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Electrical Resistance of the Solder Connections for the Consolidation of the LHC Main Interconnection Splices

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Electrical resistance of the solder connections for the consolidation of the LHC main interconnection splices

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***Abstract*— For the consolidation of the LHC 13 kA main interconnection splices, shunts will be soldered onto each of the 10170 splices. The solder alloy selected for this purpose is Sn60Pb40. In this context the electrical resistance of shunt to busbar lap splices has been measured in the temperature range from RT to 20 K. A cryocooler set-up has been adapted such that a test current of 150 A could be injected for accurate resistance measurements in the low nΩ range. To study the influence of the solder bulk resistivity on the overall splice resistance, connections produced with Sn96Ag4 and Sn77.2In20Ag2.8 have been studied as well. The influence of the Sn60Pb40 solder resistance is negligible when measuring the splice resistance in a longitudinal configuration over a length of 6 cm. In a transverse measurement configuration the splice resistance is significantly influenced by the solder. The connections prepared with Sn77.2In20Ag2.8 show significantly higher resistance values, as expected from the relatively high solder resistivity at cryogenic temperatures. The experimental results are complemented by simulations with Comsol multiphysics, showing the contribution of each splice component on the overall splice resistance.**

***Index Terms*— Interconnection, Resistance measurement, Superconducting cable, Busbar.**

I. INTRODUCTION

THE 10170 main busbar splices that interconnect the superconducting main bending and focusing magnets of the Large Hadron Collider (LHC) [1] are assembled by the soft soldering of two Rutherford type cables, of the splice copper profiles (U-piece and wedge) and of the adjacent busbar stabilizer, using lead free Sn96Ag4 solder [2,3]. When the cable is superconducting the electrical resistance of the splice with 120 mm intercable contact length is approximately 0.3 nΩ [4]. The resistance of the Cu stabilizer splice becomes of utmost importance following a magnet quench while the energy stored in the magnets is extracted in dump resistors.

In order to guarantee a sufficiently low resistance for all LHC main busbar stabilizer interconnection splices, the existing splices will be consolidated by soldering an additional shunt connection across each busbar to splice U-piece and wedge contact surface [4,5]. The shunt specification can be found in [6].

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The solder that has been chosen for the shunt to busbar stabilizer connections is the nearly eutectic Sn60Pb40, which has a significantly lower melting temperature than Sn96Ag4. This gives the ability to solder the shunt to the splice stabilizer without melting the existing Sn96Ag4 connections.

The goal of this work is to measure the electrical resistance of the solder lap copper to copper splices in the temperature range from RT to 20 K in order to study the influence of the solder alloy on the overall splice resistance. Test splices have been produced with the solders Sn96Ag4 and Sn60Pb40, which are used for the LHC cable splices and the shunts. In order to investigate the influence of the resistivity of the solder on the overall splice resistance, a solder with comparatively high 4.2 K resistivity (Sn77.2In20Ag2.8) has been tested as well.

Resistance measurements in the low nΩ range with test currents of up to 150 A have been performed with a cryocooler set-up in the entire temperature range from room temperature (RT) to 20 K.

The resistance measurements are complemented by Comsol simulations in order to determine the contribution of the different splice components on the overall splice resistance.

II. EXPERIMENTAL SET-UP AND SAMPLES

The samples consist of a 100 mm-long LHC quadrupole busbar [2] and a 15×80×3 mm^3 copper sheet (shunt), soldered together with a nominal solder contact area of 15×15 mm^2 (see Fig. 1). The Cu shunts were annealed for 2 hours at 400 °C in order to increase the RRR of the initially cold worked Cu sheets [7].

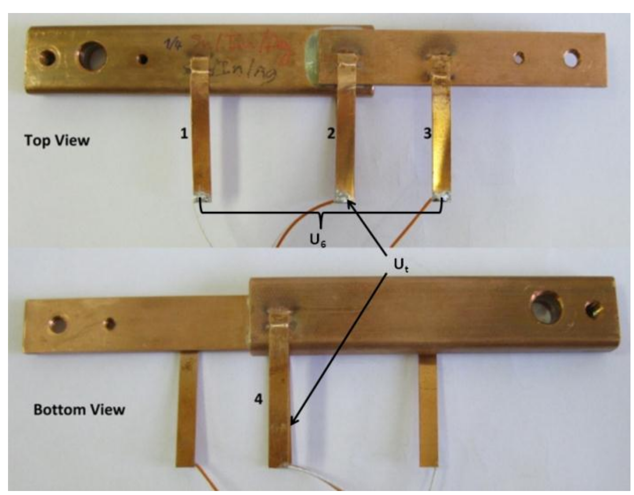

Fig. 1: Busbar to shunt solder lap splice.

An existing cryocooler set-up was modified for electrical resistance measurements at cryogenic temperatures. This set-up was used for the electrical resistance measurements of nine shunt to busbar lap splices in a temperature range from 20 K to RT using a 4-wire measurement scheme and a measurement current of 150 A.

The voltages between taps 1 and 3 in a distance of 6 cm (in Fig. 1 referred to as U_6) and between taps 2 and 4 (referred to as U_t) were measured with high precision digital mutlimeters. These voltages and the temperatures of the shunt and of the busbar were simultaneously recorded with a LabView data acquisition program. The difference between the voltages measured for a current of negative sign and of positive sign was used for the resistance calculation, removing the influence of constant offsets in the measurement signal. Fig. 2 shows a fully instrumented sample mounted on the sample holder of the cryocooler set-up.

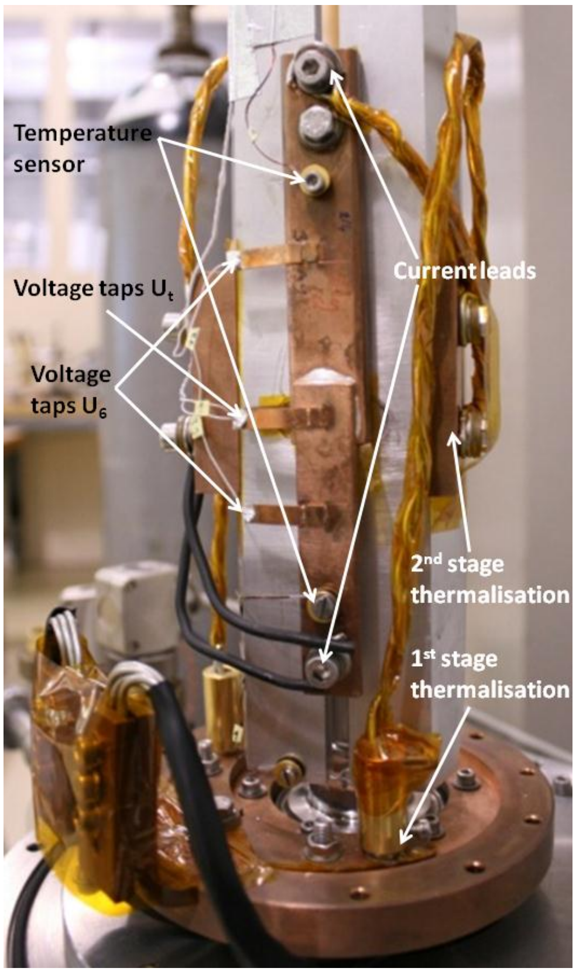

Fig. 2: Instrumented busbar to shunt solder sample with voltage taps, current leads and temperature sensors mounted onto the Aluminium sample holder on the cold head of the cryocooler.

III. Solder Alloy Electrical Resistivity

The electrical resistivity at cryogenic temperatures of the solders used for the test splices has been determined in a dedicated test facility described in [8]. Fig. 3 summarizes the electrical resistivity values of different solder alloys as a function of temperature.

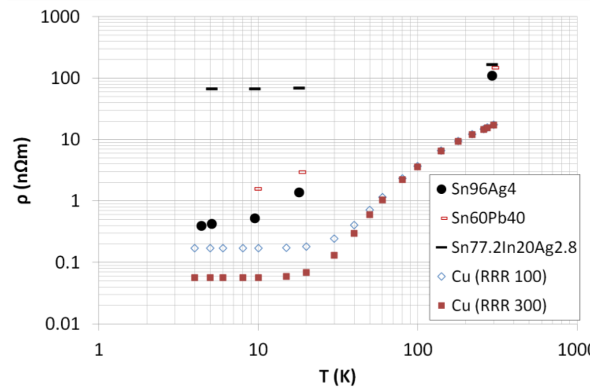

Fig. 3: Electrical resistivity ρ as a function of the temperature T. The solders selected for this study are Sn96Ag4 and Sn77.2In20Ag2.8. For comparison the resistivity values of Cu with an RRR of 100 and 300 are shown as well.

IV. Metallographic Splice Examination

The solder layer thickness across the splice was determined in metallographic cross-sections made at the center of four lap splice samples. As can be seen in Fig. 4 the solder thickness varies strongly across the solder layer. Thickness variations of the solder layers of the different samples range from 10-220 µm.

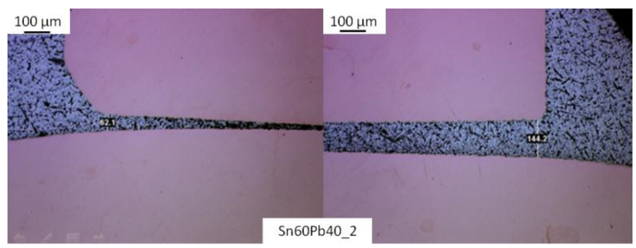

Fig. 4: Metallographic cross-sections through the center of a Sn60Pb40 soldered shunt to busbar splice.

V. Splice Resistance

Fig. 5 shows the splice resistances in transverse configuration (R_t), measured between voltage taps 2 and 4 (see Fig. 1), as a function of temperature. At 23 K R_t of Sn96Ag4 and Sn60Pb40 splices is 5.5±1.0 nΩ and 6.1±2.4 nΩ, respectively. R_t of splices soldered with the high resistivity solder Sn77.2In20Ag2.8 is with 16.6±2.6 nΩ about 3 times higher than that of splices produced with the low resistivity solders Sn96Ag4 and Sn60Pb40.

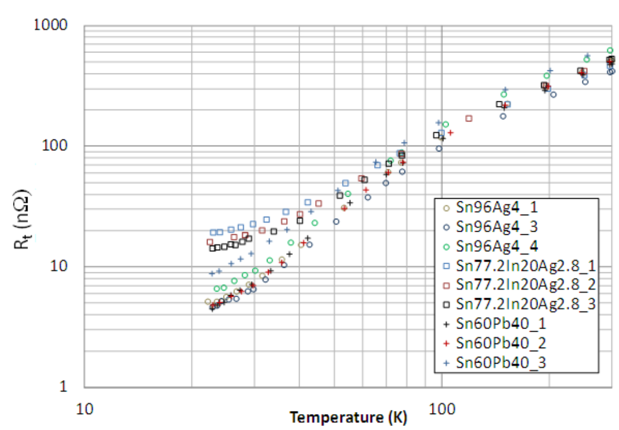

Fig. 5: R_t as a function of the temperature of lap splices produced with Sn96Ag4, Sn60Pb40 and Sn77.2In20Ag2.8.

The corresponding R_t ratios measured at RT and cryogenic temperatures are presented in Fig. 6. For comparison resistance ratio (RR) curves of pure copper with a RRR value of 20, 50 and of 100 are plotted as well. Below 100 K the data points for the solder splices deviate strongly from the pure copper curves. At 23 K the resistance ratios are 97±9, 95±17 and 32±7 for Sn96Ag4, Sn60Pb40 and Sn77.2In20Ag2.8 soldered lap splices, respectively. Thus, there is no significant difference between the electrical resistance of the Sn60Pb40 and Sn96Ag4 samples, while the resistance ratio of the Sn77.2In20Ag2.8 soldered samples is about 3 times lower.

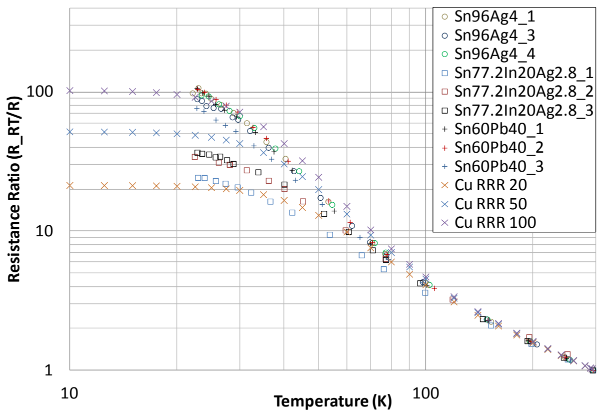

Fig. 6: R_t resistance ratio as a function of the temperature of splices produced with Sn96Ag4, Sn60Pb40 and Sn77.2In20Ag2.8. For comparison the RR of Cu with RRR values of 20, 50 and 100 is shown as well.

Fig. 7 shows resistance ratio in longitudinal direction with a voltage tap distance of 6 cm (R_6) of all measured samples as a function of temperature as well as the resistance ratio curves of pure copper with a RRR of 200 and 400. The splice R_6 resistance ratio values can be fitted approximately with resistance ratios for pure Cu with a RRR between 200 and 400. Below 50 K the R_6 ratio of Sn77.2In20Ag2.8 splices is slightly lower than the R_6 ratio of the Sn96Ag4 and Sn60Pb40 splices.

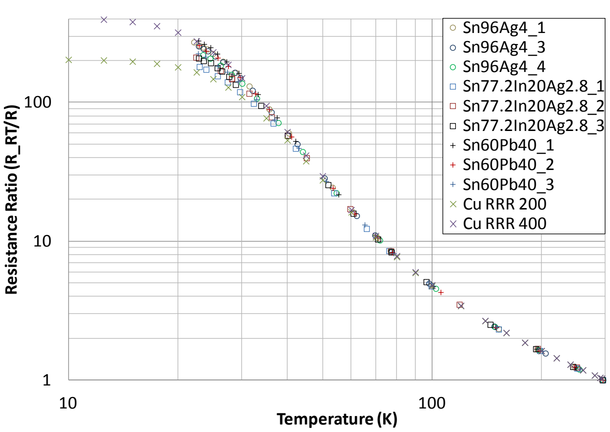

Fig. 7: R_6 resistance ratio (RR) as a function of temperature of lap splices produced with Sn96Ag4, Sn60Pb40 and Sn77.2In20Ag2.8. For comparison the RR values for Cu with a RRR of 200 and 400 are shown as well.

VI. Finite Elements (FE) Simulations

FE simulations of the electrical resistance of the splices produced with different solders and solder layer thicknesses have been performed in order to determine the bulk resistances of each splice component. The contribution of contact and constriction resistances in addition to the bulk resistances is estimated by the comparison of FE results with experimental results.

For all FE calculations the software Comsol Multiphysics was used. The shunt to busbar lap splice model consists of more than 100000 elements with tetrahedron shape. The superconducting Nb-Ti/Cu cable inside the busbar stabilizer is simplified to a homogeneous volume with an average RT resistivity of 26 nΩm and it is assumed that the cable is surrounded by a 1 mm thick Sn96Ag4 solder layer.

The current is flowing from the busbar extremity to the shunt extremity so that the current needs to pass through the solder that connects busbar and shunt. A rendering of the FE model used displaying surface electric potential is shown in Fig. 8.

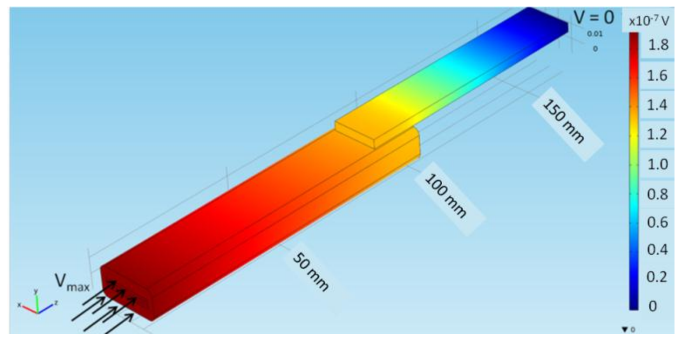

Fig. 8: FE model of the shunt to busbar solder connection with surface electrical potential.

The resistivity values that were used for the busbar, the shunt and for the different solder alloys are summarized in Table I. The RRR of the Cu busbar stabilizer and Cu shunts has been estimated from the relation between Vickers hardness (HV2.0) and RRR that had been found previously for high purity Cu with different degree of cold work [7]. The hardness of the shunt is HV2.0=52.3±5.9, corresponding with a RRR value of approximately 270, and the busbar stabilizer hardness is HV2.0=65.8±6.5, which corresponds with a RRR value of about 220.

Table I: Resistivity (ρ) of busbar, shunt and different solder alloys that were used for the FE calculations. * Resistivity values measured at 18 K.

	ρ at 23 K (nΩm)
Cu busbar stabilizer	0.0996
Cu shunt	0.0853
Nb-Ti/Cu cable	0.136 [8]
Sn77.2In20Ag2.8	69* [9]
Sn60Pb40	2.98* [9]
Sn96Ag4	1.39* [9]

The voltage drop in the FE simulations is calculated from the top of the shunt to the opposing side at the bottom of the busbar, always in the center of the solder contact area (U_t configuration shown in Fig. 1).

In Table II the calculated resistance results are compared to the experimental resistance results. The assumed solder layer thickness in the FE model is 50 µm.

Table II: Comparison of experimental and calculated 23 K R_t results of shunt to busbar splices soldered with different solder alloy.

Solder alloy	R_t calculated	R_t experiment
Sn77.2In20Ag2.8	18.2	16.6±2.6
Sn96Ag4	3.6	5.5±1.0
Sn60Pb40	3.9	6.1±2.4

The contribution of the different splice components on the overall R_t resistance is presented in Fig. 9. It can be seen that the Sn77.2In20Ag2.8 solder layer resistance is dominating the overall R_t resistance, while the influence of a 50 µm-thick Sn96Ag4 and Sn60Pb40 solder layer can be neglected in good approximation.

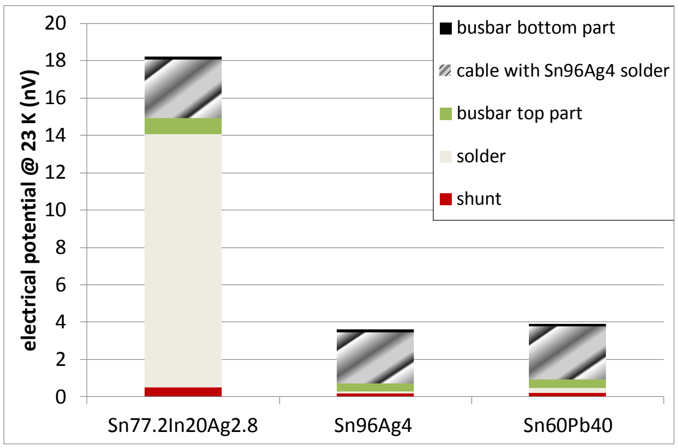

Fig. 9: Comparison of the electrical potential along the arc length for lap splices with different solders at 23 K (solder layer thickness is 50 µm).

The influence of the solder layer thickness on R_t can be seen in Fig.10. While the thickness of the high resistivity solder Sn77.2In20Ag2.8 has a strong influence on R_t, the influence of the thickness of a low resistivity solders is rather weak. As an example, R_t increases by less than 25% when the Sn96Ag4 solder thickness is increased from 10 to 150 µm.

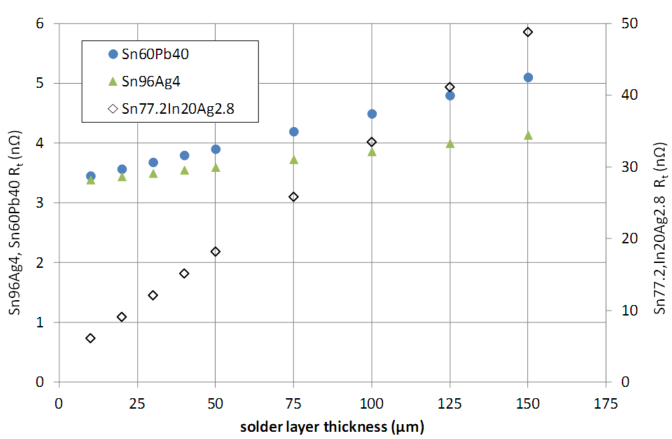

Fig. 10: Influence of the solder layer thickness of different solders on the overall splice resistance at 23 K.

VII. Discussion and Conclusion

The electrical resistance of shunt to busbar lap splices produced by soft soldering measured in longitudinal direction (R_6) is determined by the bulk resistance of the Cu components of the splice, and it is only slightly influenced by the solder layer resistance (at 23 K: $R_{6\text{-}Sn96Ag4}$=49.6±5.6 nΩ, $R_{6\text{-}Sn60Pb40}$=49.5±6.4 nΩ, $R_{6\text{-}Sn77.2In20Ag2.8}$=61.4±6.4 nΩ). The R_6 ratio of Sn96Ag4 and Sn60Pb40 splices follows approximately the resistance ratio of Cu with a RRR of about 300.

In contrast, R_t is significantly influenced by the solder layer properties. R_t of the splices soldered with the high resistivity solder Sn77.2In20Ag2.8 is about 3 times higher than that of Sn96Ag4 and Sn60Pb40 soldered splices. Sn96Ag4 and Sn60Pb40 soldered splices exhibit similarly low R_t resistances.

The Comsol simulations confirm that the solder bulk resistance determines the overall R_t of the Sn77.2In20Ag2.8 soldered sample. Therefore, the Sn77.2In20Ag2.8 solder layer thickness has a strong influence on R_t. In contrast the influence of the thickness of the low resistivity solders Sn96Ag4 and Sn60Pb on the overall R_t is relatively small.

Considering only the bulk electrical resistance good agreement between calculated and measured resistance values is obtained for the Sn77.2In20Ag2.8 soldered splice. For the samples soldered with Sn96Ag4 and Sn60Pb40 the calculations underestimate R_t. This indicates that in the splices produced with a low resistivity solder the contribution of intermetallic layer resistances, constriction resistance and contact resistances have a significant influence on R_t.

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