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Resistance of LHC main bus bar splices at room temperature and at 77.4 K

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Introduction

As part of the quality control the resistance of newly produced LHC main bus bar splices is now routinely measured at room temperature (RT) in order to conclude on the electrical continuity of the bus bar stabiliser across the splice under operating conditions.

In this note we present splice resistance measurements that have been performed at RT and in liquid nitrogen (LN) in the CERN Cryolab with “ideal” splices (represented by continuous dipole and quadrupole bus bars), and with dipole and quadrupole splices with different defects, which cause an additional RT splice resistance of up to 60 μΩ.

The RT resistance (R_{RT}) results obtained with the Cryolab set-up are compared to the calculated resistance values and with the so-called R-8 and R-16 resistance results, as they are measured in the LHC tunnel with a Digital Low Resistance Ohmmeter with a voltage tap distance of 8 cm or 16 cm.

The RT to LN resistance ratio has been determined for all splices in order to study the influence of the resistance of the splice contact surfaces on the overall splice resistance.

Experimental

The samples

The main bus bar splices of the LHC are produced by connecting two 12 cm-long Rutherford type cable ends with a Sn96Ag4 solder alloy by inductive soldering. A detailed description of the splice soldering procedure and the different splice components is given in [1,2]. The LHC quadrupole and dipole bus bars are described in [3].

The resistance of 9 samples has been measured. Continuous dipole (sample 4.3) and quadrupole (sample 4.2) bus bars have been used as a reference that presents an "ideal" dipole and quadrupole splice, without any discontinuity. Resistance measurements were also performed with a standard LHC dipole splice (sample 0), a dipole splice with large transverse gaps (sample 2.2), a dipole splice that was deliberately overheated to 550 °C (sample 2.1), a quadrupole splice with a complete transverse gap between the Cu profiles and an isolated cable length of 47 mm (sample 4.1, referred to as FRESCA sample) and a LHC quadrupole splice after cyclic tensile loading (sample 3.2). In addition a dipole stabilizer without cable (sample 1) and a dipole stabilizer without cable connected with a 1 mm thick Cu sheet that was soldered onto the stabilizer using a Sn60Pb40 alloy (sample 3.1) were tested. Photographs of the different samples are shown in Figure 3 in the appendix.

Resistance measurements

The RT splice resistance measurements in the LHC tunnel are performed with a Digital Low Resistance Ohmmeter (Avo DUCTER DLRO 10), in the following referred to as Megger. Measurements have been performed either with a voltage tap distance of 8 cm or 16 cm (referred to as R-8 and R-16, respectively). The R-16 result includes the resistance of both bus bar to splice contacts, while the R-8 result is only influenced by one contact. Since at the LHC interconnects the bus bar length that can be accessed is limited (see Figure 1), the current of 10 A is injected in a distance of 5 mm to the voltage taps. The point like current injection causes a significant error in the R-8 and R-16 results. Unless explicitly stated, voltage measurement and current injection is done at the side of the splice.

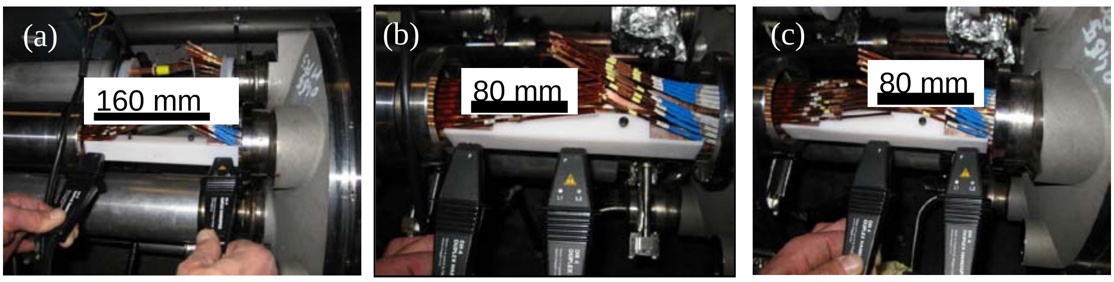

Figure 1: R-16 (a) and R-8 (b) (c) measurement with a Digital Low Resistance Ohmmeter at a quadrupole splice of a LHC interconnection.

R-16 and R-8 results are compared with splice resistance results at RT and at LN temperature that have been performed with a dedicated set-up in which a current of 10 A is injected at two sides of the bus bar extremities in a distance of at least 10 cm from the voltage taps.

Results

Splice resistance at RT and LN temperature

The resistance results for the different samples measured at RT (R_{RT}) and LN (R_{LN}) obtained with the Cryolab set-up are presented in Table 1. All measurements have been performed with a voltage tap distance of 8 cm or 16 cm, and a current of 10 A.

Table 1: R_{RT}, R_{LN} and R_{RT}/R_{LN}, for samples with different Cu cross section (A_{Cu}). An additional resistance at RT (Δ_{RT}) is calculated from the nominal Cu cross sections, assuming a Cu resistivity of ρ_{Cu}=1.724×10^{-8} Ωm.

Sample	Voltage tap distance (cm)	A_{Cu} (mm^2)	R_{RT} (μΩ)	ΔR_{RT} (μΩ)	R_{LN} (μΩ)	R_{RT}/R_{LN}
0-LHC dipole splice	16	282	12.2±0.03	2.42	1.47±0.03	**8.27**
	8 (A to center)		7.23±0.05	2.34	0.87±0.03	**8.29**
	8 (B to center)		4.94±0.03	0.05	0.69±0.03	**7.20**
	R-8A+R-8B		*12.2*		*1.56*	
1-LHC dipole stabiliser (without cable)	16	269	10.5±0.03	0.29	1.27±0.03	**8.29**
	8		5.25±0.03	0.12	0.65±0.03	**8.01**
2.1-LHC dipole splice after 550 °C heating test	16	282	13.8±0.03	4.07	1.83±0.03	**7.56**
	8 (A to center)		7.05±0.04	2.17	0.95±0.03	**7.46**
	8 (B to center)		6.71±0.03	1.83	0.86±0.03	**7.85**
	R-8A+R-8B		*13.8*		*1.80*	
2.2-LHC dipole splice with large gaps	16	288	12.4±0.03	2.58	1.50±0.03	**8.24**
	8 (A to center)		6.58±0.04	1.69	0.82±0.03	**8.05**
	8 (B to center)		5.62±0.03	0.73	0.65±0.03	**8.67**
	R-8A+R-8B		*12.2*		*1.47*	
3.1-LHC dipole stabiliser Sn60Pb40 soldered	8	282	7.39±0.03	2.26	0.87±0.04	**8.52**
3.2-LHC quadrupole splice after tensile cycling	8	161	11.8±0.03	3.28	1.49±0.03	**7.94**
4.1-LHC quadrupole splice (FRESCA sample)	16	161	81.0±0.17	63.9	10.5±0.03	**7.69**
	8 (A to center)		70.2±0.05	61.6	9.14±0.03	**7.68**
	8 (B to center)		11.5±0.03	2.93	1.54±0.03	**7.45**
	R-8A+R-8B		*81.7*		*10.7*	
4.2-LHC quadrupole bus bar	16	169	16.6±0.03	-0.47	1.89±0.03	**8.79**
	8 (A to center)		8.29±0.03	-0.26	0.90±0.03	**9.25**
	8 (B to center)		8.48±0.03	-0.07	0.94±0.03	**9.05**
	R-8A+R-8B		*16.8*		*1.83*	
4.3-LHC dipole bus bar	16	282	9.83±0.03	0.06	1.08±0.03	**9.10**
	8 (A to center)		4.96±0.04	0.07	0.51±0.04	**9.79**
	8 (B to center)		4.78±0.03	-0.11	0.65±0.03	**7.30**
	R-8A+R-8B		*9.74*		*1.16*	

There is an important scatter of the R_{RT}/R_{LN} results, which can be partly caused by measurement errors and partly by differences in the RRR of the different Cu splice components. If Δ_{RT} would only be caused by a restriction of the current flow at the contacts between bus bar stabiliser and the splice profiles (constriction resistance), R_{RT}/R_{LN} should be in the range 8.4< R_{RT}/R_{LN} <9.1, assuming that the RRR of the different splice Cu parts (bus bar stabiliser, splice Cu profiles and Cu stabiliser of the cable) varies between 100 and 300 (see R_{RT}/R_{LN} vs. RRR of Cu in Figure 5 in the appendix).

The average R_{RT}/R_{LN} ratio for all bus bars and stabiliser samples (without solder contacts) is 8.70±0.79 (average of 8 results) and the average R_{RT}/R_{LN} values for all splices with solder contacts is 7.95±0.46 (average of 12 results). Thus, it can not be excluded that the splice contact resistance has a measurable influence on the R_{RT}/R_{LN} ratio, but it is clear that the Cu bulk resistance, and in some cases the constriction resistance, are dominating the overall splice resistance.

Error in the Megger measurements

In Table 2 the RT resistance results obtained with the Cryolab set-up are compared with the R-8 and R-16 results measured with the Megger in the same way as the measurements are performed in the LHC tunnel.

Table 2: Comparison of splice resistance R_{RT} measured with the Cryolab set-up and R-8/R-16 measured with the Megger.

Sample	Voltage tap distance (cm)	R_{RT} (μΩ)	R-8; R-16 (μΩ)	Δ_{R-16}; Δ_{R-8}
0-LHC dipole splice	16	12.2	12.9	**0.74**
	8 (A to center)	7.23	8.10	**0.87**
	8 (B to center)	4.94	5.73	**0.79**
	R-8A+R-8B	*12.2*	*13.8*	
1-LHC dipole stabiliser (without cable)	16	10.5	11.1	**0.59**
	8	5.25	6.07	**0.82**
2.1-LHC dipole splice after 550 °C heating test	16	13.8	16.3	**2.46**
	8 (A to center)	7.05	8.60	**1.55**
	8 (B to center)	6.71	8.80	**2.09**
	R-8A+R-8B	*13.8*	*17.4*	
2.2-LHC dipole splice with large gaps	16	12.4	13.6	**1.28**
	8 (A to center)	6.58	7.57	**0.99**
	8 (B to center)	5.62	6.77	**1.15**
	R-8A+R-8B	*12.2*	*14.3*	
3.1-LHC dipole stabiliser Sn60Pb40 soldered	8	7.39	8.43	**1.04**
3.2-LHC quadrupole splice after tensile cycling	8	11.8	13.3	**1.47**
4.1-LHC quadrupole splice (FRESCA sample)	16	81.0	86.7	**5.71**
	8 (A to center)	70.2	74.3	**4.09**
	8 (B to center)	11.5	13.2	**1.79**
	R-8A+R-8B	*81.7*	*87.5*	
4.2-LHC quadrupole bus bar (with cable)	16	16.6	18.0	**1.40**
	8 (A to center)	8.29	9.73	**1.45**
	8 (B to center)	8.48	9.57	**1.09**
	R-8A+R-8B	*16.8*	*19.3*	
4.3-LHC dipole bus bar	16	9.83±0.03	10.6	**0.74**
	8 (A to center)	4.96±0.04	5.67	**0.71**
	8 (B to center)	4.78±0.03	5.60	**0.82**
	R-8A+R-8B	*9.74*	*11.3*	

In Figure 2 the Megger measurement error is plotted versus the RT resistance measured with the Cryolab set-up, which is assumed to be the correct resistrance value. Due to the non-uniform current injection in a distance of only 5 mm to the voltage taps, R-16 and R-8 values are systematically too high. The error in the *R-8* and *R-16* results increases with the splice resistance and in rough approximation the room temperature splice resistance R_{RT-16} and R_{RT-8} in μΩ can be determined as:

$$R_{RT-16}=0.94\times R\text{-}16-0.40$$

$$R_{RT-8}=0.96\times R\text{-}8-0.86$$

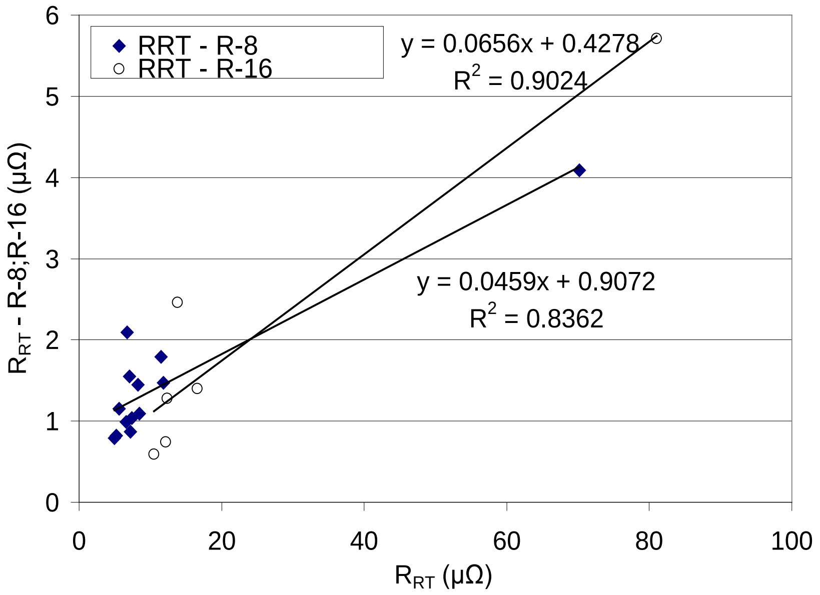

Figure 2: Error in R-8 and R-16 results (Megger measurements) as a function of the splice resistance R_{RT} measured with the Cryolab set-up.

The non-uniform current injection causes also the systematic discrepancy between R-16 and R-8A+R-8B results (see Table 2). In average R-8A+R-8B is 0.92±0.24 μΩ higher than R-16. For comparison, the average R_{RT-8A}+R_{RT-8B} results differ from the average R_{RT-16} by +0.10±0.32 μΩ.

Discussion and conclusion

The splice resistance is influenced by the Cu bulk resistance, geometrical restrictions of the current flow (constriction resistance) and a contact resistance (resistance of surface oxides, intermetallics and contamination at the interfaces between the different Cu profiles). The results presented here show that the Cu bulk resistance and the constriction resistance have a dominating effect on the overall splice resistance, while the influence of oxides and intermetallics at the interfaces is minor. Thus, when the RRR of all Cu components of the splice is known, the splice resistance at operating temperature can be predicted in reasonable approximation from RT resistance results.

The error in R-8 and R-16 measurement results increases with increasing constriction resistance. An approximate relation between the RT splice resistance and the R-16 and R-8 results as measured in the LHC tunnel has been established. The accuracy of this relation could be improved with more measurements of samples with an additional RT resistance in the range 20-40 μΩ.

Acknowledgements

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Distribution

TE-MSC and TE-MPE scientific staff, Task Force LHC Splices Consolidation, authors.

Appendices

Figure 3: Different samples used for resistance measurements. The voltage tap positions and the RT resistance results are indicated for all samples.

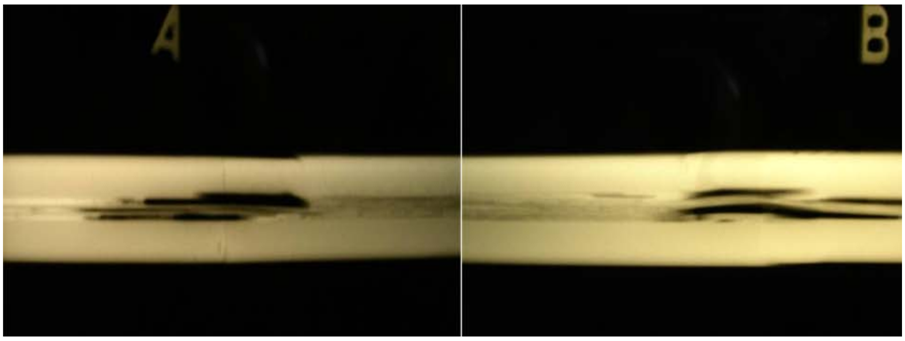

Figure 4: Gamma ray images of insulated cable inside a LHC dipole splice (sample 0). Courtesy J.-M. Dalin.

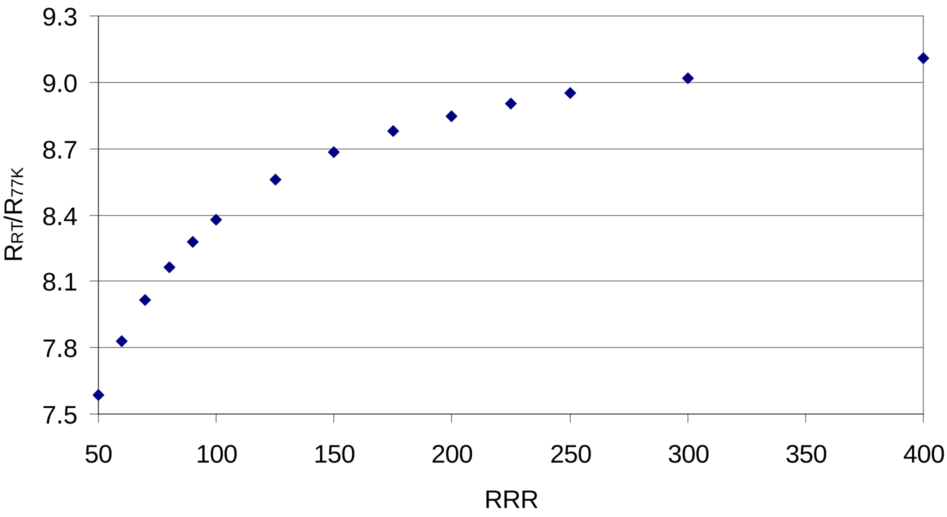

Figure 5: Calculated ratio of Cu resistance at RT and at 77 K as a function of RRR (ratio of the resistance at RT and 10 K) [4].

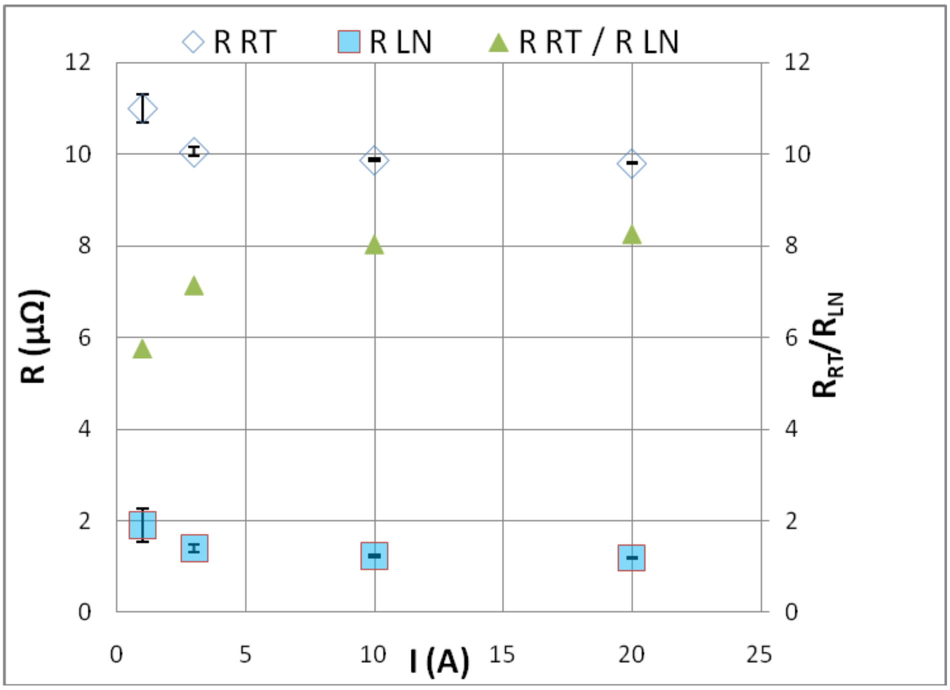

Figure 6. Influence of current (*I*) on the electrical resistivity (*R*) and the ratio R_{RT}/R_{LN} results for sample 4.3 at RT and LN temperature. The voltage tap distance is 16 cm. Systematic and random errors in the resistance results decrease strongly with increasing current.

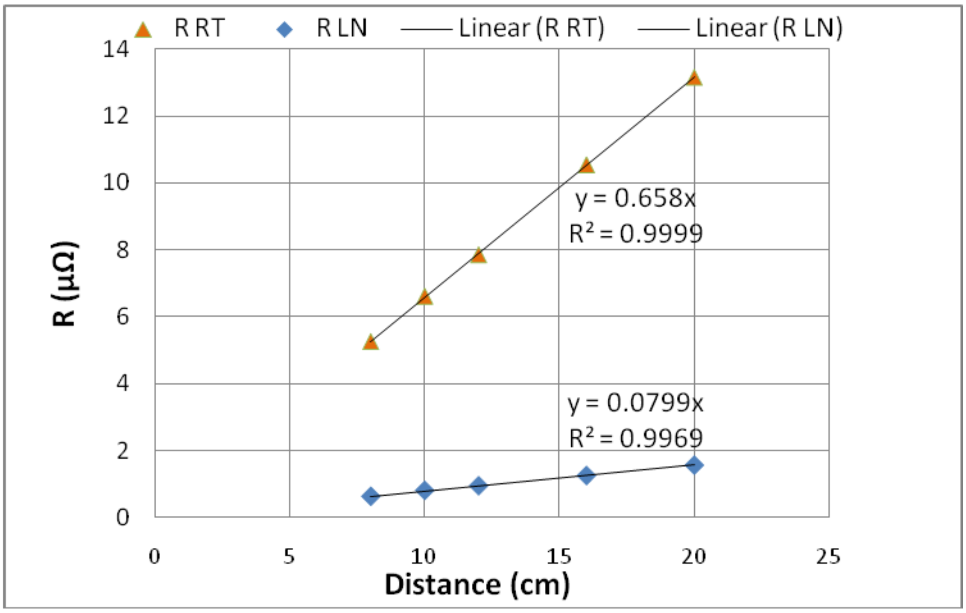

Figure 7. Electrical resistance *R* of LHC dipole stabiliser (sample 1) as a function of voltage tap distance.

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