temperature after completion of the bus-bar manufacture.

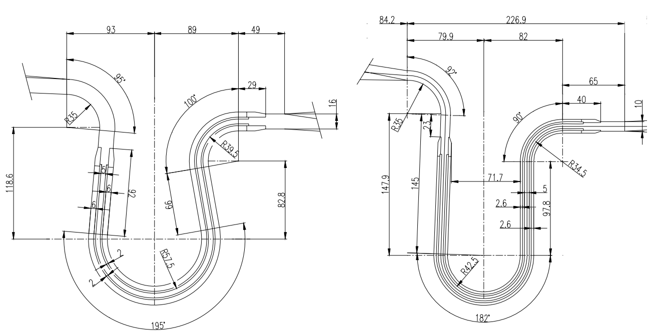
A high temperature annealing in a protective atmosphere is to be carried out to remove all oil traces from the section inner surface in view of the superconducting cable soldering. This final annealing treatment offers two other advantages: on one hand it increases the residual resistance ratio of the copper section and on the other hand it allows the conditioning of the sections in flat pancake coils. This later is a substantial payoff, because it eases the handling of the 260 tons of hollow copper sections required for LHC bus-bars.

Table 1: Hollow copper section characteristics

Copper grade	Cu-OF, with oxygen content below 10 ppm.
Electrical resistivity	$\leq 1.724\ 10^{-8}\ \Omega$.m at 20 °C
Residual resistivity ratio	≥ 100
Hardness	≤ 65 HV

Thermal Compensation Joints

The variations in the length of the busbars due to temperature differences of the order of 300 K are compensated by lyre-shaped thermal compensation joints hereafter referred to as lyres. All the busbars have been designed in such a way as to suffer no mechanical constraints whatsoever once the machine is cold and in operation. However, when the machine is heated up, the lyres are subjected to forces of compression. Fig. 2 shows the two types of lyres used for the main dipole bus-bars.



Lyre of dipole bus-bars with cross- section A

Lyre of quadrupole bus-bars with cross- section B

Figure 2: Schemes of LHC main dipole lyres.

The lyres are an integral part of the bus-bars rather than added components. The continuity of the hole inside the copper section containing the superconducting cable is preserved. The copper section is not constant every where but is machined at the level of the lyres to reduce the copper thickness and thereby increase transverse flexibility in that region. To prevent an increase in the current density, this reduction in thickness is compensated by the addition of two packs of copper blades, diffusion-welded at the ends. These packs are brazed onto each of the recessed parts of the copper section.

The lyre is mechanically formed at the same time as all the other parts of the bus-bar, namely once the superconducting cable has been inserted.

SOFT-SOLDERING OF THE SUPERCONDUCTING CABLE

Soft-soldering operation is carried out when the superconducting cable is inside its copper stabiliser and the process of mechanical forming, including the lyre-shaped part, has been completed.

Prior to inserting the superconducting cable, holes are drilled at each extremity of the bus-bar connecting the hole containing the superconducting cable to two receptacles, to be filled first with soldering flux and then the filler metal.

Filler metal is a silver-tin alloy (4% Ag - 96% Sn).

The orifice and the superconducting cable are rinsed using a halogen-free soldering flux.

The filler metal is introduced into one of the receptacles.

A water circulation device cools the extremities of the bus-bar thereby preventing the filler metal from escaping via the extremities. This end-cooling device will remain in operation throughout the soldering and cooling processes.

The bus-bar and receptacles are heated up to the fusion temperature of the filler metal at a level of 230 °C.

Once this temperature has been uniformly achieved, a compressed air at a pressure of 5 bars is applied to the receptacle containing the filler metal. After a short time, the filler metal surges up into the receptacle that was initially left empty.

The pressure on the first receptacle is released and applied to the second receptacle in order to reverse the direction of flow of the filler metal.

The pressure is then removed everywhere.

The whole bus-bar is gradually cooled down, starting from the centre and spreading out to the extremities. A cooling rate of 10°C per minute with a temperature gradient of 20° per metre has proved to be highly satisfactory.

INSULATION

Bus-bar insulation must withstand voltage of 4000 volts between the metallic part of the bus-bar and surroundings. This requirement has to be fulfilled in superfluid, gas or liquid helium for any pressure between vacuum and 20 Bars and any temperature between 2 K and 400 K. The insulation is permeable to superfluid helium. In case of a quench, insulation allows the evacuation of the helium gas without any degradation of the insulating materials.

Plain Bus-Bar Insulation

In order to fulfill the above requirements the bus-bars are insulated with two layers of polyimide tape followed by a pre-impregnated layer, with a 3mm gap between turns. The two layers of polyimide tape without any glue are wound in opposite direction with an overlapping of 50%. The pre-impregnated layer is wound in opposite direction to the outer polyimide one. This layer is cured at a temperature of 170° C.

Lyres Insulation

The two sets of copper blades and the central hollow copper conductor of the lyres are insulated separately with two layers of polyimide tape wound in opposite direction with overlapping of 50%. To reduce the stiffness, the external pre-impregnated layer is replaced by rings of polymerized fiberglass tape to hold the two polyimide layers.

For safety reasons, each lyre is embedded in a glass-cloth sleeve.

Insulation Test Of The Bus-Bars

The dielectric strength of the insulation is tested between the metallic part (stabilization copper - superconducting cable) and its outside environment using 4000 V DC.

For the first dipole bus-bar sets, insulation tests of the bus-bars are carried out on each face of the bus-bar according to Fig 3. For all the other sets the tests are carried out by replacing the soft roller with an aluminum foil tightly and completely wrapped around the tested bus-bar. The 4000 V DC voltage is maintained for 30 seconds. Insulation higher than 100 MΩ is required without any voltage breaking down during the test.

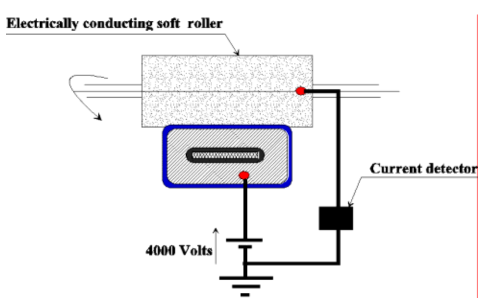


Figure 3: Insulation test.

IMPACT OF THIS METHOD

Improvement Of The Bus-Bar Performances

Because of the central location of the superconducting cable within the copper section, a better thermal coupling is achieved between the cable and the stabilizing copper. This implies lower propagation velocity, as well as higher cable stability with regard to external disturbances.

Improvement Of Reliability

The plane of zero mechanical deformation lies in the plane of the superconducting cable; hence there is less stress in the cable especially in the region of the lyres during warm-up and cool-down.

PARAMETERS MEASURED

Measurement Of The Bus-Bars RRR

The RRR values measured were between 210 and 220. The measured RRR of similar bus-bars produced using the full conductor method was of the order of 70.

This remarkable increase in the RRR is due to, first to the annealing treatment to which the sections are submitted at the end of the manufacturing process and, second to the reduction in the thermal constraints during soldering of the superconducting cable inside the copper stabilizer.

Lyre Mechanical Reliability

Destructive mechanical endurance tests have been performed on both types of the lyres of the main dipoles. Their extremities were submitted to compression cycles with amplitude of 55 mm with respect to the rest position.

In liquid nitrogen no deterioration was observed after 2000 cycles.

Solder Filling Coefficient

The solder filling coefficient, defined as the ratio of the mass of the solder inserted to the mass of solder required to fill entirely the hole of the section with the superconducting cable inside, is higher than 95%. This filling quality, very easy to obtain using fluxes containing corrosive halogens, can now be guaranteed using pure collophane-based fluxes.

Operational Results Of The Bus-Bars

An experiment designed to quantify the operational parameters of the new-generation bus-bars has been carried out. These tests principally measured the heating up of the bus-bars after a quench and the velocity of the quench propagation along the bus-bars. These measurements were carried out in superfluid, liquid, and gaseous helium.

BUS-BARS INSIDE THE COLD MASSES

Insulating profiles provide the housing for the superconducting bus-bars inside the cold masses of the LHC main magnets. Fig 6 shows the installation of the main dipole bus-bars inside the dipole cold mass.

CONCLUSION

At the time of publication of this paper, production of LHC bus-bar set production is ending successfully at Budker institute of Nuclear Physic in Novosibirsk.

More than 180km of superconducting high current bus-bars have been produced to manufacture more than 1800 bus-bar sets.