NON-DESTRUCTIVE TESTING OF BUS-BAR JOINTS POWERING LHC SUPERCONDUCTING MAGNETS, BY USING GAMMA SOURCES

B. Skoczen, CERN, Geneva, Switzerland
J. Kulka, AGH, University of Science and Technology, Cracow, Poland

Abstract

The main LHC superconducting magnets (dipoles and quadrupoles) use Rutherford type cables, stabilized electrically and thermally with copper profiles. The portions of cables are connected to each other by a soft soldering technique ($Sn_{96}Ag_4$) with an overlapping length corresponding to one pitch of the superconducting strands. The splice constitutes a "composite" structure with the interchanging layers of $Sn_{96}Ag_4$ and NbTi superconductor, located inside a Cu cage. In order to ensure a high level of reliability (failure probability not exceeding 10^{-8}) for some 10000 connections in the LHC, a non-destructive technique to check the quantity of solder in the joint is forseen. The technique is based on a gamma ray source (^{241}Am) and the detection is position-sensitive in the transmission mode. Scintillating detectors of gamma rays are used and their accumulated length corresponds to the length of the radioactive source (120 mm). The method can be used in-situ, the equipment being optimized and portable, with implementation of direct on-line operation mode. The relevant criteria of acceptance of the splices have been defined. The first results of application of this technique are presented.

LHC MAIN MAGNETS AND THEIR INTERCONNECTIONS

The classical LHC FODO lattice contains bending magnets (main dipoles) and focusing/defocusing magnets (main quadrupoles housed in the Short Straight Sections) as well as drift spaces located between them. The drift zones fulfil a very fundamental function of providing the accelerator with space for all the necessary connections of the beam and cryogenic lines, power supply, thermal shielding and vacuum vessels. However, the drift space does not provide beam bending strength and is therefore neutral for beam energy. Therefore, one design requirement of accelerators and storage rings optimised for high beam energy is to minimize the ratio drift-to-magnetic length. This imposes, however, a stringent space constraint for all systems located in the drift spaces like the thermal contraction/expansion compensation system [1], RF contacts between the beam screens, joints of the superconducting bus-bars etc. The goal achieved in the LHC interconnections is expressed by only 3.7 % of the accelerator length in the Arc and Dispersion Suppressors occupied by the drift zones (Fig. 1). One of the most severe limitations has been imposed on the geometry and low temperature performance of the joints of the superconducting bus-bars (splices).

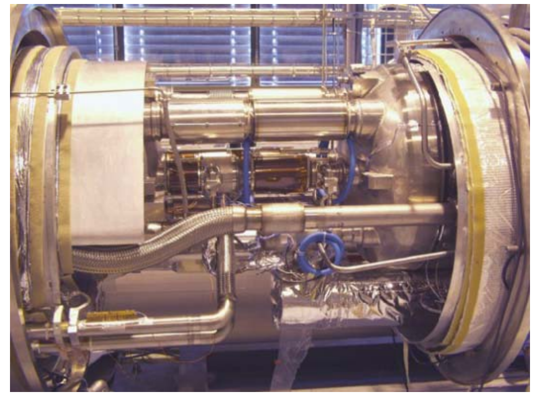

Figure 1: Interconnections between the LHC magnets.

The family of the joints comprises connections between the Rutherford type superconductors powering the main magnets and the small superconducting bus-bars powering the corrector magnets. Since each joint contains two overlapping superconductors separated either by a thin layer of copper or strip of $Sn_{96}Ag_4$ (depending on the joining technology) the dissipation of energy due to the Joule effect is localized in this non-superconducting layer. Typical resistances at 1.9 K of the joints of Rutherford type superconductors remain below 0.6 nΩ [2], [3], whereas the joints located in the corrector circuits show some 3 nΩ of resistance [4]. Given the number of joints in the dipole - quadrupole interconnection the maximum dissipation of energy at 1.9 K, integrated over a single interconnection zone, amounts to around 670 mW.

JOINTS OF THE SUPERCONDUCTING MAIN BUS-BARS

The electrical interconnections are essential to the powering scheme of the LHC and are present in all the zones of the accelerator. Both the main and the auxiliary superconducting bus-bars cross each interconnection zone. The main bus-bars (Fig. 2) powering the main dipoles and quadrupoles carry a current of nearly 13 kA. They are housed in the so-called interconnection channels M1-3 and are joined by means of an induction soldering technique. The particularity of this technology consists in the fact that a copper stabilizer of rectangular cross-section, inserted at the extremities of the Rutherford type superconducting cables, is heated by the induced eddy currents. Three strips of $Sn_{96}Ag_4$ per joint and a colophony based non-corrosive flux are applied. The structure of a single joint is shown in Fig. 2. Given the maximum resistance of each joint (0.6 nΩ) the heat generation rate per joint at nominal current does not exceed 100 mW, which amounts to around 1 kW for all the interconnections in the 1.9 K zones of the accelerator.

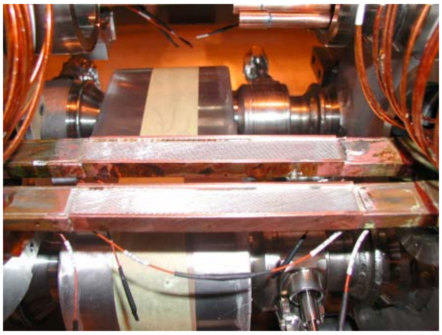

Figure 2: Joints of the superconducting main bus-bars.

The expected reliability levels

Possible failures in the powering system of the LHC are strongly related to the quality of splices of the superconducting bus-bars and may result in the malfunction of the main or the corrector magnets. These failures are classified in the following way [5]:

- failures that violate the logic of the electrical scheme (connection errors),
- failures that violate the continuity of the electrical scheme (lack of connection),
- failures related to the quality of connections (electrical resistance at cold).

The latter is represented by the reliability diagram (constructed by using the measurements of the resistance of splices at 4.2 K) showing the achievable reliability as a function of the target value of resistance (Fig. 3).

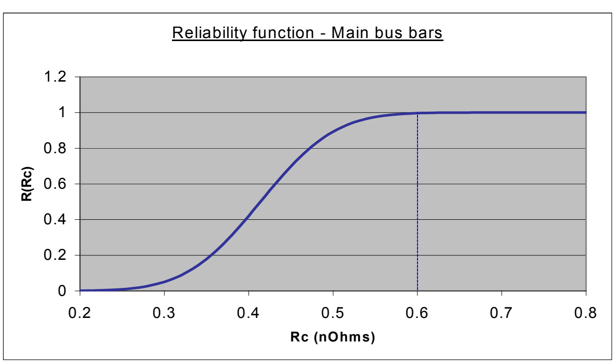

Figure 3: Reliability function “R” for the main bus-bars.

For the target value of 0.6 nΩ (or higher) the predefined reliability level can be reached.

Risk associated with joining technology

The joints of main LHC bus-bars (Fig. 4) constitute “composite” structures that include the Rutherford type superconducting braids, copper profiles and wedges as well as thin layers of solder ($Sn_{96}Ag_4$) [6]. The main risk associated with the application of the technology of inductive soldering consists in the lack of uniformity of solder distribution (local gaps) or lack of solder layer between the superconducting cables.

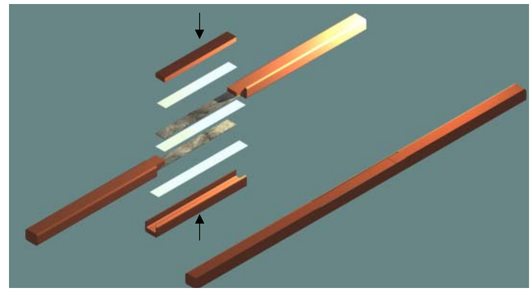

Figure 4: Structure of a joint of superconducting bus-bars.

All the imperfections may affect severely the electrical resistance of joints in superfluid helium and such joints should be re-made during the assembly of the accelerator.

NON-DESTRUCTIVE TESTING OF JOINTS BY USING A GAMMA SOURCE

The problem of elimination of the faulty joints can be solved by application of an appropriate non-destructive (ND) technique. Typical ND techniques used in the case of standard metallic components, like: acoustic methods (ultrasonic waves), thermography, X-ray defectoscopy etc. prove not to be efficient in the case of composite structures. Therefore, a special imagery technique using gamma rays of calibrated energy has been adopted. A radioactive source ^{241}Am emitting gamma rays of energy of around 60 keV has been chosen. The technique is based on the following considerations:

- in the energy range 30-60 keV, the absorption level of Cu is small when compared to Sn,
- the chosen energy of gamma rays is close to the absorption edge of Sn (~ 30 keV),
- local lack of Sn is visible as a high transmission signal (the detected flux depends exponentially on the thickness of Sn).

The absorption coefficient for Sn and Cu as a function of photon energy is illustrated in Fig. 5.

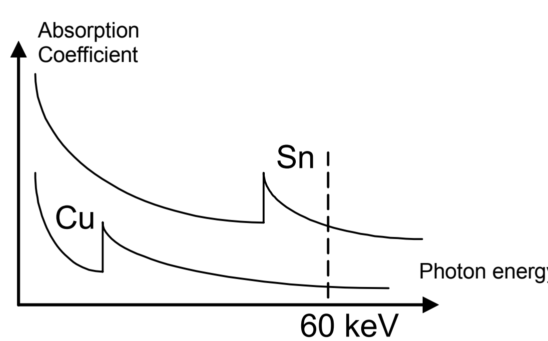

Figure 5: Absorption coefficient as a function of energy

The instrument necessary to perform the scanning operation is shown in Fig.6. It is composed of a cage containing the source (located below the joint) and a combination of collimator, scintillating detector and photomultiplier connected to a PC. The instrument was developed based on the following:

- the flux of photons is assumed to be completely deposited in the instrument,
- the flux is measured by up to 5 scintillating detectors (in the case of scanning technique 1 detector is sufficient),
- local lack of Sn or lack of Sn layer is reflected by a high transmission signal (locally or over the whole length of the joint),
- the flux of particles is collimated and the collimators can move along the joint,
- the scanning speed can be adjusted as a function of the required resolution.

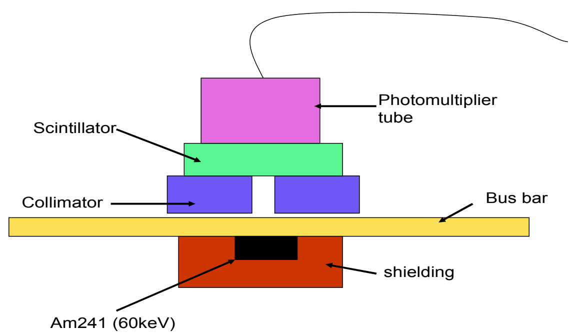

Figure 6: Instrument based on the gamma absorption technique.

The set-up has been tested on the LHC bus-bar joints (~ 200 mm long) by applying different scanning velocities. The technique proves to be sensitive enough. Fig. 7 shows the number of counts per channel as a function of time for a configuration with a local lack of Sn. Thanks to a considerable difference in absorption factor between Nb, Ti, Cu and Sn only Sn imperfections are detected through the scan output.

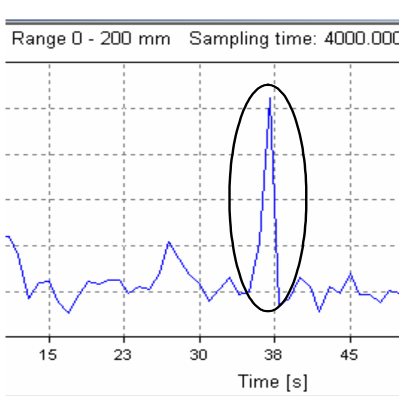

Figure 7: Scan of LHC bus-bar joint with a local imperfection.

Further sensitivity analysis has been performed with respect to the Sn accumulated thickness. It is worth pointing out that – given the configuration of the joint – an increase of the Sn layer by 0.4 mm reduces the count rate by a factor 4. The overall weight of the instrument does not exceed 2 kG (including the source).

CONCLUSIONS

A non-destructive testing technique applied to the joints of main LHC superconducting bus-bars has been developed. The technique is quite novel in the domain of testing the hybrid multi-layer structures, containing Sn. The method, based on application of the ^{241}Am gamma source, involves construction of a light instrument containing the scintillating detector(s) that can be connected to a portable PC. Thus, the testing technique is perfectly applicable for the in-situ measurements and qualification of the electrical connections of superconducting magnets. It will help to keep the reliability of the LHC electrical interconnections to the predefined level.

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