HIGH-CURRENT BUS SPLICE RESISTANCES AND IMPLICATIONS FOR THE OPERATING ENERGY OF THE LHC

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Abstract

At each interconnection between LHC main magnets a low-resistance solder joint must be made between superconducting cables in order to provide a continuous current path through the superconductor and also to the surrounding copper stabilizer in case the cable quenches [1]. About 10,000 such joints exist in the LHC. An extensive campaign has been undertaken to characterize and map the resistances of these joints. All of the superconducting cable splices were measured at 1.9 K and no splices were found with a resistance larger than 3 nΩ. Non-invasive measurements of the stabilizer joints were made at 300 K in 5 of the 8 sectors, and at 80 K in 3 sectors. More precise local measurements were made on suspect interconnects that were opened up, and poor joints were repaired. However, it is likely that additional imperfect stabilizer joints still exist in the LHC. A statistical analysis is used to place bounds on the remaining worst-case resistances. This sets limits on the maximum operating energy of the LHC, prior to a more extensive intervention [2].

SPLICES

Types of splices

The main circuits of the LHC – one dipole (RB) and two quadrupole (RQ) per sector – contain about 24,000 splices in total. Out of these 10,170 are interconnect splices (Figure 1) and the rest are magnet splices.

Magnet splices are protected by the magnet bypass diodes and in case of a quench, heaters are fired and the current decays in less than a second. Interconnect splices are not protected by diodes and have to withstand current with the time constant of the energy extraction circuit which is much larger (and depends on the energy and circuit – between 10 s for RQ at 3.5 TeV and 100 s for RB at 7 TeV). The nominal interconnect splice resistance is about 300 pΩ at 1.9 K, whereas at room temperature the resistance of 16cm of copper stabilizer is about 10 μΩ and 17 μΩ for the RB and RQ buses respectively.

Individual splices are measurable only with invasive methods. Under non-invasive conditions what can be measured is a *busbar segment* between adjacent voltage taps. A typical busbar segment for the RB bus contains 2 or 3 splices, whereas a typical busbar segment for the RQ bus contains 8 splices. Non-invasive methods at non-superconducting temperatures measure the resistance of the splices but also the resistance of the busbar segment. Busbar *excess resistance* ($R_{EXC,BB}$) is the resistance of a busbar minus its nominal resistance at non-superconducting temperatures.

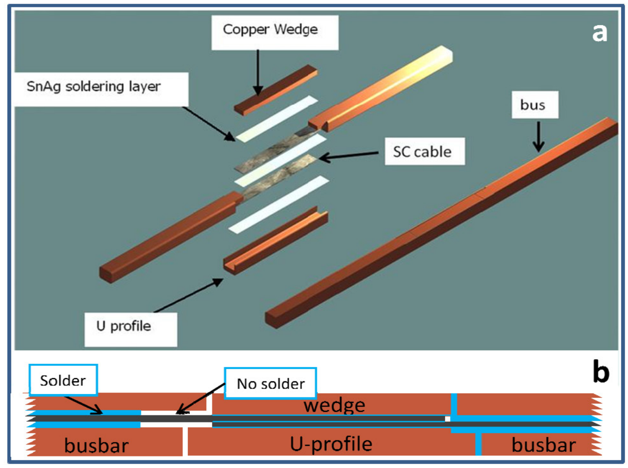

Figure 1: (a) An interconnect splice and (b) an example of poor copper stabilizer continuity (2D projection).

Measurements at cold

Motivation for measuring splice resistances comes from the 19 September 2008 accident. The calorimetric analysis of a circuit test performed a few days before the accident yields the value of 234±15 nΩ [3] for the excess resistance at 1.9 K ($R_{EXC,SC}$) in the vicinity of the problem. This is orders of magnitude higher than the nominal splice resistance and has prompted a campaign to measure the resistance of as many splices as possible in a variety of ways:

Calorimetry [4]: taking benefit of the superfluid properties of helium, together with the very small heat capacity of the system at 1.9 K, it is possible to measure the resistive heat released by a high-resistance splice. Resistive power as low as 1 W in one cryogenic subsector (16 magnets, 350 t of cold mass, 250 m long) can be detected using this method. The temperature rise is 1 mK/hour/W. $R_{EXC,SC}$ as low as 40 nΩ can be detected using this method.

Electrical: We have also performed (*ad-hoc*) measurements using the quench protection system (QPS) which covers 6 out of 7 magnet splices (RB) and 6 out of 10 magnet splices (RQ).

Using both methods, two significant $R_{EXC,SC}$ in magnet splices were found, one 100 nΩ and the other 50 nΩ, and the magnets were replaced.

The enhanced QPS (nQPS) system [5] became operational in 2009/2010. Operateed essentially as a series of accurate voltmeters, it has a better accuracy than the above methods, especially when measuring busbar segment $R_{EXC,SC}$ where the accuracy is better than 1 nΩ. Regarding magnet splice resistances no value above

25 nΩ has been found, whereas for busbar segment resistances, no $R_{EXC,SC}$ above 3 nΩ has been seen anywhere in the machine. The highest splice resistance seen is 2.99±0.02 nΩ (RQ circuit, sector 23), with only a couple of $R_{EXC,SC}$ above 2 nΩ.

$R_{EXC,SC}$ of a few nΩ poses no problems under normal operation; however it might suggest a structural problem or a problem with the soldering procedure that could result in a high $R_{EXC,BB}$.

Measurements at non-superconductive temperatures – non-invasive

A copper stabilizer with no continuity coupled to a superconducting cable badly soldered to the stabilizer (Figure 1) limits the maximum safe energy of the machine [6]. Such a bad joint manifests itself as a splice with higher than nominal resistance at warm. Measuring such a resistance is challenging, with only the measurement at 300 K for the RB bus being relatively easy. For measuring the RB busbar segment resistances at 80 K we need very good knowledge of the temperature and the RRR of the copper stabilizer (RRR_{CS}). Measuring the RQ at 300 K is on the limit of accuracy, whereas measuring the RQ at 80 K is very difficult. Table 1 shows the factors affecting the resistance measured at warm, together with the typical resistance of a segment and of a defect that we are trying to measure. Column 4 shows the effect of a temperature change in the segment by 1 K. Column 5 shows the effect of an increase in the cross section of the copper stabiliser by increasing the width and the height of the copper by 50 μΩ, whereas the last column shows the effect of the RRR_{CS} increasing from 100 to 150.

Table 1: Factors affecting segment resistance at warm

Busbar segment	Typical resis. (μΩ)	Typical defect (μΩ)	Temp. change +1 K	Xsection change	RRR_{CS} change
RB@ 300K	2000	50 (2.5%)	7 (0.4%)	12 (0.6%)	7 (0.3%)
RQ@ 300K	11000	50 (0.5%)	40 (0.4%)	85 (0.8%)	40 (0.3%)
RB@ 80K	270	7 (2.5%)	8 (2.9%)	2 (0.6%)	7 (2.6%)
RQ@ 80K	1500	7 (0.5%)	44 (2.9%)	11 (0.8%)	40 (2.6%)

A substantial effort to map all busbar segment resistances was undertaken during the period April to July 2009 [1]. Measurements (referred to as *Biddle* measurements) were taken manually using an accurate hand-held device in the tunnel in all sectors.

The overall analysis achieved an accuracy (depending on the sector) of 9-17 μΩ for the RB and 25-36 μΩ for the RQ at room temperature (about 0.7% and 0.3% respectively) whereas at 80 K the accuracy was between 4-5.5 μΩ for the RB and 6-12 μΩ for the RQ (2% and 0.7% respectively). This was sufficient for the RB bus at 300 K but was marginal for the RQ and insufficient at 80 K. Five sectors were measured at room temperature and the worst splices were opened up and repaired. Three sectors were measured at 80K. Table 2 shows the situation in the RB of the sectors measured at room temperature (where accuracy is good) after the repairs. The last column shows the estimated highest excess resistance in a sector at the 90% confidence level. This is higher than column 4, as the measurement accuracy is of the order of 10-17 μΩ.

Table 2: recap of RB Biddle measurements at 300 K

Circuit/ Sector	Temperature spread (K)	$R_{EXC,BB}$ spread (μΩ)	Highest remaining $R_{EXC,BB}$(μΩ)	$R_{EXC,BB}$ 90%CL (μΩ)
A12 RB	1.1	13	37	51
A34 RB	1.9	10	35	47
A45 RB	0.9	17	53	78
A56 RB	0.4	9	20	34
A67 RB	0.6	14	31	48

Measurements at warm – invasive

In addition to the Biddle measurements, a number of individual interconnect splices were opened and measured invasively (referred to as *R16* measurements). Most of these were made following an opening of an interconnect after an indication of a high excess resistance by the Biddle measurements. The worst R16 resistance measured was 70μΩ, where the average resistance of a 16 cm-long continuous RB busbar is about 10 μΩ. Therefore the highest R16 *excess* resistance ($R_{EXC,R16}$) is 60 μΩ.

The gamma-ray picture of one side of that specific splice interconnect can be seen in Figure 2.

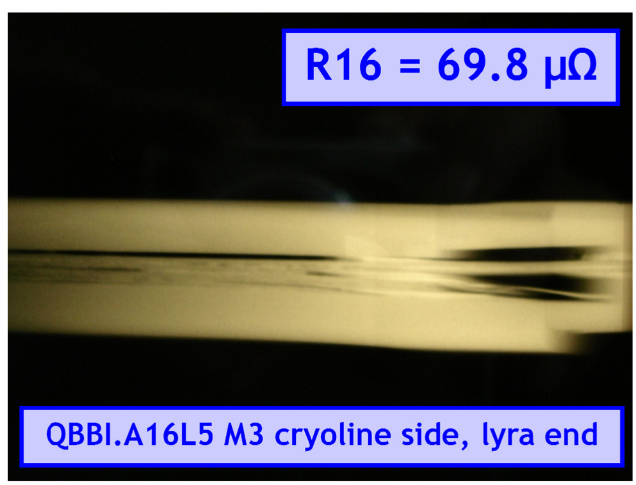

Figure 2: The interconnect with the worst measured R16 resistance. The side seen has an absolute resistance of 42 μΩ (the other side measured at 28 μΩ).

Worst remaining splice

Since reliable information about the resistance of splices exists only for part of the machine, a statistical method is needed to estimate the worst possible splice present at the LHC, R_{max}. The only reliable Biddle measurements are the RB measurements at 300 K (5 sectors). The worst *measured* $R_{EXC,BB}$ before repairs for the RB is 74±15 μΩ (sector A45), whereas the worst *remaining* $R_{EXC,BB}$ after repairs 53±15 μΩ (again sector A45). The worst $R_{EXC,R16}$ is 60±1 μΩ. The cumulative distribution of the R16 measurements can be seen in Figure 3. The red curve, an exponential function, is constrained to give the observed number of samples above 20 μΩ, and fits the data well. This fit predicts that the underlying distribution, from which these data are a sample, would, on average, have 0.8 joints above 60 μΩ. The limit for 0.1 (0.01) bad joints is $R_{EXC,R16} > 82$ (106) μΩ.

The next question is how to use these data to place limits on what remains in the machine. Although the sample contains about 2.3% of the total number of joints in the machine, they were selectively chosen after an indication of the non-invasive measurements. These had sufficient resolution in terms of $R_{EXC,R16}$ (~15 μΩ), that they provided a meaningful basis for locating bad joints and for deciding which interconnects to open in 5 out of 8 sectors for the RB bus. In this case the sample of R16 measurements represents about (1/3) x (5/8) =~ 20% of the high-current joints in the machine. This value of the sampling fraction leads to the following value of the maximum excess resistance for all main circuits at the 90% confidence level: $R_{max,R16}$ = 98 μΩ. Various systematic effects were considered both in the estimation of the form of the distribution and the sampling fraction, giving an overall uncertainty to the confidence bounds from this analysis of the order of ±10 μΩ. The value derived, however, is still larger than the resistance of the worst identified failure mode (it would mean that 10cm of superconducting cable remained unsoldered from the busbar segment). Therefore, a more realistic value which was used for subsequent discussions on the safe energy of the LHC was $R_{max} \approx 90$ μΩ.

CONSTRAINTS ON THE LHC ENERGY

The safe energy limit of the LHC is a function of the worst splice in the machine and depends on if the defect is concentrated on one side of a splice, on the time constant of the energy extraction (τ_{EE}) and on the RRR_{CS}. Detailed calculations of what is the worst single-side defect that can be tolerated as a function of energy (using RRR_{CS} =100) give [6]: For **5.0 TeV** operation (RB τ_{EE}=75 s, RQ τ_{EE}=15 s):

- RB: 43 μΩ
- RQ: 41 μΩ

For **3.5 TeV** operation (RB τ_{EE}=50 s, RQ τ_{EE}=10 s):

- RB: 76 μΩ
- RQ: 80 μΩ

If the RRR_{CS} is 200 instead of the (conservative) 100, the above values increase by 10 μΩ for both RB and RQ.

However, if the defect is split on both sides of a splice the 3.5 TeV limits become 120 μΩ and 140 μΩ. In reality such large defects cannot be concentrated only on one side of the splice, therefore the 90 μΩ R_{max} limit is compatible with 3.5TeV operation.

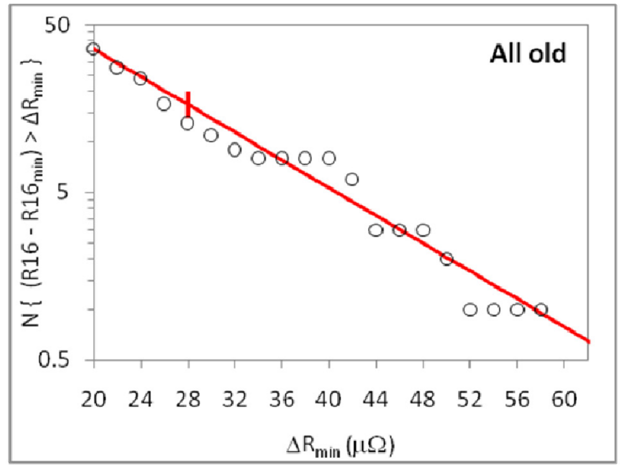

Figure 3: The cumulative distribution of all available R16 splice excess resistance data.

CONCLUSIONS

The splice resistance has been measured for all interconnect splices and no excess resistance above 3 nΩ has been seen. The quality of the copper stabilizer joints of the high current circuits of the LHC limit the energy at which the LHC can safely operate. An extended campaign of measuring splices in a non-invasive way as well as targeted repairs and accurate resistance measurements were performed in part of the machine. We have used a statistical method to estimate the worst remaining splice in the sectors that were not measured with the required accuracy. This defines the maximum safe energy at which the LHC can operate before more measurements (and, possibly, repairs) can take place.

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