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A&T Sector Note

Electrical resistance and mechanical strength of LHC busbar cable splices as a function of intercable contact length

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Abstract

The electrical resistance of LHC main busbar cable splices without busbar Cu stabiliser at 4.3 K has been measured as a function of intercable overlap length with two independent methods. Splice resistances of 3 nΩ and 10 nΩ correspond to a cable overlap length of approximately 14 mm and 3 mm, respectively. The tensile strength at 4.3 K of these splices exceeds 2 kN (10 nΩ) and 3 kN (3 nΩ). The comparison of direct resistance measurement results (FRESCA and LHC) with resistance values calculated from the current decay constant of test loops show that over the resistance range 0.3-10 nΩ, the inductance of the test loops is about 310 nH, about 1.9 times the value that has been assumed so far.

Introduction

Electrical resistance results for 10170 main interconnection splices in the LHC show that the average splice resistance at 1.9 K is about 0.3 nΩ. The maximum resistance value determined for all main interconnection splices is 3.3 nΩ. Several internal magnet splices have resistances >10 nΩ [1]. It is therefore of interest to investigate the mechanical strength of splices whose resistance significantly exceeds the average splice resistance.

Previous splice tests with the Sn96Ag4 coated LHC busbar cables [2] have shown that even when the Sn96Ag4 solder foils is omitted the resistance of interconnection splices does not exceed 2 nΩ, as long as the Sn96Ag4 melting temperature is reached.

Analysis of LHC splice imperfections found during the 2008 shutdown has shown that a main defect mechanism is insufficient soldering peak temperature, which prevents the external parts of the splice extremities to be soldered. Insufficient temperature at the splice extremities has been clearly revealed in several cases by gamma ray imaging, as well as by unmolten Sn96Ag4 foil that was found in dismounted LHC splice profiles [3]. The reason for the insufficient peak temperature might possibly be that an incorrect thermocouple has been used to control the heating power of the inductive soldering machines, or that the thermocouple was incorrectly positioned.

In first approximation it can be assumed that the cable splice resistance is inversely proportional to the intercable contact area, and a certain unsoldered splice length causes a corresponding splice excess resistance. Therefore, strongly reduced intercable contact area can be considered as a possible, if not likely reason for excess resistances in LHC main interconnection splices.

The main goal of the experiments described here was to determine the mechanical strength of splices that exhibit a relatively high resistance when a large part of the splice is unsoldered. Other defect mechanisms have not been considered.

A second goal was to determine the correlation between direct resistance measurement results (e.g. as measured in the LHC and the FRESCA test station) and the resistance values determined from current decay constants by the CERN Cryolab.

The samples

Splices made out of non-oxidised LHC main busbar cable have been assembled by inductive soldering [4] with cable overlap lengths varying between 3 and 120 mm. All overlap lengths have been measured after fracturing, and the accuracy of the stated lengths is ±1 mm. Before connection the cable extremities have been pre-tinned in a dedicated resistively heated furnace. The entire pre-tinning HT lasts about 5 minutes and the peak temperature reached is about 240 °C (see Figure 13).

Inductive soldering was performed using 0.2 mm thick Sn96Ag4 foil (CERN SCEM: 29.20.01.600.4) and non-activated rosin liquid flux Kester 135. In order to simulate the mechanically worst case in which the splice mechanical strength relies entirely on the cable to cable solder connection, the busbar Cu stabiliser profiles which surround the LHC main interconnection splices have been omitted in this study.

Figure 1: LHC busbar cable test loops for current decay constant measurements in the CERN Cryolab. The cable splices have been prepared with different cable overlap lengths ranging from 3 to 120 mm.

The test loops with the splices with different intercable contact length are shown in Figure 1. Sample production parameters (temperature and pressure) correspond to the parameters used for the existing main interconnection splices during LHC installation. A typical temperature cycle that was recorded during the production of one connection is shown in the appendix in and Figure 2.

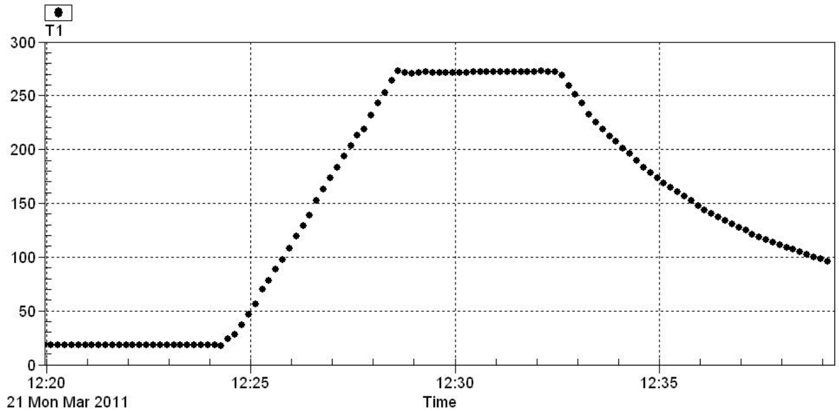

Figure 2: Temperature cycle recorded during inductive soft soldering of 13 kA test loops. The peak temperature of 270 °C was held for 4 minutes.

Experimental

Current decay measurements (Cryolab)

The measurement of the current decay time in test loops with a well defined geometry using a dedicated set-up in the CERN Cryolab [5] allows to determine very low splice resistances, which are difficult to determine otherwise.

The test loops have been connected with a nominal intercable contact length of 3 mm, 9 mm, 24 mm and 120 mm. Three samples have been produced for each overlap length. The measured overlap length varies up to 2 mm from the targeted overlap length. The current decay constants determined for the cable splices with various intercable contact lengths are shown in Figure 3.

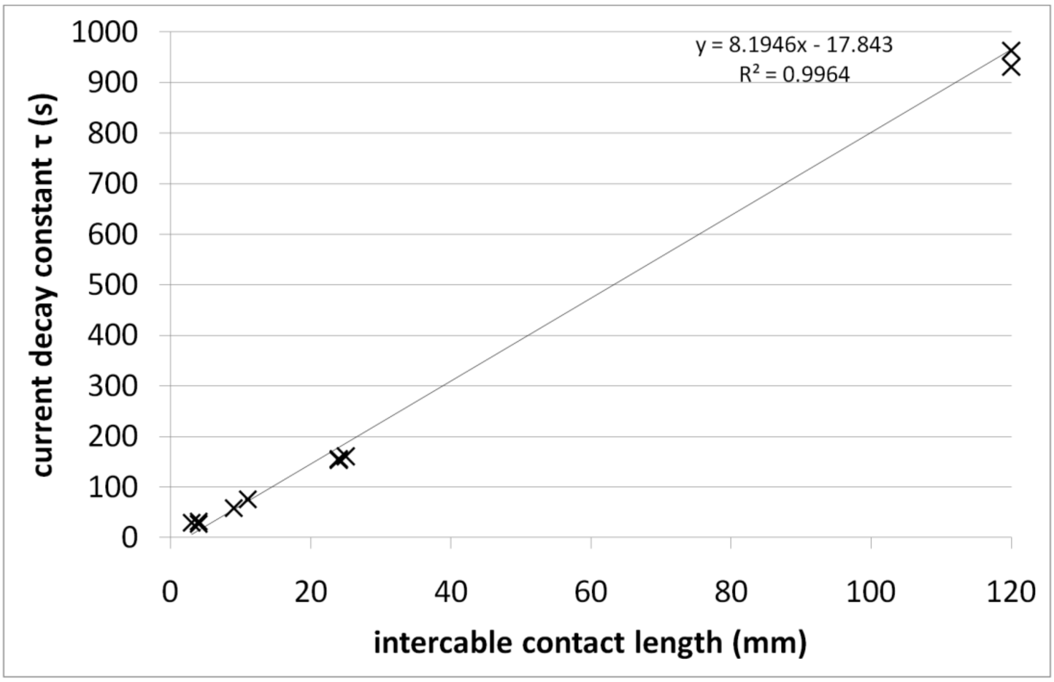

Figure 3: Current decay time constant τ as a function of intercable contact length of different soldered 13 kA test loops. The equation of the slope is shown in the insert.

The resistance R is determined from the loop inductance L and the current decay time constant τ (Equation 1).

Equation 1: $R = L/\tau$

Four point resistance measurements with FRESCA

Four selected loops that have been previously tested in the cryolab have been cut in order to measure their 4.3 K splice resistance with the four point method in FRESCA [6]. The splices were connected in series. The distance between each overlap area and the interconnection between each sample is about 120 mm. The voltage taps are placed in a distance of 50 mm from each splice extremity. A 0.2 mm thick spacer and two 0.15 mm thick Kapton (Polyamide) tapes insulate the two cables from each other. A sample sketch and a photograph of the tested cable splices are shown in Figure 4 and Figure 5, respectively.

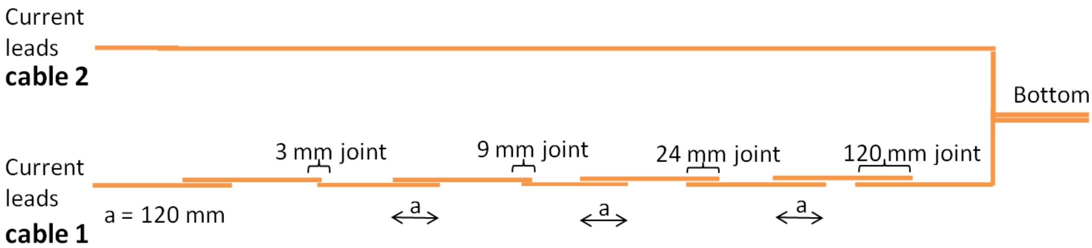

Figure 4: Sketch of FRESCA sample for four point resistance measurements at 4.3 K.

Figure 5: Photographs of the soldered cable splices with 3, 9, 24 and 120 mm intercable contact length.

The four point resistance measurements at FRESCA have been performed at 4.3 K and without external field. The maximum quench current of the sample was about 17 kA. Resistance measurements have been performed in 1 kA steps 1 to 15 kA. The voltages measured across the different splices as a function of the test current are presented in Figures 5-8. Each data point has been averaged over a time of 300 sec. The current ramp was about 300 A/s. Voltages below 2 µV have not been taken into account for the resistance calculations.

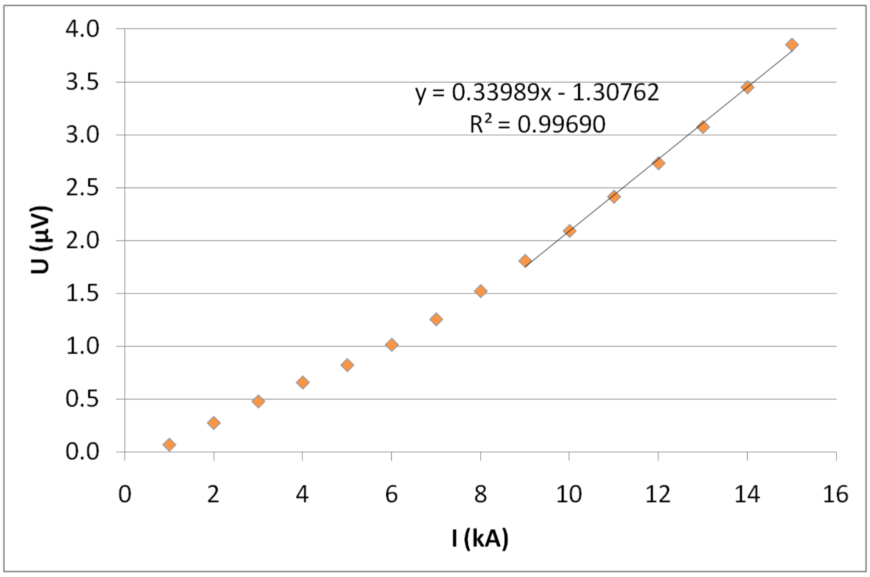

Figure 6: Electrical potential U as a function of current I at 4.3 K without external field for a splice with 120 mm intercable contact length.

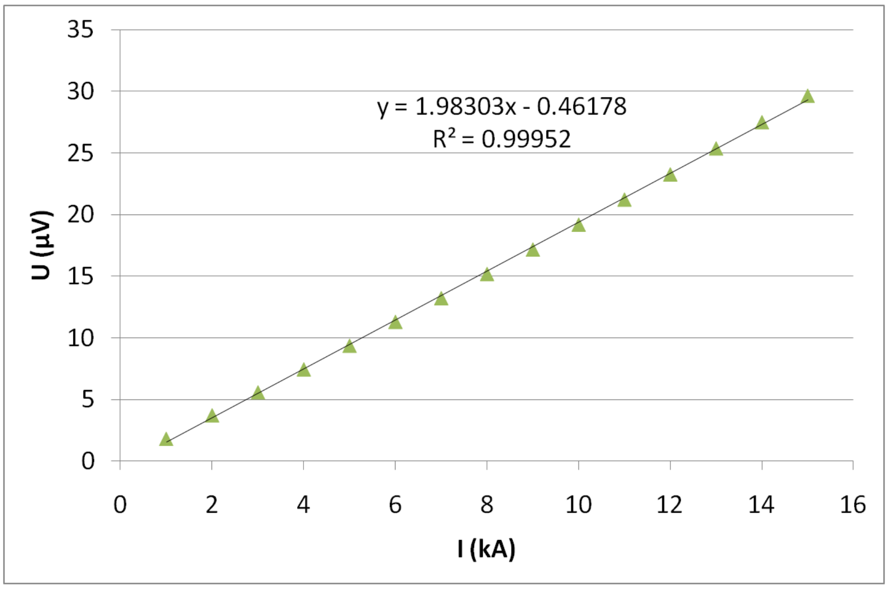

Figure 7: Electrical potential U as a function of current I at 4.3 K without external field for a splice with 24 mm intercable contact length.

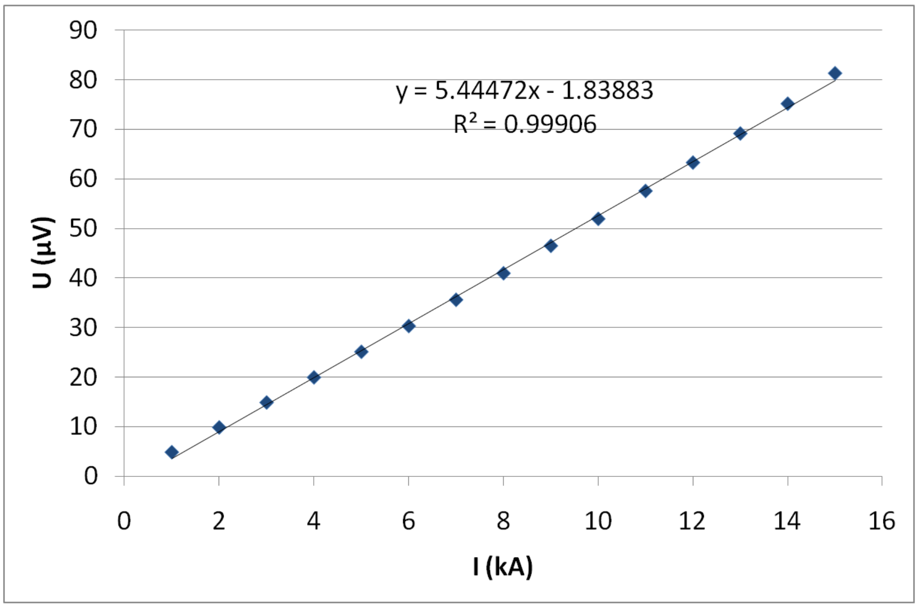

Figure 8: Electrical potential U as a function of current I at 4.3 K without external field for a splice with 9 mm intercable contact length.

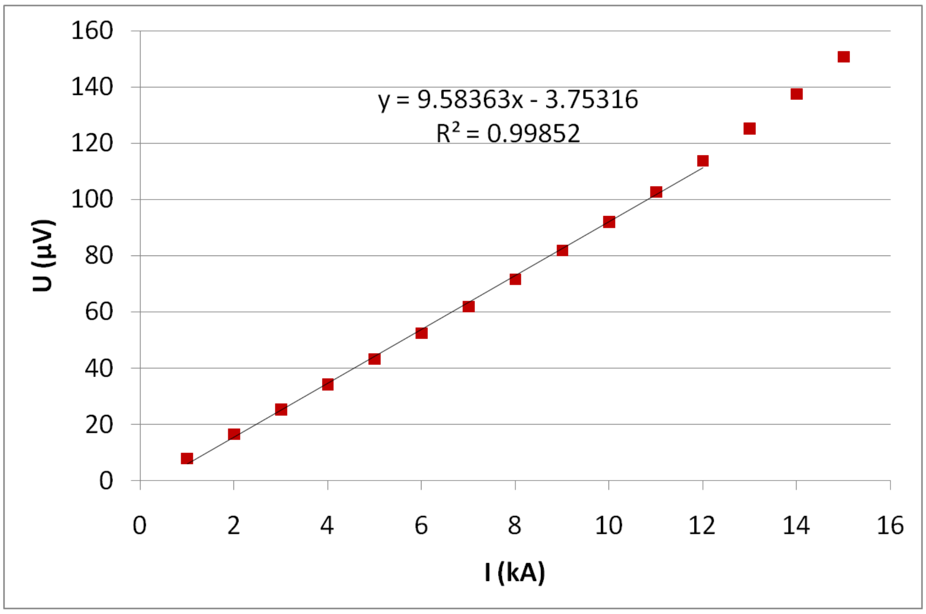

Figure 9: Electrical potential U as a function of current I at 4.3 K without external field for a splice with 3 mm intercable contact length.

The 4.3 K resistances vary between 0.34 nΩ (120 mm overlap) and 9.6 nΩ (3 mm overlap). The voltages measured for the splices with 9 mm and 24 mm overlap length show a linear correlation with the test current. For the 3 mm-splice the data points above 12 kA have not been considered because they appear to deviate from the linear relationship, possibly because the critical current of the splices is approached (the quench current was about 17 kA).

For the 120 mm-overlap splice the voltage vs. current slope appears to increase when the test current exceeds about 8 kA. The reason for this apparent change is not fully understood, but it might possibly be explained by the fact that the measured voltages are very low and that the influence of measurement errors increases with decreasing test current. When the results are fitted over the entire current range from 1-15 kA a resistance of 0.27 nΩ would be determined, instead of the value of 0.34 nΩ obtained with a test current >8 kA.

The splice resistance at 4.3 K does not significantly differ from the 1.9 K resistance and, therefore, FRESCA resistance results are valid also for the LHC operational temperature of 1.9 K.

Comparison of four point resistance results (FRESCA) with resistance values determined from current decay constant (Cryolab)

In Table 1 the four point resistance results (FRESCA) are compared with resistance values calculated from current decay constants (Cryolab). The comparison shows that the loop inductance of 161 nH that is presently used to calculate the splice resistance is too low. Good agreement between FRESCA and Cryolab results is obtained when using a test loop inductance of 310 nH [[7]]. An inductance of 260 nH has been estimated with the ROXIE software [[8]] for a test loop with ideal dimensions.

Table 1: Comparison of 4.3 K splice resistances for different cable overlap lengths as determined with FRESCA and with the current decay method. *Assuming L=161 nH. **In the current range 8-15 kA.

Nominal overlap length (mm)	R_{FRESCA} (nΩ)	$R_{Cryolab}$ (nΩ)*	$R_{FRESCA}/R_{Cryolab}$*
3	9.6	5.4	1.8
9	5.4	2.8	1.9
24	2.0	1.0	2.0
120	0.34**	0.17	2.0

In Figure 10 the resistances measured with FRESCA are compared with calculated splice resistances. It can be seen that in the contact length range 3-120 mm the splice resistance can be predicted in good approximation when assuming that the splice resistance is inversely proportional to the contact length.

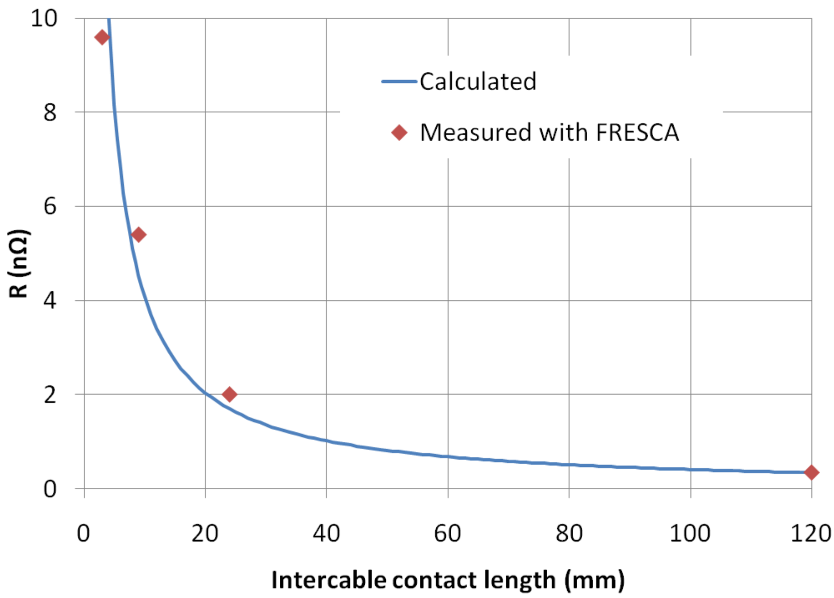

Figure 10: Comparison of the splice resistances measured with FRESCA for different intercable contact lengths and the calculated resistances. For the calculations it is assumed that the splice resistance is inversely proportional to the contact length, and that a splice with 120 mm overlap length has a resistance of 0.34 nΩ.

Mechanical strength at 4.3 K as a function of intercable contact length

The tensile strength of the test splices at 4.3 K has been measured at the Institut de fabrication, des matériaux et de la mécanique et de la mecanique des fluides (IMEC) at the Haute école du paysage, d'ingénierie et d' architecture de Genève (Hepia) in liquid Helium cryostat. The force at fracture at 4.3 K for different splice contact lengths is shown in Table 1.

Table 2: Force at fracture at 4.3 K of 13 kA LHC busbar cable splices for different intercable contact lengths.

nominal cable overlap length (mm)	average force at fracture (kN)
4	2.6 ± 0.7
10	3.2 ± 0.2
24	5.7 ± 1.5
120	8.7 ± 0.5

In Figure 11 the force at rupture is presented for all splices that have been tested at 4.3 K. Even for the very small cable overlap lengths the fracture force exceeds 2 kN.

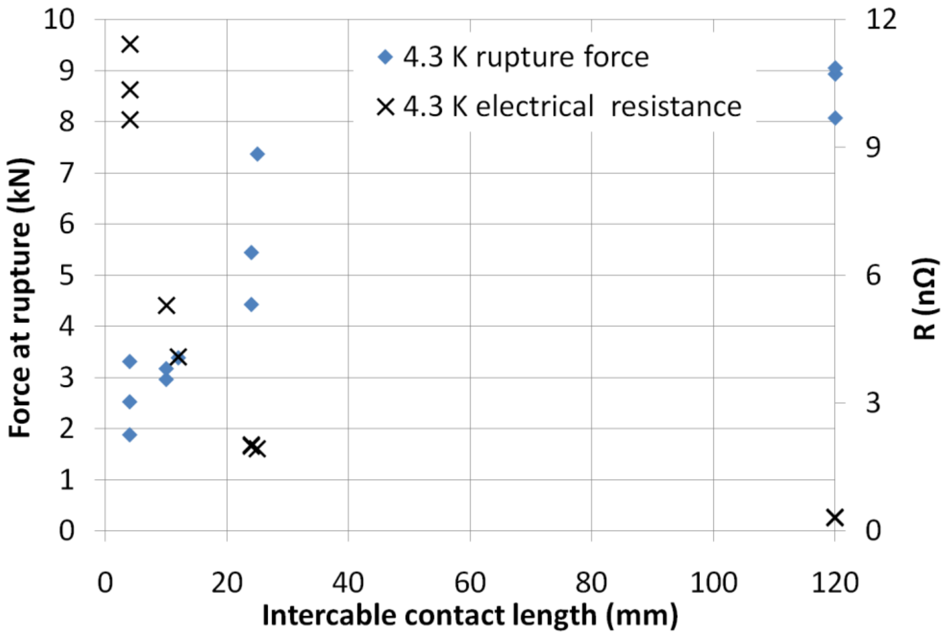

Figure 11: Force at rupture at 4.3 K and resistance R at 4.3 K as a function of the intercable contact length of 12 different LHC busbar cable splices. The same samples were used first for Cryolab electrical resistance measurements and then for tensile tests.

Discussion and conclusion

A splice resistance of 3.3 nΩ (the highest value measured for all LHC interconnection splices) corresponds with a cable overlap length of about 12 mm. The tensile strength of a 3.3 nΩ splice can exceed 3.5 kN at 4.3 K. The maximum force to which an interconnection splice can be subjected in the LHC is 0.7 kN, corresponding with the force needed to fully elongate a lyra [2].

The tensile strength at 4.3 K of splices with 4 mm overlap (corresponding with an electrical resistance of about 10 nΩ) is 2.6±0.7 kN.

Appendix

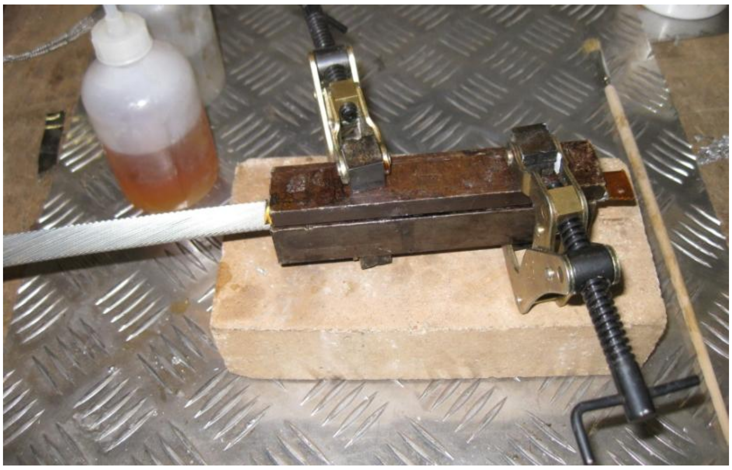

Figure 12: 120 mm resistively heated furnace for pre-tinning of the LHC busbar cable extremities.

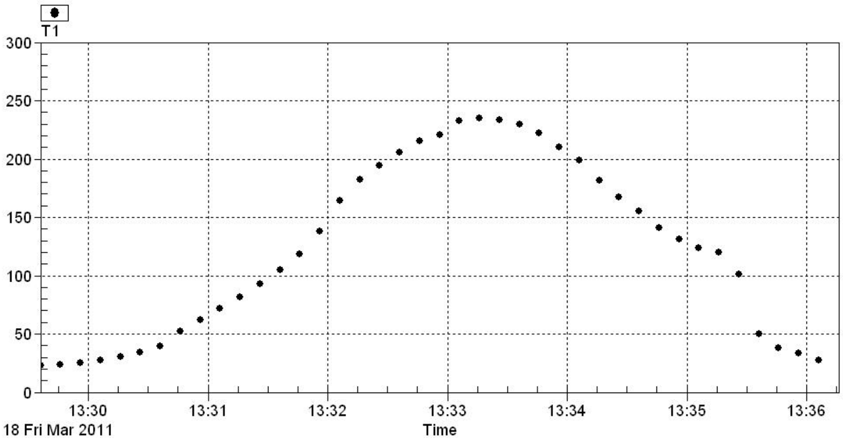

Figure 13: Temperature cycle recorded with a thermocouple during the pre-tinning process of the cables of the 13 kA test loops.

FRESCA 3 (3 mm)

FRESCA 9 (9 mm)

4-1 (4 mm)

9-2 (9 mm)

4-2 (4 mm)

11 (11 mm)

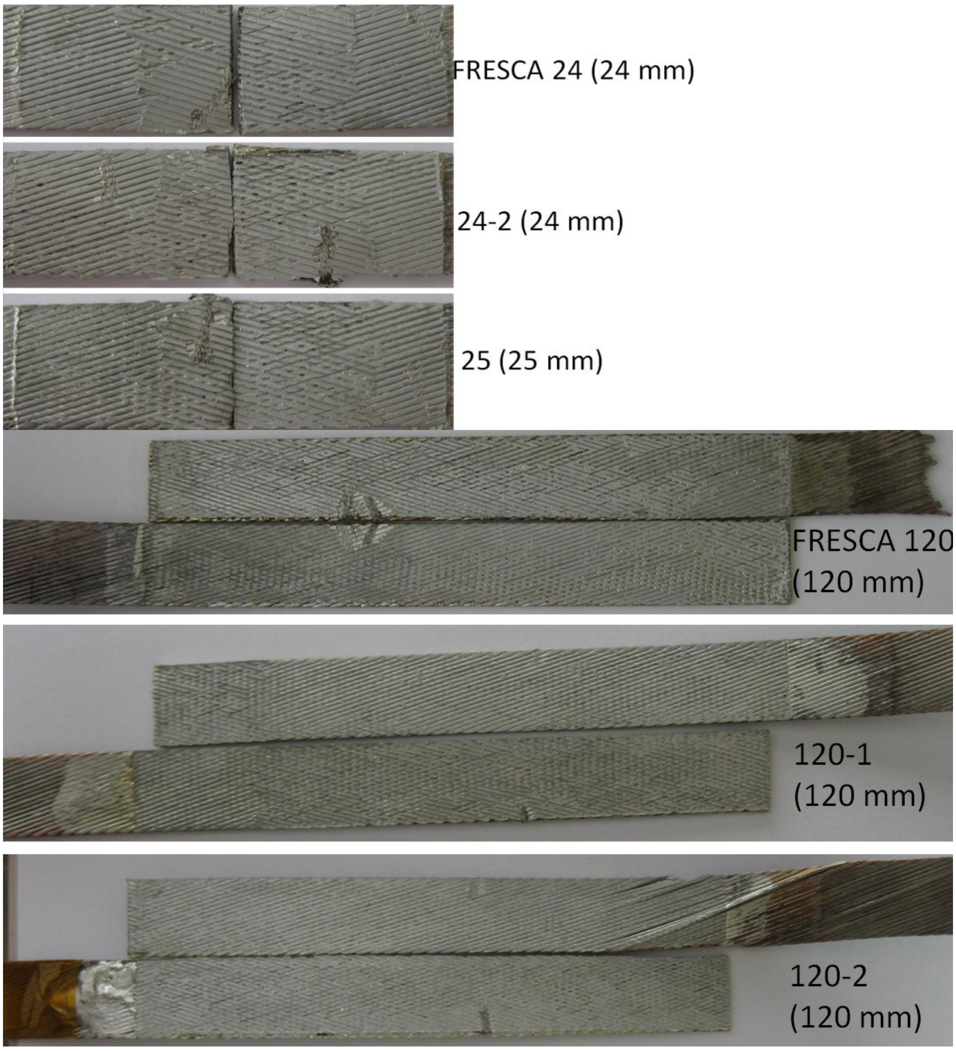

Figure 14: Photographs of fracture surfaces of 13 kA busbar cables after tensile test at 4.3 K. The nominal overlap lengths (values in brackets) vary in the range of 3 to 120 mm. For all samples apart from "FRESCA 120" fracture occurred in the splice at the solder interface between both cables.

References

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