Thermal Runaway of the 13 kA Busbar Joints in the LHC

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Abstract—Triggered by the incident in the LHC in September 2008, the thermo-electrical stability of the 10,000 soldered busbar joints in the 13 kA circuits of the LHC has been re-assessed. For this purpose the computer model QP3 has been developed. In this paper the results of some calculations are presented, and it is shown how the results have been used to improve the quench detection system and ensure safe future operation.

First the layout of the 13 kA circuits, the geometry of the soldered joints and the quench detection system will be described. Special focus is put on several types of defects in the joint that have been found in the LHC. The difference between *slow* and *fast* thermal run-away will be discussed, focusing on quench propagation and reduced thermal and electrical contacts between the various parts of the joint. It is shown that an enhancement of the LHC quench detection system with a much lower threshold will greatly reduce the risk of burn-out of the joint. Finally it is discussed that protection is not feasible for *fast* thermal run-aways, and that a reduction of the operating current is needed for safe operation until all defective joints have been repaired.

Index Terms—Busbar, joint, LHC, stability.

I. INTRODUCTION

ON 19 September 2008, during powering tests of the main dipole circuit in sector 3–4 of the LHC [1], an electrical fault occurred in the 13 kA busbar producing an electrical arc and resulting in mechanical and electrical damage, release of helium from the magnet cold mass and contamination of the insulation and beam vacuum enclosures [2]. This accident has led to a re-assessment of the stability of the busbar joints, i.e. the detection thresholds, and the possibilities of thermal runaway in view of possible manufacturing defects.

The main dipole and quadrupole magnets in each of the eight sectors of the LHC are powered in series (see Fig. 1 for a schematic layout of the dipole circuit), and 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 the fast current discharge. This discharge has a time constant τ of about 100 s for the dipole circuit (RB) and 30 s for the quadrupole circuits (RQ). The diodes however do not encompass the sections of the superconducting (SC) busbars

between the magnets nor the interconnections. Their protection is based on heavy stabilization by soldered copper which, in case of a quench of the cable, would bypass the current and conduct the heat away. This will then lead to either recovery or slow temperature increase until the threshold level of 1 V for the complete circuit is detected at the power converter, then triggering fast discharge. The required amount of copper stabilizer was based on modeling [3], [4] and validated by model tests [5], assuming good soldered contact with the SC cables, a propagating normal zone, and continuity of the stabilizer (or possible discontinuity over a few mm). Recent modeling with the code QP3 shows that the threshold was much too high to detect in time a *localized* thermal runaway of a thermally well-insulated joint in a long, well-cooled busbar acting as quench stopper. In this case the melting temperature of the solder is exceeded and the circuit thus broken open well before the 1 V threshold is detected. Subsequent investigation of the quality of the busbar joints has shown that the SC cable in many joints is in bad thermal and electrical contact with the copper stabilizer, and that the copper stabilizer itself is in many cases interrupted. Repair of these defective joints at short term is not feasible, since the LHC contains about 10,000 13 kA joints, which are difficult to access. These manufacturing defects may cause fast thermal runaway of the joint in case it quenches. In this paper the ‘new’ threshold for the enhanced QDS is introduced, and the improvements with respect to the ‘old’ system are discussed. Finally it is shown that protection is not feasible for all types of defects and that a reduction of the operating current is needed for safe operation until all defective joints have been repaired. Note that descriptions of the enhanced quench detection and the code QP3 are beyond the scope of this paper. Results of recent quality testing on the joints and the busbars in the machine will be presented in separate papers.

II. BUSBAR AND JOINT LAYOUT

The cross-section of the 13 kA busbar for the RB circuit is shown in Fig. 2(a). The busbar has a cross-section of 20 mm $\times$ 16 mm, and contains a single Nb-Ti Rutherford type 02 cable, soldered with SnAg into a hole of 16 $\times$ 3 mm² in the center of the busbar. The cross-section of the copper ‘busbar stabilizer’ is about 282 mm² with RRR > 100. The busbar is insulated by two layers of 50 mm thick polyimide tape, each wound with 50% overlap, and one layer of polymerized fiber glass, wound with 2 mm spacing. The RQ busbar is the same as the RB busbar except that the cross-section is 20 mm $\times$ 10 mm.

The joint between the two SC cables is 120 mm long, and soldered while being compressed between a 120 mm long copper wedge and a 155 mm long copper U-profile. The final cross-section of a RB joint is shown in Fig. 2(b), and the general layout

Manuscript received October 19, 2009; First published March 25, 2010; current version published May 28, 2010.

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Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TASC.2010.2043350

Fig. 1. Schematic of a dipole circuit in one of the eight sectors of the LHC. The circuit includes 154 dipoles, each bypassed by a cold diode, a 13 kA power converter, two energy extraction systems, and a total of about 400 13 kA joints.

Fig. 2. (a) Cross-section of a properly solder-filled RB busbar and (b) RB joint.

Fig. 4. Perfectly solder-filled joint. The arrows indicate the thin slots between the copper stabilizer and the joint stabilizer.

slots between the busbar stabilizer and the joint stabilizer (see Fig. 4). A well-made joint is mechanically strong enough so that it does not open due to the mechanical and electromagnetic forces acting on it.

III. JOINT DEFECTS

After the incident in the LHC, a deep investigation of the quality of the busbar joints has shown that the following three different types of non-conform joints can occur (see Fig. 5 and [7]):

- Unsoldered joints (with $R_{\text{joint}} \gg 1 \text{ n}\Omega$) with a bad thermal and electrical contact between cable, U-profile, and wedge, and between busbar stabilizer and joint stabilizer.
- Soldered joints (with $R_{\text{joint}} \cong 0.3 \text{ n}\Omega$) with a lack of SnAg on at least one side of the joint, and possibly a lack of SnAg inside the adjacent busbar extremity. This is probably caused by pouring out of the SnAg during the soldering process.
- Badly soldered joints (with R_{joint} expected to be about $0.3\text{--}2 \text{ n}\Omega$) with a lack of melted SnAg on both sides of the joint. This is probably caused by soldering at too low a temperature, so that the SnAg did not melt in the extremities of the joint.

For all three cases the SC cable is more or less Non-Stabilized over a certain effective length l_{NS} . Note that l_{NS} is the sum of two lengths if the joint has a defect on both sides. Defect type B occurs very often with l_{NS} of about 15 mm (for a single-sided defect) or 30 mm (for a double-sided defect), which is intrinsic to the design of the busbar in combination with the soldering procedure. All three defects, when quenching above a certain current, may act as a kind of a fuse because the electrical bypass through the copper is interrupted or severely degraded.

Fig. 3. Layout of a joint (also called interconnect) between two RB busbars.

in Fig. 3. In the following the wedge and U-profile together are referred to as 'joint stabilizer'. The joint is insulated by means of two U-shaped polyimide pieces with a length of 240 mm and a thickness of 0.125 mm, and two U-shaped G10 pieces with a length of 190 mm and a thickness of 1 mm. More details on the joint can be found in [6].

In a properly soldered joint the resistance R_{joint} between the two SC cables is typically $0.3 \text{ n}\Omega$, so that, even at ultimate current of 13 kA, the heating is less than 0.1 W. Furthermore, the joint stabilizer and the busbar stabilizer (on both sides of the joint) should work as a continuous electrical shunt to the SC cables. This is achieved when the solder fills all the voids in and around the joint (see Fig. 2(b)), as well as the thin

Fig. 5. Three different types of non-conform joints that could cause *fast* thermal runaway in case of a quench: 1. Unsoldered joint, 2. Soldered joint with lack of SnAg on one side, 3. Badly soldered joint with unmelted SnAg at both joint extremities. The arrows denote areas with a bad electrical and thermal contact.

Fig. 6. Calculated propagation speed along a uniformly insulated RB and RQ busbar in liquid helium.

IV. PROTECTION AGAINST SLOW THERMAL RUN-AWAY

During operation several disturbances can release heat in the busbar, such as beam losses (either transient or steady-state), mechanical movement, and warm gaseous helium from an adjacent quenching magnet. Below a certain current, the resistive losses, that are the consequence of the initial disturbance, will be equal or smaller than the cooling, leading to recovery of the SC state. Above a certain current the quench propagates (see Fig. 6), the resistive losses exceed sooner or later the cooling, causing a temperature rise of the busbar, hence increasing the resistivity, which in turn increases the resistive losses and so on.

This thermal runaway can only be stopped by reducing the current in the circuit. This is realized by inserting an extraction resistance in series as soon as the QDS system detects a voltage over the busbar larger than a certain threshold U_{thr} (the original value was set to 1 V). The external extraction resistance causes an almost exponential current decay with a time constant τ equal to about 100 s for the RB circuits and 30 s for the RQ circuits. A properly functioning protection should avoid overheating, i.e. limit the maximum busbar temperature T_{max} to below 500 K, hence avoiding that the polyimide insulation and solder inside the busbar and joint start to melt. The typical characteristic time t_{TR} of the thermal runaway can be defined as the time it takes to warm up the busbar from the current sharing

Fig. 7. The maximum temperature as a function of the number of MITTs assuming $RRR = 100$ and adiabatic conditions.

Fig. 8. Thermal runaway time t_{TR} as a function of the operating current assuming a busbar or joint without defects ($RRR = 100$ and adiabatic conditions).

temperature (equal to about 9 K) to T_{max} at constant current. Of course, when cooling is included, t_{TR} will increase significantly, becoming infinite below 6.3 kA (RQ) and 8 kA (RB).

The entire electrodynamics and thermal process of a quenching busbar and joint is very complex due to the strong dependency of electrical resistivity, thermal conductivity and heat capacity on temperature, field, and current, and due to variations in geometry and cooling. This process is therefore solved numerically with the computer code QP3 [8]. However, a first qualitative feeling of the stability can be obtained by assuming no cooling to the helium, and uniform temperature along the length of the busbar. Neglecting cooling, then one can easily calculate the maximum temperature of the busbar (or joint) as a function of the number of MITTs (i.e. the integral $\int I^2 dt$ from 0 to ∞), see Fig. 7.

The time t_{TR} can be directly deduced from this relation, which depends basically on the amount and quality of the stabilizing copper, and on the operating current I . Fig. 8 shows t_{TR} vs. I for uniformly soldered RB and RQ busbars, assuming $RRR = 100$.

A *slow* thermal runaway can be defined as a runaway with $t_{TR} > \tau/2$ since $\int (I_0 \exp(-t/\tau))^2 dt$ from 0 to ∞ equals $I_0^2 \tau/2$. In order to avoid overheating the threshold voltage of the QDS has to be set so that $t_{thr} < t_{TR} - \tau/2$, with t_{thr} the duration between the start of the resistive transition and the detection of the quench. As an example consider the RQ busbar at 10 kA, so $t_{TR} = 50$ s. The quench should then be detected faster than

$t_{\text{thr}} = 50 - 30/2 = 35$ s. Fig. 6 shows that at 10 kA the uni-directional propagation speed is 0.55 m/s so that the normal zone after 35 s has a length of $2 \times 0.55 \times 35 = 38$ m. The voltage over such a long stretch of busbar is relatively easy to detect. Note that t_{thr} reduces for higher currents, but since the propagation speed increases, the resistive voltage will be equally well detectable. Detailed numerical calculations show that a threshold voltage of 1 V is sufficient to protect a *uniform* busbar (including joints) against overheating.

However, in reality the busbar is not uniform and consists of areas with better cooling (such as the lyres) and worse cooling (such as the joints). This may result in a stagnant normal zone inside the joint that does not propagate along the busbar, or only over a short length. Such a trapped quench may occur especially below 8 kA (RB) and 6.3 kA (RQ), where the normal zone does not propagate through the busbar (see Fig. 6). The voltage build-up is therefore very local and hence smaller (for the same hot spot temperature), requiring a lower U_{thr} . Additional defects in the busbar (see Section III) reduce the local t_{TR} and require therefore a further reduction of U_{thr} . This effect is demonstrated for a RQ joint with a defect type B (see Fig. 5) with 15 mm of non-stabilized cable on both sides of the joint, quenching at $I = 7.5$ kA; cooling through the busbar insulation is included. Calculations with QP3 show that t_{TR} is 22 s. Because $t_{\text{TR}} > \tau/2$, it means that the thermal runaway is *slow*, but that protection against overheating is only possible when U_{thr} is sufficiently small. Fig. 9 shows the current, voltage and maximum temperature for $U_{\text{thr}} = 200$ mV (resulting in overheating within a few seconds from the start of the decay) and $U_{\text{thr}} = 150$ mV (resulting in a maximum temperature of only 65 K).

Lowering the threshold means that the resistive voltage becomes small with respect to the inductive component and voltage noise, so that the quench detection has to be subdivided in multiple segments.

V. PROTECTION AGAINST FAST THERMAL RUN-AWAY

From the previous section one can conclude that small U_{thr} is needed to detect thermal runaways fast enough so that they do not result in overheating. Unfortunately there is a limit to this protection, namely if $t_{\text{TR}} < \tau/2$, which can be referred to as *fast* thermal runaways. Such small t_{TR} can occur in joints where the stabilizing copper is in bad thermal contact with the cable, and at the same time has a high longitudinal resistivity, or even electrical discontinuity.

The value of t_{TR} is mainly determined by the operating current, and the length l_{NS} , and can be as small as 1 s. Only repair of the defects or limitation of the operating current can avoid thermal runaway in case of a quench of such a joint. One can of course stretch the operating current by reducing the decay time constant τ . This possibility will be applied in the LHC by increasing the extraction resistance. Voltage constraints and ramp-rate sensitivity of the magnets limit this increase, and finally a decay time of 50 s (RB) respectively (10 s) is feasible, at least for currents up to about 7 kA [9].

Indirect protection is possible in case of an unsoldered joint (defect type A, see Fig. 5). The incident in the LHC is believed to be caused by such a defect because post-mortem analysis of the

Fig. 9. Current, voltage and maximum temperature reached in a joint with a double-sided defect type B ($l_{\text{NS}} = 30$ mm) for a) $U_{\text{thr}} = 200$ mV, b) $U_{\text{thr}} = 150$ mV.

temperature data of an adjacent magnet revealed the presence of high ohmic heating, corresponding to a resistance of about 220 n Ω [2]. Simulations indicate that a phase of steady resistive dissipation moved into a fast thermal runaway (with t_{TR} of about 1 s), quickly leading to local melting of the busbar and arcing. This phase of steady resistive dissipation can be regarded as a precursor and therefore protection against this type of defect is possible, but requires detection of very small resistive voltages. This protection can be considered as *indirect* because it is not based on the detection of the normal-zone resistance but on the detection of the voltage of the resistive joint while the joint is still below the current sharing temperature. Using the code QP3 the maximum allowable joint resistance is calculated as a function of the operating current, see Fig. 10. In the same graph the curve for $R_{\text{thr}} = U_{\text{thr}}/I$ is shown with $U_{\text{thr}} = 0.3$ mV, showing that a protection threshold of 0.3 mV is needed to ensure safe operation up to 13 kA. This new threshold will be adopted in the LHC, whereas it might be increased by a factor 2 when operating at currents below about 8 kA.

Protection against defects type B and C is unfortunately not possible when $t_{\text{TR}} < \tau$ because there is no precursor. Until all defects are repaired one should therefore keep the operating current below a certain value, which of course depends on the severity of the defect (denoted by the effective length of insulated cable l_{NS}). Using QP3 one can now calculate the maximum safe current, i.e. the maximum current for which over-

Fig. 10. Maximum allowable joint resistance as a function of the operating current. Setting $U_{thr} = 0.3$ mV (corresponding to a 'threshold resistance $R_{thr} = U_{thr}/I'$) will prevent overheating up to 13 kA.

Fig. 11. Maximum safe current as a function of the effective length of insulated cable for single-sided defects of type B (with $\tau = 50$ s for the RB circuit, $\tau = 10$ s for the RQ circuit).

heating will not occur. Fig. 11 shows the results for single-sided defects type B for the RB and RQ circuits for $\tau = 50$ s (RB) and $\tau = 10$ s (RQ), and assuming RRR = 100 for the busbar stabilizer, RRR = 120 for the SC cable, and cooling in superfluid helium. The safe current is larger than shown in Fig. 11 for double-sided defects type B and C.

At present, about 62% of the 10,000 joints are assessed by means of warm resistance measurements [7]. The maximum l_{NS} observed is about 40 mm, and it is estimated that about 1% of the splices show $l_{NS} > 25$ mm, and 2–5% show $l_{NS} > 15$ mm. However, based on the measured data, the presence of lengths up to 70 mm can statistically not be excluded, meaning that an operating current above 6.5 kA is potentially unsafe. It is possible that this provisional safe operating current will be slightly

modified in the near future based on i) further investigation into the quality of the joints and the RRR of the various components, ii) laboratory tests on defective joints, used to validate the calculation code QP3. Operation at the nominal LHC current of 11.85 kA imposes discharge time constants of about 100 s (RB) and 20 s (RQ), resulting in a shift of the curves in Fig. 11 towards lower currents. Safe operation at nominal requires that all defective joints with l_{NS} larger than about 10–15 mm have to be repaired.

VI. CONCLUSION

In several hundreds of the 10,000 13 kA joints of the LHC the stabilizing copper is in bad thermal contact with the cable, and at the same time has a high local longitudinal resistivity (or even electrical discontinuity) at the interface between the joint and the busbar stabilizer. In case such a joint quenches (due to mechanical movement, resistive heating, beam losses, or warm helium gas from an adjacent quenching magnet) they may experience a *fast* thermal runaway with an increase of the maximum temperature to above 500 K. The incident in the LHC on 19/9/2008 is believed to be due to such a defective joint, where the quench was initiated by excessive joint heating. Protection against fast thermal runaway is unfortunately not possible because the thermal runaway time is too fast as compared to the decay time constant of the circuit. In order to operate the LHC at full energy all defective joints have to be repaired. In the meantime, the operating current has to be limited, so that the risk of overheating a defective joint is negligible even under worst case scenarios.

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