



The RRR of the Cu components of the LHC main bus bar splices

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Summary

The different LHC main bus bar splice components (bus bar cable, splice U-piece and wedge and bus bar stabilizer) are subjected to different heat treatments (HTs) during bus bar assembly and splice soldering. The influence of soldering HTs on the RRR of the LHC main bus bar cable strands has been determined. The RRR of several splice U-pieces and wedges dismantled from the LHC has been measured. A correlation between the Vickers hardness and the RRR of the high purity Cu profiles has been established. All U-pieces tested that were produced before 2009 have a $RRR > 200$, while the RRR of all wedges and of U-pieces of 2009 production have a much lower RRR. All tests of LHC main bus bar samples performed so far in the laboratory indicate a RRR of approximately 200 or higher.

Introduction

The LHC main bus bar splices [1,2] consist of the Nb-Ti/Cu cables, a Cu U-piece and a Cu wedge, which are soldered together with the adjacent bus bar stabilizer [3] using a Sn96Ag4 solder alloy. The electrical resistivity of the different splice components has an influence on the maximum current that can be safely transported through the splice in case of a quench.

The electrical resistivity of the splice components at operating temperature can be assessed by Residual Resistivity Ratio (RRR) measurements (here defined as the ratio of the resistance measured at 293 K and at 10 K).

The splice Cu parts are produced by different processes (wire drawing, extrusion and milling), and subsequently subjected to different heat treatments (HT), during bus bar assembly and splice soldering. A HT cycle recorded during soft soldering of a main bus bar splice is shown in Figure 1. The nominal ramp rate and peak temperature are $100\text{ }^{\circ}\text{C/h} + 4\text{ h} - 270\text{ }^{\circ}\text{C}$.

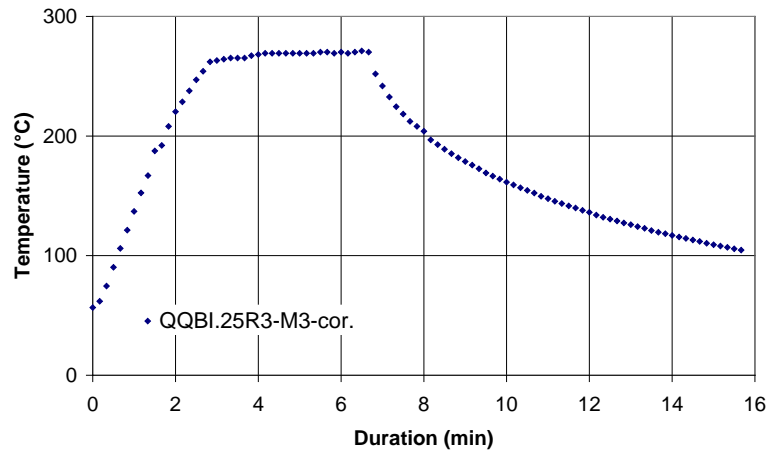


Figure 1: Heating cycle recorded in the LHC splice center during inductive soldering. The nominal peak temperature is 270 °C.

In this note we present RRR results and estimates that have been obtained for strands extracted from LHC bus bar cables, for the splice Cu profiles and the bus bar stabilizer.

The origin of the Cu profiles used for the fabrication of the main bus bar splices

All LHC main bus bar stabilizers have been produced by hot extrusion by Outokumpu out of OFE Cu. A minimum RRR of 100 has been specified for the bus bar stabilizer.

The so-called U-pieces and wedges used for the production of splices before 2009 have been provided by the IEG consortium during the execution of the interconnection work for the sectors 7-8, 8-1, 4-5, 3-4, 5-6, 2-3, 6-7 and partly 1-2 (order of interconnection execution). These components have been procured by IEG via the SISO company and cleaned by Fini Metaux. The Cu certificates control is ongoing (info to be provided by IEG).

Approximately 400 pieces, which have been used by IEG to complete sector 1-2, were machined out of Outokumpu bus bar profiles, and therefore are made of Outokumpu OFE Cu.

All wedges and U-profiles that have been used for the main bus bar splices during the repair and consolidation work during the 2009 shutdown have been machined out of OFE Cu sheet from the CERN store (e.g. SCEM 44.09.56.210.1).

Experimental

All RRR measurements reported here have been performed with the experimental set-up described in [4], with which previously more than 12 000 RRR measurements have been performed for the LHC strand quality control. The RRR is an average result over a sample length of approximately 80 mm (the 02 cable transposition pitch length is 100 mm).

In order to measure the RRR of the splice Cu profiles, bars with a cross section of 2×2 mm² have been machined out of the U-pieces and wedges (see Figure 2).



Figure 2: RRR sample machined out of U-piece disconnected from a LHC main bus bar splice.

During machining of the RRR samples care is taken not to heat the Cu pieces above 100 °C. However, a partial work-hardening of the machined faces can not be avoided. The additional cold-work is revealed by the indentation hardness measurements shown in Figure 3. Thus, it is assumed that, due to the additional cold-work, the RRR measured for the machined samples is somewhat lower than the RRR of the Cu profiles before machining the samples.

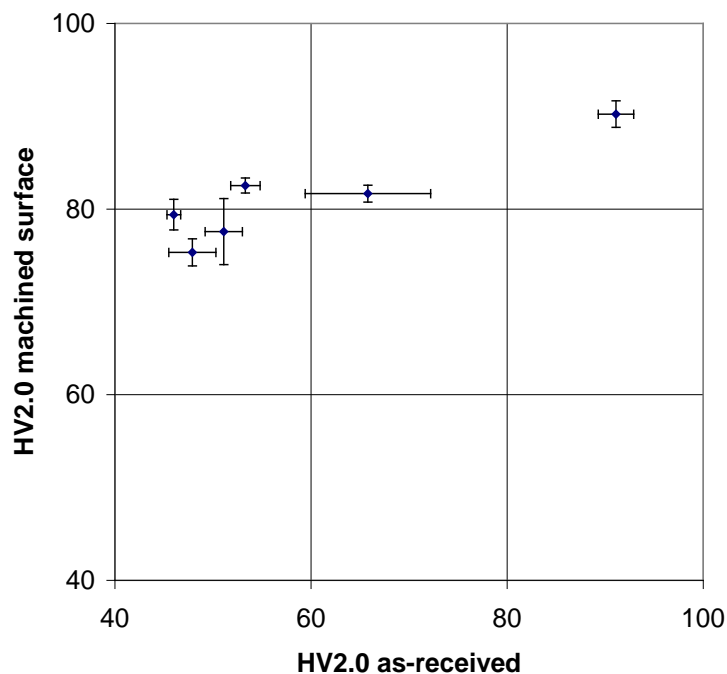


Figure 3: HV2.0 measured on the machined surface of RRR samples vs. HV2.0 measured on the corresponding Cu profiles before machining. The thickness that is indented with a load of 2 kg is about 30 μ m.

Indentation hardness measurements have been performed with a Leica VMHT MOT hardness tester using a Vickers diamond pyramid indenter. The maximum test load of 2000 gf was applied during 15 s. For all measurements an objective with a magnification factor of 10 has been used. Prior to the hardness measurements the instrument was tested using a polished stainless steel standard samples with nominal hardness $HV0.5=712\pm 17.4$. The respective hardness results measured with the Leica VMHT MOT are $HV0.5=709\pm 3$ (with a magnification factor of 50) and $HV2.0 = 660 \pm 14.5$ (with a magnification factor of 10).

Despite the systematic error in the HV2.0 measurements, these are preferred over HV0.5 measurements, because the larger indent diagonals in the unpolished samples can be measured more precisely. At a load of 2000 gf and HV=100 the indent depth is about 30 μm .

Results

RRR evolution of the Nb-Ti/Cu cable stabilizer during splice soldering

RRR measurements of strand extracted from LHC cables before final cable annealing show that during the cabling process the RRR of the strands is reduced from typically 170 to about 80 [4].

In Figure 3 the RRR vs. temperature behavior of non-cabled reference strand and a strand from the same manufacturer extracted from a cable are compared. Due to the strong strand cold-work during cabling, low temperature HT have a comparatively stronger influence on the RRR of the cabled strand. At relatively high temperatures (not relevant for the splice soldering process) the RRR of cabled and un-cabled strand decreases.

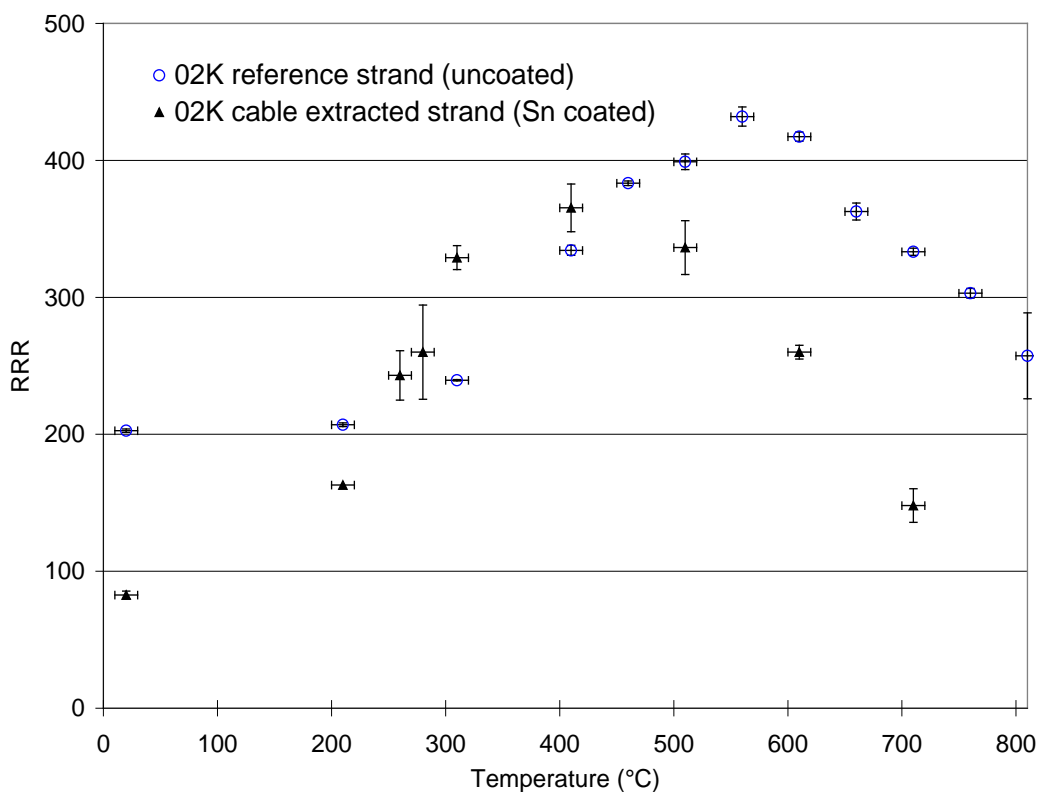


Figure 4: Comparison of RRR vs. peak temperature evolution of LHC Nb-Ti/Cu virgin strand (before cabling) and strand from the same manufacturer extracted from cable 12K20701AR [5].

In order to study the influence of a splice soldering HT on the RRR of the LHC bus bar cables, strand samples were extracted from cables of two different manufacturers that have been used for the production of the LHC bus bars. In Figure 5 the RRR evolution of cabled strand in the temperature interval of interest for splice soldering is presented. The RRR vs. temperature behavior of the strand extracted from two different manufacturers is identical within the experimental error. The ramp rate has a significant influence on the RRR evolution. The open triangles represent heat treatments with a ramp rate >100 $^{\circ}\text{C}/\text{min}$ (the nominal ramp rate of the soldering heating cycle is 100 $^{\circ}\text{C}/\text{min}$). When the cable is heated with >100 $^{\circ}\text{C}/\text{min}$ to the Sn96Ag4 melting temperature (222 $^{\circ}\text{C}$) and to the nominal peak temperature (270 $^{\circ}\text{C}$), the RRR is increased to about 130 and 200, respectively.

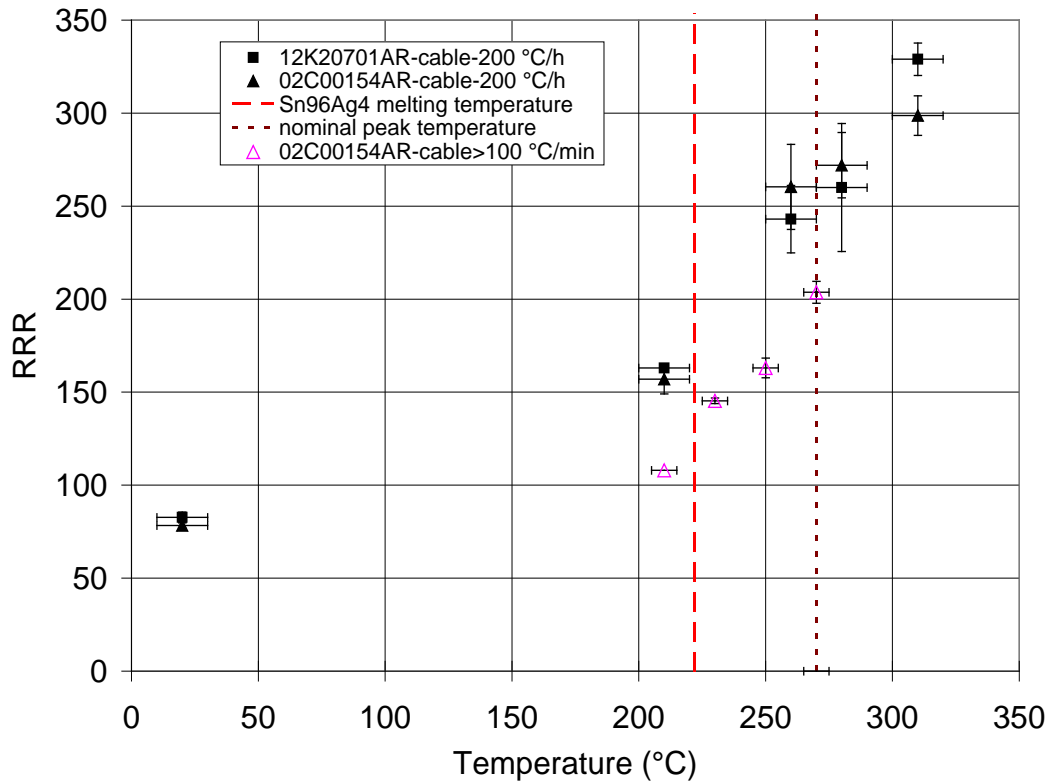


Figure 5: Comparison of RRR vs. peak temperature evolution of strand extracted from LHC cables 02C00154AR and 12K20701AR. The empty and full symbols represent HTs with a ramp rate of 200 °C/h and >100 °C/min, respectively. The dotted lines indicate the Sn96Ag4 melting temperature and the nominal peak temperature of the LHC main bus bar soldering HT.

The RRR of Cu profiles (U-pieces and wedges) of main bus bar splices

In Figure 6 the RRR of different splice profiles of “old” (i.e. before 2009) and 2009 shutdown production are compared. U-pieces of “old” production can be clearly distinguished from wedges and U-pieces of 2009 production. After the two heating cycles for soldering and un-soldering all U-pieces dismantled from the LHC have a RRR>250. All wedges and the U-pieces of 2009 production have a RRR in the order of 100. Because of the additional cold-work during machining, it is assumed that the RRR values presented in Figure 6 underestimate the RRR of the corresponding Cu-profiles before machining the RRR samples.

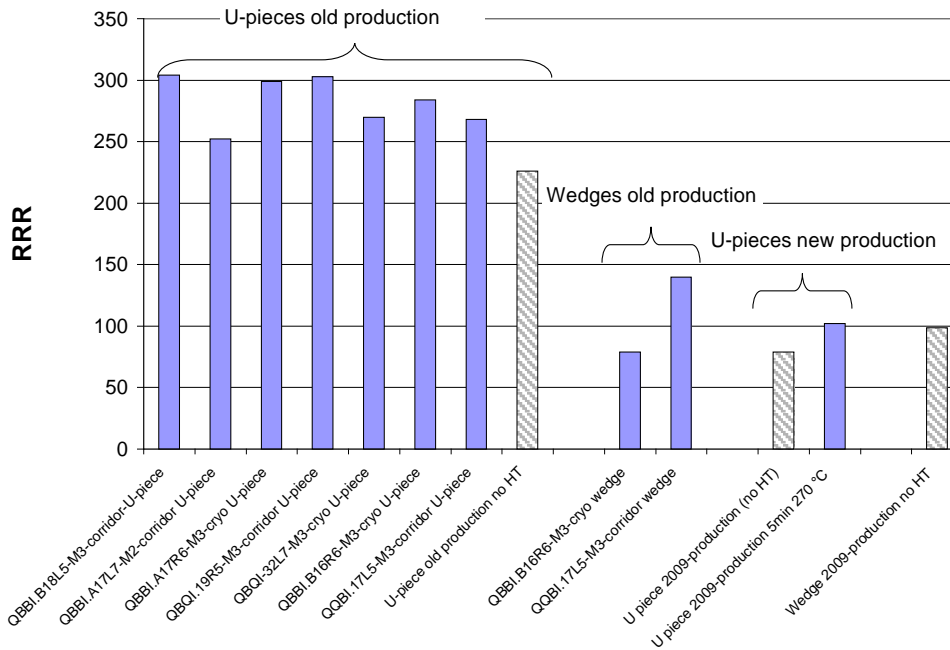


Figure 6: RRR of different U-pieces and wedges before and after HT.

The RRR evolution vs. peak temperature (ramp rate 200 °C/h) for Cu profiles that are machined out of OFE Cu sheet (2009 production) and of “old” U-pieces (presumably produced by hot extrusion) is shown in Figure 7. It can be seen that a soldering HT cycle can have a significant influence on the RRR of the different Cu-profiles, but its influence seems to be less important than it is on the RRR of the LHC cable Cu stabilizer.

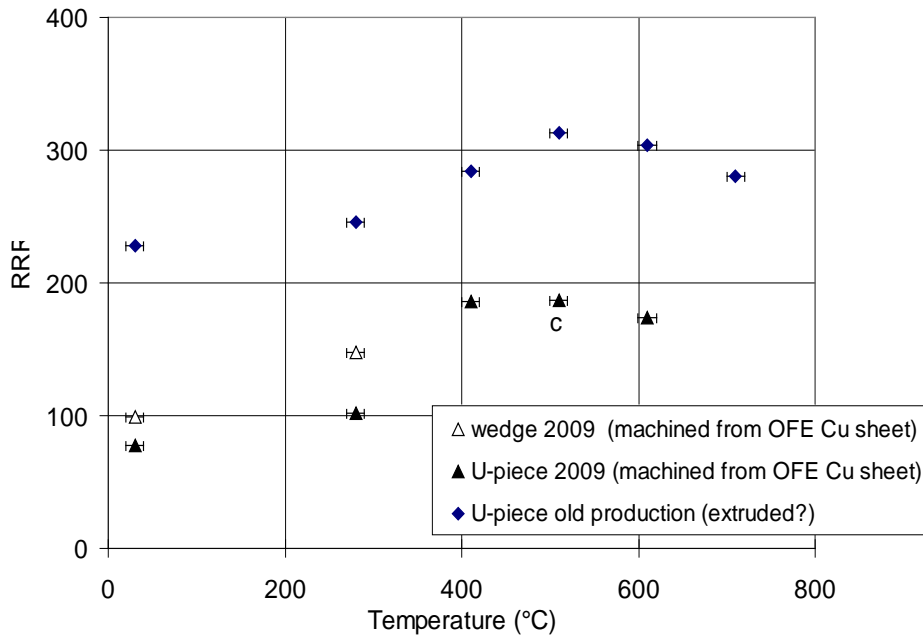


Figure 7: RRR vs. peak temperature for Cu samples machined from an extruded U-piece of old production, and a U-piece and a wedge of 2009 production (OFE Cu sheet from CERN store).

Correlation of the RRR and the Vickers hardness of Cu U-pieces and wedges

RRR measurements of splice and bus bar components are laborious and not always possible. Therefore, a correlation between the RRR and the Vickers hardness (HV) of different splice components has been established, assuming that the RRR of high purity copper can be estimated from the mechanical properties. RRR estimates from the Vickers hardness are fast, allow to compare the RRR of bus bar parts with complicated shapes, and can reveal temperature (and RRR) gradients.

In Figure 8 the RRR of different U-pieces and wedges (measured for 2×2 mm² Cu bars) that were used for LHC splice production is compared with the Vickers hardness (HV2.0) that has been measured in the corresponding profiles before machining the RRR samples. There is a reasonable correlation between RRR and HV2.0 values for the different high purity Cu samples. Thus, the RRR may be estimated from the approximate relation:

Equation 1: $RRR = -3.976 \times HV2.0 + 482$

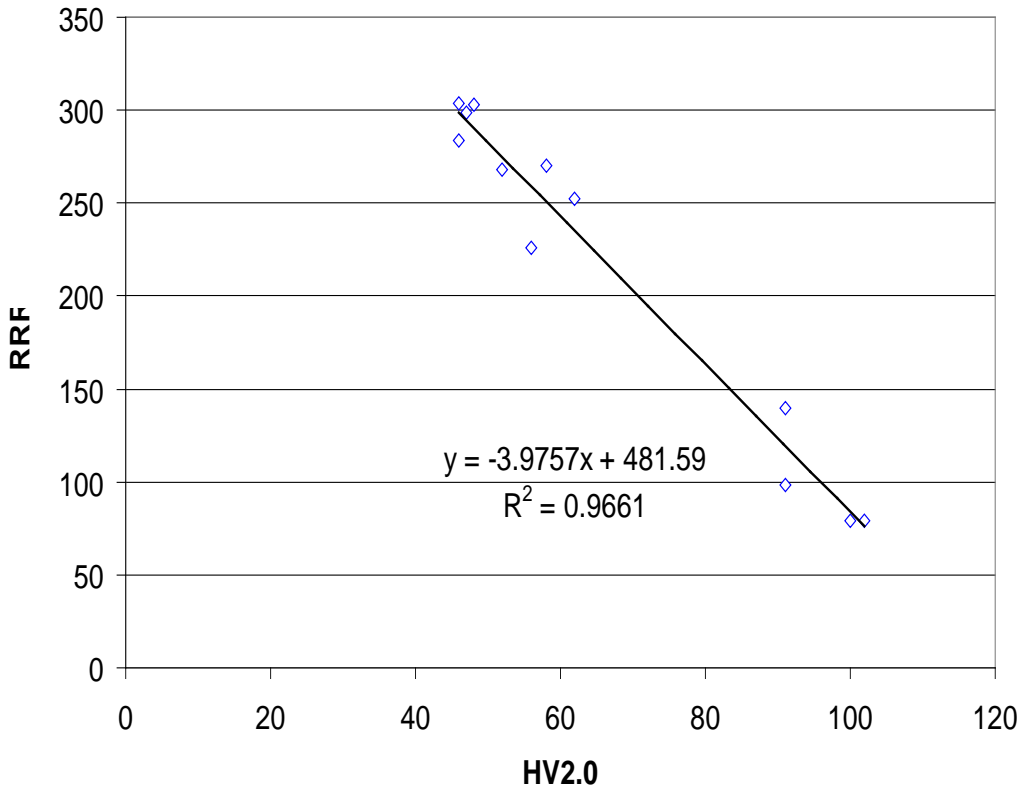


Figure 8: RRR as a function of Vickers hardness (HV2.0) for Cu U-pieces and wedges of LHC splices (“old” and 2009 production).

A random error of ± 17 ($\pm 1\sigma$) is estimated for the RRR results determined according to Equation 1. In addition there is systematic error that is due to the additional cold Cu work during the machining of the RRR samples (see Figure 3), which causes an underestimation of the RRR values that are determined from the Vickers hardness according to Equation 1.

Vickers hardness (HV2.0) of Cu U-pieces and wedges of old production

After solder connection of the LHC main bus bar splices the hardness of the Cu U-pieces increases (and the RRR decreases) from the center to the outside, due to a temperature gradient during the soldering cycle (see Figure 9). Unless explicitly stated, all HV2.0 results presented in this note have been measured in the center of the wedge and the U-piece.



Figure 9: U-piece and wedge disconnected from LHC interconnection QBBLB16R6-M3-cryoline with Vickers indent positions. In the U-piece there is a significant hardness increase from the center to the extremities, due to a temperature gradient during soldering. After the HT for splice connection and disconnection, the wedge is still strongly cold worked.

A summary of the HV2.0 results achieved for U-pieces and wedges that have been dismantled from the LHC interconnections and of production loops are presented in Figure 10 and Figure 11, respectively. The Cu profiles of the production loops were subjected to one heating cycle (nominal 100 °C/min + 4 min-270 °C), while the Cu pieces from the LHC interconnections were subjected to two heating cycles (during connection and disconnection). All Cu pieces for which results are shown in Figures 10 and 11 have been produced before 2009. There is clear difference in the hardness of U-pieces and wedges of the old production.

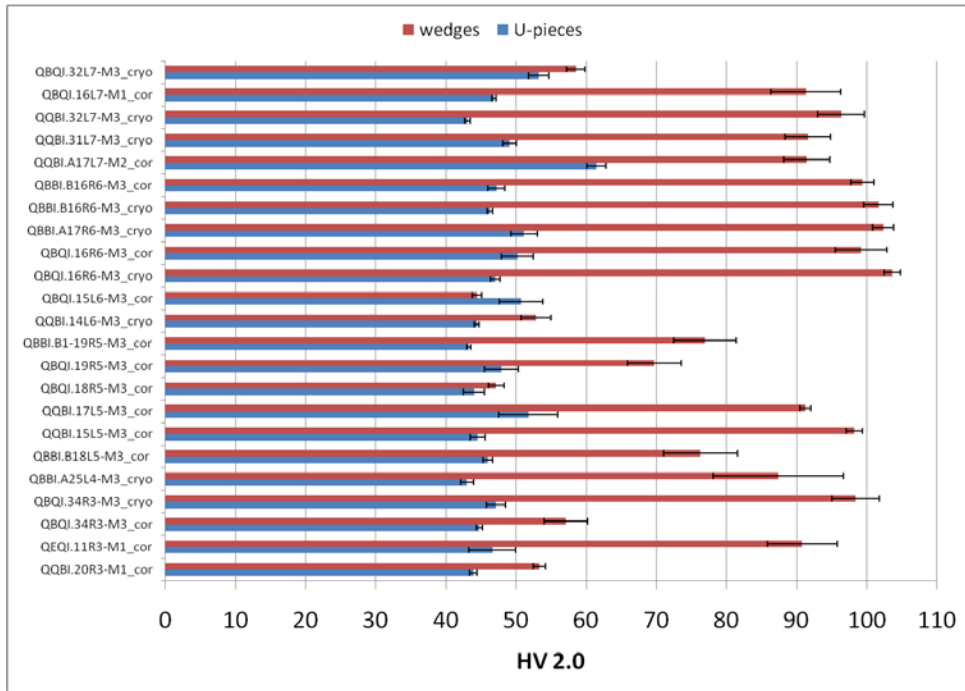


Figure 10: Vickers hardness (HV2.0) of Cu U-pieces and wedges that have been dismantled from the LHC during shutdown 2009. All Cu pieces have been produced before the 2009 shutdown.

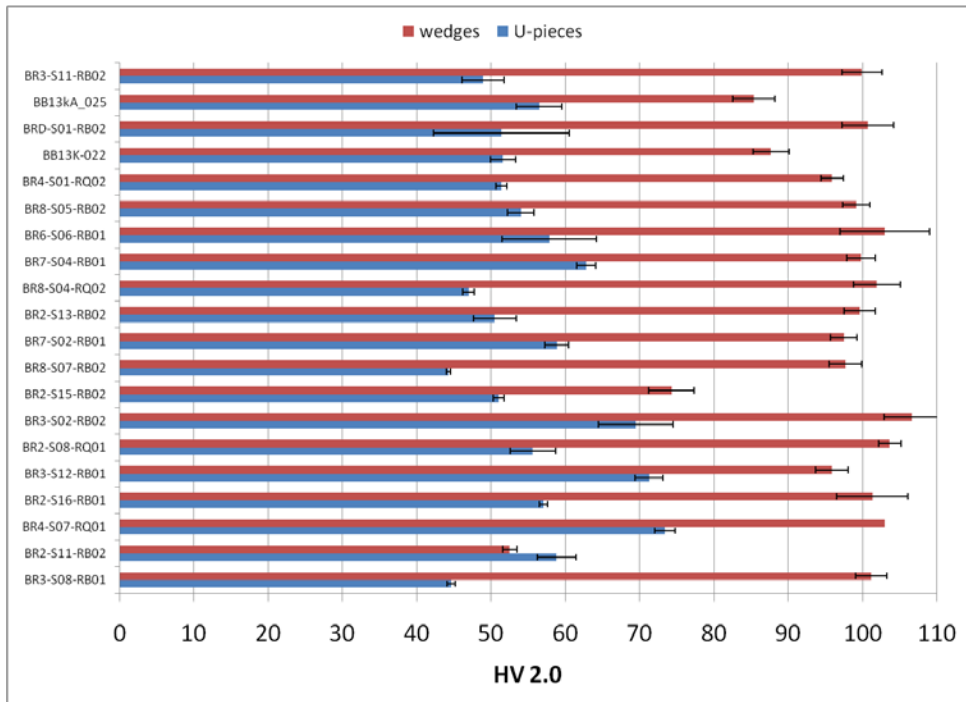


Figure 11: Vickers hardness (HV2.0) of Cu U-pieces and wedges of production loops that have been produced for quality assurance during previous LHC production. All Cu pieces have been produced before the 2009 shutdown.

In Figure 12 the Vickers hardness of Cu U-pieces and wedges produced during 2009 for the LHC repair and consolidation are presented.

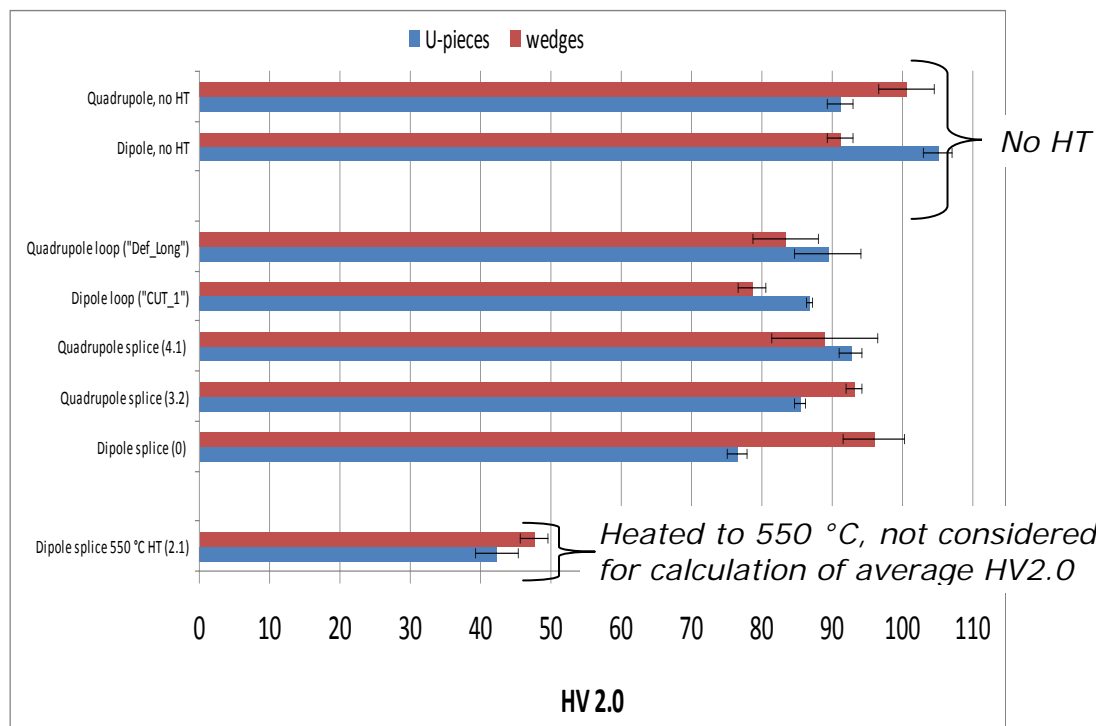


Figure 12: Vickers hardness (HV2.0) of Cu U-pieces and wedges (production loops and test splices) made of Cu profiles produced during the 2009 shutdown. For more details about the samples see Figure 13 in the appendix and [6].

The average HV2.0 values of the U-pieces and wedges dismantled from the LHC and of the loops are presented in Table 1. The hardness of the U-pieces and wedges in the loops are about 15 % higher than the respective values of pieces dismantled from the LHC. This difference is probably due to the second heating cycle that the pieces dismantled from the LHC followed during splice disconnection.

Table 1: Average Vickers hardness (HV2.0) measured for U-pieces and wedges of “old” production (before 2009) and 2009 production. Cu profiles in the production loops have been subjected to one heating cycle, while the pieces from the LHC were subjected to a second heating cycle during disconnection.

	U-pieces-average HV2.0	Wedges-average HV2.0
“Old” production (test loops, 20 samples)	55.8±8.6 estimated average RRR 260	95.3±12.5 estimated average RRR 100
“New” production (5 samples)	86.2±6.1 estimated average RRR 130	88.5±6.5 estimated average RRR 140
“Old” production (from LHC, 23 samples)	47.7±4.2	81.7±19.8

The maximum HV2.0 value measured for all U-pieces and wedges that have been tested from “old” production is HV2.0= 61±1.3 and HV2.0=104±3.5, respectively.

RRR of the LHC main bus bars

The RRR of different bus bar parts has been estimated from HV2.0 measurements. Images of the different bus bar pieces with the indent positions are presented in Figure 13 of the appendix. The HV2.0 results for different bus bar samples and the RRR values estimated according to Equation 1 are presented in Table 2. The estimated random error of the RRR values is ± 17 .

Table 2: Vickers hardness (HV2.0) of different stabilizer and bus bar samples and estimated RRR.

	Average HV2.0	(under-) estimated RRR
Dipole bus bar M3 1/0117	76 \pm 3.5	180
Dipole bus bar M3 2/0180	69 \pm 5.9	210
Dipole bus bar (“6” from 183)	58 \pm 9.0	250
Quad bus bar (“6.1” from 183)	75 \pm 13	180
Quad bus bar (“4.1” FRESCA sample 1)	66 \pm 6.4	220
Lyra quadrupole bus bar	72 \pm 5.5	200
Dipole bus bar (“2.2” from 183)	65 \pm 1.9	220
Quadrupole bus bar (“3.2” from 183)	60 \pm 6.7	240
Dipole bus bar (“4.3” from 183)	71 \pm 1.7	200
Dipole 1235-lyra-M1 cryo (6/4182)	65 \pm 4.0	220
Dipole 1235-lyra-M1 cor. (5/4164)	64 \pm 2.6	230
Dipole 1132-lyra-M3 cryo (2/3303)	69 \pm 6.3	210
Dipole 1132-lyra-M3 cor. (1/3297)	63 \pm 6.4	230

The RRR predicted from the HV2.0 result for the stabilizer of “FRESCA sample 1” is 220 and the RRR measured for a 2x2 mm² RRR machined out of this sample is 230. The RRR measured for this bus bar with the FRESCA experiment is between 290 and 330 [7].

Discussion and conclusion

The nominal soldering HT cycle can have a strong influence on the RRR of the LHC main bus bar cables. After a 4 min HT at the Sn96Ag4 melting temperature of 222 °C and the nominal soldering cycle peak temperature of 270 °C, the RRR of a 02C cable is approximately 130 and 200, respectively (when heated with a ramp rate >100 °C/h). The RRR vs. temperature/duration evolution for strand extracted from 02K and 02C cable is identical within the experimental error.

When the temperature profile in the cable across a splice is known accurately, it would thus be possible to predict the cable RRR after the soldering cycle. However, RRR differences obtained for both isolated cable defects in one splice of the FRESCA sample 2, indicate that there can be significant temperature differences on both sides of a splice during a standard soldering cycle.

All U-pieces of “old” (before 2009) production that have been analyzed have a RRR>200. Provided that all U-pieces used before 2009 have been produced by hot extrusion, it can be assumed that the RRR of “old” U-pieces is generally above 200.

The RRR of U-pieces produced during the 2009 shutdown (machined from OFE sheet) and of all wedges (“old” and 2009 production) is in the order of 100, significantly lower than that of the extruded U-pieces.

All bus bar stabilizer RRR results obtained so far in the laboratory indicate a RRR~200 or higher for the LHC main bus bar stabilizers.

Appendix

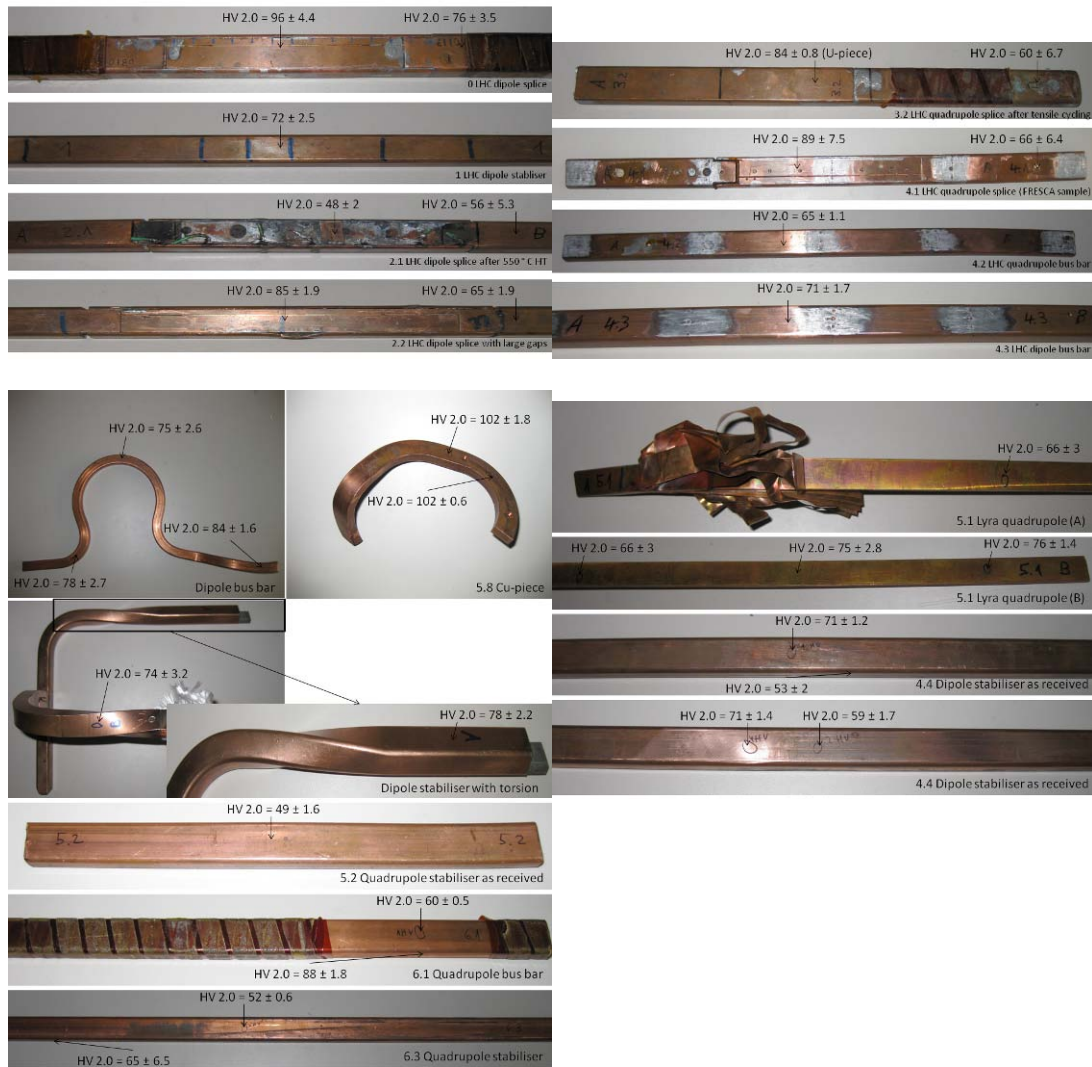


Figure 13: Different LHC main bus bar pieces tested with HV2.0 indent positions.



Figure 14: Vickers hardness measurements of the main dipole bus bar stabiliser in the LHC cryodipole 1132.

Acknowledgements

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Distribution

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