

CSCM: EXPERIMENTAL AND SIMULATION RESULTS

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Abstract

The Copper-Stabilizer Continuity Measurement (CSCM) was devised to obtain a direct and complete qualification of the continuity in the 13 kA bypass circuits of the LHC, especially in the copper-stabilizer of the busbar joints and the bolted connections in the diode-leads, as well as in lyra connections. The circuit under test is brought to about 20 K, a voltage is applied to open the diodes by-passing the magnets, and the low-inductance circuit is powered according to a pre-defined series of current profiles. The profiles are designed to successively increase the thermal load on the busbar joints up to a level that corresponds to worst-case operating conditions at nominal energy. In this way, the circuit is tested for thermal runaways in the joints - the very process that could prove catastrophic if it occurred under nominal conditions with the full stored energy of the circuit. A type test of the CSCM was successfully carried out in April 2013 on one main dipole and one main quadrupole circuit of the LHC. This paper describes the analysis procedure, the numerical model, and results of this first type test.

INTRODUCTION

During initial powering tests of the LHC's main dipole circuits in September 2008, an unforeseen fault occurred in one of the superconducting busbar splices, which resulted in a catastrophic quench event [1]. Investigations discovered that a number of splices had not been soldered correctly (Fig. 1), producing hazardous discontinuities in the copper stabilizer [2].

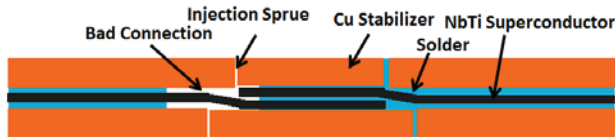


Figure 1: Illustration of an LHC 13 kA busbar splice, showing poorly soldered connection (left side) and perfectly soldered connection (right side).

Throughout Long Shutdown 1 (LS1), over 10,000 splices are being consolidated to prevent such an event from reoccurring [3]. Large efforts are made to ensure the quality of the work. To eliminate any residual risk, the CSCM was devised to provide a comprehensive and safe qualification of the main circuits for operation at nominal energy.

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TEST DESCRIPTION

Unique Operating Conditions

It is essential that such a test be carried out with minimal stored energy in the magnet circuits. Due to this, the CSCM is performed at approximately 20 K operating temperature, ensuring that the magnets remain in a resistive state. To qualify each connection, the circuit is powered up to a current level where the resistive voltage across the magnets opens the bypass diodes. At this point, all of the current passes through the bypass with little magnetic energy left in the circuit (Fig. 2).

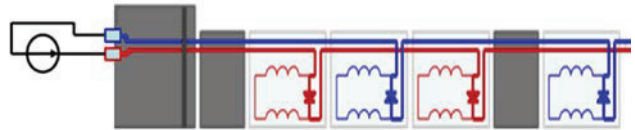


Figure 2: Illustration of current flowing through the magnet bypass during CSCM on LHC main dipole circuit.

To provide sufficient voltage to open the diodes in an RB circuit, two 13 kA/200 V power converters (PCs) have to be connected in series. Furthermore, the operating temperature of 20 K means that the helium coolant is gaseous, and thus requires adjusted pressure limits.

Test Profiles

The test sequence is devised such that each circuit undergoes a number of successive current cycles, each increasing in current level or plateau length. This exposes the splices and diode leads to a gradual increase in Joule heating, measured in MIITs (the time integral of the current squared (MA^2s)). Furthermore, the MIITs accumulated after the onset of a runaway are proportional to the heating of the bad connection itself.

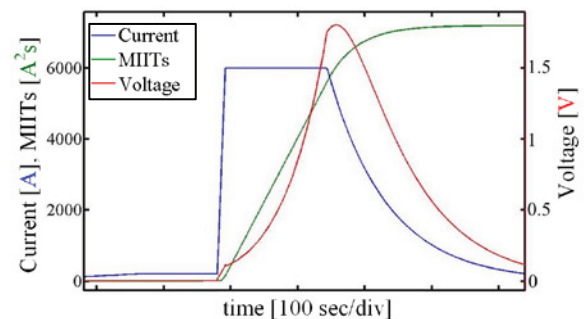


Figure 3: Typical current profile carried out during CSCM, as well as the simulated circuit voltage and the accumulated MIITs.

Following this process, a thermal runaway, indicative of a bad connection, can be detected at the lowest current possible, triggering a fast power abort (FPA) to minimise the risk of damage. In an FPA, the energy extraction (EE) system is triggered and the current decays with 0.03 s decay constant (inductance during CSCM 3 mH). Otherwise the power converter (PC) ramps down with a time constant of 104 s, corresponding to an FPA in the RB circuit under nominal conditions (15.7 H inductance). Figure 3 shows a typical current cycle carried out on the RB circuit during CSCM without an FPA.

SYSTEM PROTECTION

In the case of a substandard busbar splice or a bad diode lead connection, a thermal runaway occurs when the Joule heating exceeds a critical value; that is, the heating exceeds the cooling power, and the localised temperature rises exponentially. Without protection against such an event, the connection would melt and result in physical damage. Note, however, that in the absence of stored energy in the magnets, the damage would remain localised to the interconnection.

To prevent such damage, CSCM-specific detection boards were designed and included as part of the LHC's quench protection system (QPS) [4] to detect the onset of a thermal runaway and, if so, to trigger a fast power abort. These boards (type A at each magnet voltage tap, measuring the busbar voltage, and type B at each diode tap, measuring the busbar and diode lead voltage) allowed the setting of individual detection thresholds for the voltage V , dV/dt , and d^2V/dt^2 , across each busbar section, as well as each diode path. All boards were thoroughly tested on their detection capabilities prior to installation.

Calculation of QPS Thresholds

As the circuit is resistive, the thresholds required for safe operation are heavily dependent on the current level. Thus, it is important that thresholds be calculated individually for each test. However, due to the potentially varying starting temperatures and uncertainties on the cooling factor to the gaseous helium, the thresholds were calculated in real time prior to each new powering cycle, using the previous test as a point of reference. For both circuit types, an initial low current test was performed to determine the average RRR of each busbar segment, which was used throughout for threshold calculations.

The procedure for calculating the thresholds was as follows (based on a previous test at lower MIITs):

- Map the arc's temperature profile from cold mass temperature probes.
- Simulate V_{\max} and dV/dt_{\max} of each busbar segment during the previous run via use of a field and temperature dependent resistivity and the heat balance equation.
- Tune cooling parameters to match the measured voltage data of the previous run.

- Simulate the successive current profile with the new cooling parameters.
- Compute thresholds by adding a 10% margin to the simulated peak V and dV/dt (Fig. 3), unless the margins exceed predefined minimum or maximum values.
- Finally, an additional margin is added to the Board B thresholds to take into account the diode leads.

TYPE TEST RESULTS

To prove a CSCM test could be carried out successfully, with minimal system risk, a type test was carried out prior to splice consolidation in April '13. The aim was to deliberately induce, successfully detect, and protect against the occurrence of a thermal runaway. The type test was carried out in Sector 23 of the LHC on one of each main circuit types, namely RB.A23 and RQF.A23. The results were as follows:

RQF.A23 Results

Table 1: Results of CSCM current cycles carried out on the LHC's RQF.A23 circuit, April 2013. Tests during which thermal runaways occurred are marked in red

Test Current [A]	Ramp dI/dt [A/s]	Nominal plateau [s]	Runaway detection [s]	Measured MIITs [A ² s]
900	200	25	n/a	50
2000	133.3	40	n/a	260
4000	300	24	n/a	710
6000	466.6	13	n/a	720
6000	466.6	25	16.5	850
8000	633.3	14	0.3	463

As shown in Table 1, the circuit did not successfully reach nominal current and a thermal runaway started occurring at 6 kA after 16.5 s on the plateau. At this point, it was of note that the runaway was, indeed, detected (by both V and dV/dt thresholds) and the QPS system successfully initiated a power abort. Further investigation found that as many as 5 splices showed the onset of a thermal runaway at the moment of detection, see Figure 4.

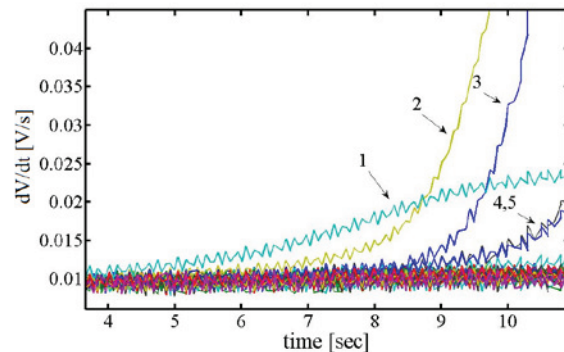


Figure 4: Zoom of on-set of thermal runaways occurring in 5 different splices along the RQF.A23 magnet circuit.

Interestingly, runaways, including the worst, were found in both end busbar segments (from current lead to first/last magnet). This is likely due to the higher number of splices present in these segments, increasing the probability of a runaway. To complete the test and to allow for validation of simulations, a final test was carried out at 8 kA and due to the increased ohmic power, a thermal runaway occurred moments after the ramp had ended. Overall, the tests carried out in the RQF.A23 were deemed a success.

RB.A23 Results

Table 2: Results of CSCM current cycles carried out on the LHC's RB.A23 circuit, April 2013

Test Current [A]	Ramp dI/dt [A/s]	Nominal plateau [s]	Runaway detection [s]	Measured MITs [A ² s]
1000	66.6	40	n/a	94
2000	150	40	n/a	360
4000	316.6	70	n/a	1900
6000	483.3	46	n/a	3400
7000	566.6	40	24	1400
8000	650	14	6.6	710
7000	566.6	40	31.5	1770
9000	1466.6	10	4.25	710
6000	483.3	90	76	2900

Table 2 shows the results of tests carried out on the RB.A23 circuit. Regarding thermal runaways, several were induced at various current levels between 6-9 kA. The table illustrates that the onset of thermal runaways is not simply a function of MITs, but due to the interplay between cooling and heating, also of the maximum current level. Furthermore, after reaching the perceived limit and carrying out a second 7 kA run, an FPA was not triggered until much later on the plateau. It was found that in this case the runaway itself began to "slow down" after a few seconds (also found in the RQF circuit test, see 1st runaway in Figure 4), which significantly reduced the dV/dt and prolonged the time it took for the voltage to rise above the threshold. As a consequence, the estimated hotspot temperature rose to approximately 560 K, close to the melting point of solder. For subsequent tests, the maximum margin between measured voltage and threshold was reduced from 500 mV to 200 mV. These much tighter thresholds adequately protected the circuit and any future CSCM test will incorporate this lesson. Overall, the RB tests were as successful as those carried out on the RQF, thus proving that a CSCM test can be carried out with minimal system risk to fully qualify either of the main 13 kA circuit types.

RUNAWAY SIMULATIONS

In an attempt to determine the extent of the defects, several runaways of each circuit were simulated using CERN's QP3 program [6] for 1-dimensional electro-thermal network modelling of busbars and splices. The average splice resistances required to attain an accurate fit

were found to be 43.1 and 28.3 $\mu\Omega$ at 300 K for the RQF and RB's worst splices, respectively. This is in very good agreement with an independent measurement of 36.7 and 25.9 $\mu\Omega$, respectively [6].

It was also of interest to model the aforementioned "slow-down" to further understanding of protection against such a scenario. It was found that implementing a parallel resistance similar in magnitude to that of the defect produced the observed characteristics (Fig. 5). One could imagine this be possible if a small amount of solder remained in the splice's injection sprue (Fig. 1) which would begin to carry the current once the splice path becomes too resistive, re-distributing the ohmic heating.

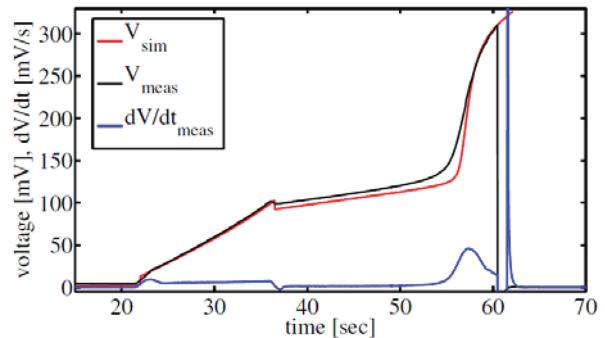


Figure 5: Graph comparing simulated thermal runaway in the B22L3.1 busbar segment with measured data. The effect of a parallel resistance to the splice, modelling the aforementioned "slow-down", can be seen around 58 s.

CONCLUSION

It was proven that a CSCM test can be carried out on either of the main 13 kA circuit types. The type test saw multiple thermal runaways being induced at varying current levels and plateau durations in both the RB.A23 and RQF.A23 circuit's busbar splices. The runaways could be successfully detected and protected against and, thus, further CSCM tests, if required, could indeed be carried out to fully qualify the continuity in all the 13 kA bypass circuits of the LHC with minimal system risk.

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