Consolidation of the 13 kA Interconnects in the LHC for Operation at 7 TeV

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Abstract—The accident in the LHC in September 2008 occurred in an interconnection between two magnets of the 13 kA dipole circuit. Successive measurements of the resistance of other interconnects revealed other defective joints, even though the SC cables were properly connected. These defective joints are characterized by a poor bonding between the SC cable and the copper stabilizer in combination with an electrical discontinuity in the copper stabilizer. A quench at the 7–13 kA level in such a joint can lead to a fast and unprotected thermal run-away and hence opening of the circuit. It has therefore been decided to operate the LHC at a reduced and safe current of 6 kA corresponding to 3.5 TeV beam energy until all defective joints are repaired. A task force is reviewing the status of all electrical joints in the magnet circuits and preparing for the necessary repairs. The principle solution is to resolder the worst defective joints and, in addition, to apply an electrical shunt made of copper across all joints with sufficient cross-section to guarantee safe 12–13 kA operation at 7–7.5 TeV. In this paper the various actions that have lead to this solution are presented.

Index Terms—Busbars, interconnections, resistance, soldering.

I. INTRODUCTION

THE MAIN dipole and quadrupole magnets in each of the eight sectors of the LHC are powered in series. Each main dipole circuit (RB) consists of 154 magnets with a total inductance L_{tot} of 15.1 H and a stored energy E_{st} of 1.3 GJ at 13 kA. Each quadrupole circuit consists of up to 51 magnets with $L_{\text{tot}} = 0.286$ H and $E_{\text{st}} = 24$ MJ at 13 kA. Each magnet is individually protected by a Quench Detection System (QDS), with a threshold of 100 mV, and quench heaters spreading the resistive transitions over the volume of the magnet coils. The parallel-connected diode over a magnet acts as a current bypass during a quench and the fast current discharge. This discharge has a time constant τ of about 100 s for the RB circuit and 20 s for the RQ circuits. The diodes however do not encompass the sections of the superconducting (SC) busbars between the magnets. The RB busbar has a cross-section of 20×16 mm², and contains a single Nb-Ti Rutherford cable soldered with Sn96Ag4 alloy into a hole of 16×3 mm² in the center of the busbar. Each RB circuit contains 156 busbar segments (i.e. sections between voltage taps) with a length of about 30–40 m. The RQ busbar is similar but has a slightly

Fig. 1. (a) Layout of the different components of a 13 kA joint. (b) Schematic view of a defective 13 kA joint. (c) Gamma-graphic image of a defective joint.

smaller cross-section of 20×10 mm². Each RQ circuit contains 96 or 104 busbar segments with a length of about 100 m. The 10170 connections between busbars are made by inductive heating using Sn96Ag4 alloy, see Fig. 1(a). During this process the two superconducting cables are connected (with an overlap of 120 mm, and a typical resistance R_{spl} of 0.3 n Ω at 1.9 K) and the cables are bonded with the stabilizing copper U-profile and wedge. Also, the copper stabilizer of the joint is soldered onto the busbar stabilizer. The protection of the busbars and interconnects is based on this stabilization which, in case of a quench of the cable, would bypass the current and conduct the heat away.

The accident in the LHC in Sept. 2008 [1] started in the RB busbar, where an excessive resistance, most likely in the splice between the two superconducting cables, caused the joint to quench. This resulted in a thermal run-away due to limited bonding between the cables and the copper stabilizer, and between the busbar stabilizer and the joint stabilizer. Such a defective joint is schematically shown in Fig. 1(b) and a gamma-graphic image is given in Fig. 1(c) [2]. Note that a joint can have a defect on one side or on both sides.

The defect produces an additional bus resistance R_{addit} which is in first approximation proportional to the length of the non-stabilized cable, or about 13 $\mu\Omega$ /cm at 300 K.

During the repair of the damaged magnets several other defective splices were found. Various actions have been taken following these findings, especially:

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- Calculations were performed in order to determine the maximum safe operating current in view of the presence of defective splices.
- A new busbar QDS was implemented in order to detect superconducting-to-normal transitions of individual bus segments (including two or more interconnects).
- The resistance between the two superconducting cables of individual bus segments was measured.
- A measurement campaign was conducted in order to map splices with poor bonding between the busbar stabilizer and the interconnect stabilizer.
- An experimental program was carried out to validate the calculations, and to study design improvements.

The results of the above mentioned actions are detailed in the next sections. Furthermore, a ‘Splices Task Force’ was set up at CERN in order to develop and test the design improvements, and to prepare a consolidation campaign.

II. CALCULATIONS ON THE SAFE CURRENT

Two types of calculations are performed:

- 1) Calculation of the maximum allowable splice resistance $R_{\text{spl,max}}$ at 1.9 K to avoid quenching of the joint due to resistive heating. $R_{\text{spl,max}}$ depends not only on the operating current but also on the joint and busbar geometry, cooling conditions, and material properties. A best estimate is given in Fig. 2. In the same graph the curve for U_{thr}/I is shown with a threshold voltage $U_{\text{thr}} = 0.3$ mV. Application of this threshold is needed to assure that, for any current I , resistive heating in the splice will never initiate a quench. More details can be found in [3].
- 2) Calculation of the maximum allowable additional stabilizer resistance $R_{\text{addit,max}}$, to avoid overheating in case of a quench, caused by resistive heating, quench propagation from an adjacent magnet (through the busbar or by means of warm gaseous helium), cable movement, or beam loss.

It is assumed that the copper stabilizers of the busbar and the joint have no direct electrical and thermal contact. $R_{\text{addit,max}}$ depends on the operating current, joint and busbar geometry, cooling conditions, and material properties. The latter two are not very well known, and a conservative approach is therefore taken, namely a low RRR of 100 for the bus material and 80 for the non-stabilized cable. Furthermore, the cooling is fixed at the lowest value deduced from experiments (see Section VI). It is important to note that a reduction of the time constant (i.e. an increase in the resistance of the energy extraction) is possible when limiting the current in the circuits. The limiting factors are the maximum voltage in the circuit, saturation of the QDS electronics, and possible ramp rate induced quenching. Shorter decay times allow for larger $R_{\text{addit,max}}$ since the resistive heat dissipation is smaller. Decay times and maximum allowable R_{addit} are given in Table I for several current levels (or energies). More details can be found in [4].

Based on these values and on the experimental data of R_{addit} (see Section V), it has been decided in early 2010 to initially operate the LHC at 3.5 TeV (6 kA), which is safe up to $R_{\text{addit,max}} = 80 \mu\Omega$. It could not be excluded that higher R_{addit} are present in one of the three sectors that are not

Fig. 2. Maximum allowable splice resistance as a function of the operating current, in order to avoid quenching of the joint due to resistive heating.

TABLE I
MAXIMUM ALLOWABLE ADDITIONAL STABILIZER RESISTANCE ($R_{\text{addit,max}}$)
FOR THE RB AND RQ CIRCUITS

Energy (TeV)	Current (A)	RB circuit		RQ circuit	
		τ_{RB} (s)	$R_{\text{addit,max}}$ ($\mu\Omega$)	τ_{RQ} (s)	$R_{\text{addit,max}}$ ($\mu\Omega$)
3.5	6.0	50	76	10	80
5.0	8.5	75	43	15	41
7.0	11.9	100	11	20	14

measured at room temperature. However, the probability of a burn-through of a defective splice is extremely small at 6 kA, considering the conservative approach in the calculations, the very small probability of actually quenching a joint, and the small probability of actually having $R_{\text{addit}} > R_{\text{addit,max}}$ in the joint that quenches.

III. UPGRADE OF THE QUENCH DETECTION SYSTEM

The ‘old’ QDS for the busbars was based on voltage detection on the entire busbar (with a length of about 6 km) with a threshold of 1 V. The QDS has been upgraded to a multi-channel system [5], [6] where the total RB busbar is segmented in stretches of about 30–40 m containing 2 or 3 joints. Similarly, the RQ busbar is segmented in 100 m long stretches, containing usually 8 joints. The voltage on each busbar segment is detected with a threshold of 0.3 mV (see also Fig. 2). For operation up to 6 kA the threshold can be increased to 0.5 mV. The threshold is sufficiently low to detect the resistive power dissipated in the SC-SC joints, before it could cause the joints to quench, and to avoid overheating of the busbar in case of a trapped quench (or stagnant normal zone).

IV. MEASUREMENT OF THE SPLICE RESISTANCE BELOW TC

Using the upgraded QDS system as a series of accurate voltmeters, the resistance R_{segment} of all busbar segments has been measured at 1.9 K. Each segment contains n splices (with $n=2-3$ for the majority of the RB segments and $n = 8$ for the majority of the RQ segments) and it is hence not possible to measure the resistance of an individual splice. The results reveal that the average splice resistance ($R_{\text{spl,aver}}$) is about 0.30 nΩ, both for the RB and RQ. An estimate of the maximum splice

Fig. 3. Distribution of maximum splice resistances in all 13 kA busbar segments of the LHC.

resistance in a segment can be made assuming that the surplus resistance is localized in one splice of a busbar segment only, so $R_{spl,max} = R_{segment} - (n - 1) * R_{spl,aver}$. The distribution, as shown in Fig. 3, gives $R_{spl,aver} = 0.30 \text{ n}\Omega$ with $\sigma = 0.08 \text{ n}\Omega$ (RB), and $0.34 \text{ n}\Omega$ with $\sigma = 0.29 \text{ n}\Omega$ (RQ). The results of the RQ have a much larger spread, probably due to the larger segment length and higher n . About 6% of the splices have $R_{spl,max} > R_{spl,aver} + 3\sigma$, with a maximum of $3.3 \text{ n}\Omega$. These outliers pose no problem for operation up to 13 kA, because their values are well below the maximum allowable resistance of about $20 \text{ n}\Omega$ at 13 kA (as shown in Fig. 2). However, an abnormally high splice resistance might indicate a mechanical weakness of the joint, or an improper soldering procedure, and deterioration of such splices in time can therefore not be excluded. Monitoring of these resistances during operation of the LHC is performed at each high current plateau. A large splice resistance may as well be correlated to a large additional stabilizer resistance (see Section V). More details can be found in [7].

V. MEASUREMENT OF THE ELECTRICAL DISCONTINUITY OF THE STABILIZER

A huge effort was undertaken to map R_{addit} by measuring the resistances of the busbar segments of 5 sectors at room temperature. The accuracy of the measurements was limited because an excess value of the order of $10 \text{ }\mu\Omega$ had to be measured over busbar segments of 30–100 m length, having a resistance of about $2 \text{ m}\Omega$ (RB) to $11 \text{ m}\Omega$ (RQ). The measurement accuracy was $\sigma = 9 - 17 \text{ }\mu\Omega$ for the RB and $\sigma = 25 - 36 \text{ }\mu\Omega$ for the RQ [7]. Attempts at 80 K were done, but turned out to be less accurate due to variations in temperature and RRR of the busbar. The interconnects showing some of the largest defects have been opened, and R_{addit} has been measured locally (thus suppressing the large background). The correlation between R_{addit} deduced from segment measurements and R_{addit} measured locally is shown in Fig. 4. The good correlation confirms that there are actually many joints with high R_{addit} in the machine. It is also concluded that measurements of the segment resistance are not accurate enough to detect values down to $11\text{--}14 \text{ }\mu\Omega$, required for operation at 13 kA (see Table I). Some of the largest outliers are repaired but it is sure that many defective joints are still present in the machine. It is estimated that about 2% of the 10170 joints has $R_{addit} > 40 \text{ }\mu\Omega$ with a possible maximum of $90 \text{ }\mu\Omega$ [7].

Fig. 4. Locally measured R_{addit} for some of the outliers deduced from segment measurements in 5 RB circuits.

Fig. 5. Measured voltage as a function of time over a joint with built-in single-sided defect (with $R_{addit} = 42 \text{ }\mu\Omega$) for different current levels. Quench recovery occurs for 6, 7 kA, a stable normal zone is present for 8 kA, and thermal runaway occurs for 9, 9.6, 10, 11 kA.

VI. EXPERIMENTAL PROGRAM

Several tests have been performed at CERN on joints between two RQ busbars with purposely built-in defects. The main purpose of these tests was to validate the calculations, and obtain an empirical value for the heat transfer to the helium. In total 7 samples have been prepared with different R_{addit} , RRR, and joint insulation. Some samples had a single-sided defect and others a double-sided defect. While being immersed in liquid helium and carrying constant current, a quench is triggered in the joint of the sample by means of a short heat pulse. Depending on the current level, cooling, and sample characteristics, the normal zone will a) shrink to zero, b) stabilize, c) grow and cause a thermal runaway. Typical measurements performed at various currents demonstrate these 3 scenarios (see Fig. 5). The duration between the start of the normal zone and the thermal runaway is indicated by t_{TR} . It is important to note that protection against these thermal runaways is in many cases not possible because t_{TR} is often small compared to the decay time of the circuit. Results of the tests are in good agreement with the calculations, and also show that the heat transfer to helium varies significantly among the samples [4]. An overview of the various samples and the main test results is given in [8].

VII. CONSOLIDATED SPLICE DESIGN

After analysis of R_{addit} , based on segment data and local measurements, it was estimated by the ‘Splices Task Force’ that

Fig. 6. Current design of the improved 13 kA joints [9].

about 15% of the joints have $R_{\text{addit}} > 10 \mu\Omega$, the typical limit for 7 TeV operation (see Table I). However, since the error in the measurement is large, and since the segmentation of the measurements makes it impossible to localize the exact position of a defective splice, the Task Force concluded that all interconnects will have to be opened and all joints have to be inspected. Joints with $R_{\text{addit}} > 10 \mu\Omega$ and joints with significant visual imperfections will be unsoldered and resoldered according to improved procedures. Furthermore, *all* joints will be shunted by copper strips, dimensioned to be able to carry the full current during a decay with $\tau = 100$ s (RB) or 30 s (RQ), assuming no cooling to the helium. The decision to shunt *all* joints, so also those with $R_{\text{addit}} < 10 \mu\Omega$, was taken because the time evolution of R_{addit} , due to thermal and electromagnetic cycling, is unknown. Calculations show that a shunt with a section of 25 mm² is sufficient [3], assuming that the distance between the soldering zones on both stabilizers is 10 mm maximum, and that the resistance of the soldering is very small. For redundancy, the cross-section of the shunt will be 45 mm², a second parallel shunt will be added on the opposite face of the joint, the distance between the soldering zones will be controlled to less than 8 mm, and the RRR of the shunt will be larger than 200. The current design for the improved 13 kA joints is shown in Fig. 6 [9].

The shunts will be soldered with Sn60Pb40, which has a significantly lower melting temperature than the Sn96Ag4 solder used in the rest of the joint. Soldering the shunts to the joints will therefore not affect the already existing soldered connections. The thermo-electric behavior of the solder between 300 K and low temperature is being studied. Advantages and disadvantages among various soldering processes, namely cartridge oven heating, induction heating, and resistive heating, are being investigated. The limited space available for the soldering is an important criterion as well as the reliability of the soldering and the possibility for proper quality control.

The mechanical design is able to cope with the 550 N longitudinal load (from deformation of the lyre), and 1100 N/m transversal load (from the electromagnetic forces) during the entire lifetime of the LHC.

Two RQ samples with built-in defects have been retested after having been fitted with shunts (on one face of the joint). Fig. 7 shows $t_{\text{TR}}(I)$ for the sample with the largest defect. The large increase in t_{TR} resulting from the shunt is a clear validation of the proof of principle. Recalculation of the results for the real LHC configuration confirms that the shunted joint can easily carry 13 kA with $\tau = 30$ s. Note that, from a MII's point of view, $\tau = 30$ s should be compared to $t_{\text{TR}} = 15$ s in Fig 7, since these data are given at constant current. As comparison

Fig. 7. Thermal run-way time versus current level for a defective joint with and without shunt. The calculated t_{TR} curve for $R_{\text{addit}} = 0 \mu\Omega$ is also shown.

also the calculated t_{TR} curve for a) is added. Both curves cross at 12 kA; t_{TR} of the shunted defect is lower at higher currents due to the localized heating, but higher at lower currents due to cooling to helium.

A final validation test of the consolidated splice design will be performed in autumn 2010. In a new test set-up, two 9 m long busbars will be connected in an interconnect geometry which is identical to the LHC. A worst case defective joint with copper shunts will be subjected to a 13 kA, $\tau = 100$ s decay, and the voltage and temperature pattern along the busbar and joint will be measured. Furthermore, the joint will be subjected to the same number of electromagnetic cycles as foreseen for the entire lifetime of the LHC.

After final validation of the improved joint design, all 13 kA joints in the LHC will be shunted. This consolidation intervention requires a chain of activities, such as opening of the interconnections, machining, soldering, insulating, quality control, electrical testing, welding, and leak testing. The actual planning foresees that all 8 sectors will be completed in slightly less than one year. A strict quality control will be applied, not only relying on visual inspection but also on quantitative measurement of R_{addit} and the resistance between the shunt and the stabilizer.

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