ELECTRICAL AND CALORIMETRIC MEASUREMENTS

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Abstract

During the incident of sector 3-4 on September 19th, the temperature of a number of magnets increased with respect to neighbouring magnets prior to the circuit failure. A review of the data logged during powering tests on all circuits indicated potential resistive splices in sectors 1-2 and 6-7. Calorimetric and electrical measurements confirmed a high resistance in magnet B16.R1 and B32R6. Systematic measurements have been performed in other cold sectors of the LHC during which the temperature increase and voltage across magnets were acquired at different currents. Cryogenic subsectors on which the temperature increase was abnormal were equipped with precise voltmeters to detect eventual resistive splices in the bus-bars. The findings of the measurement campaign will be shown as well as the plans to implement similar diagnostics as a routine check prior to powering the superconducting circuits of the LHC.

INTRODUCTION

A resistive splice in the magnet interconnection has been identified as a potential cause of the incident occurred in sector 3-4 of LHC on September 19th [1]. Even if the real origin of the fault is not known, it has become clear that a resistive heating was present in the affected cell during the last ramp and in previous powering tests. This resistance is estimated to be about 200 nOhms and could not be detected by the electrical measurements done at room temperature and at 1.9 K as part of the electrical quality assurance of the circuits prior to powering.

Dedicated calorimetric and electrical measurements were performed at the end of 2008 in some sectors of the LHC aimed to detect very small resistance. They involve powering the superconducting circuits and thus need to be part of the powering tests. These measurements are invaluable to spot high resistance joints in the superconducting circuits in the order of nanoOhms otherwise undetectable by other means.

SECTOR 3-4 INCIDENT

As part of the investigation that followed the incident on September 19th in sector 3-4 [1], the temperatures measured in the superconductor magnet chain was scrutinized. As shown in Fig. 1, the average temperature rise for most magnets is about 8mK. However, the magnets close to the dipole C24R3 show an increase of temperature between 10 and 13 mK and, above all, a parabolic dependence with time and hence current.

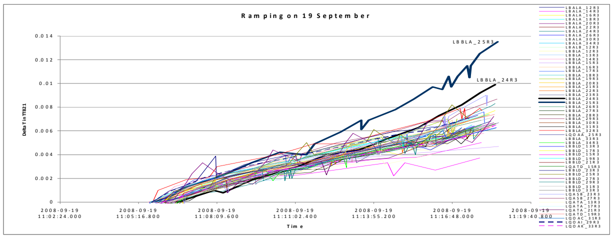


Figure 1: Temperature rise during the ramp to 8074 A of 19th September of the magnets in sector 3-4.

This indicates an important resistive heating coming from cell 24R3. Indeed, as shown in Figure 2, the data from previous powering tests during hardware commissioning shows an excessive heating. The estimated resistance at the origin of the heating would be between 180 and 270 nOhms.

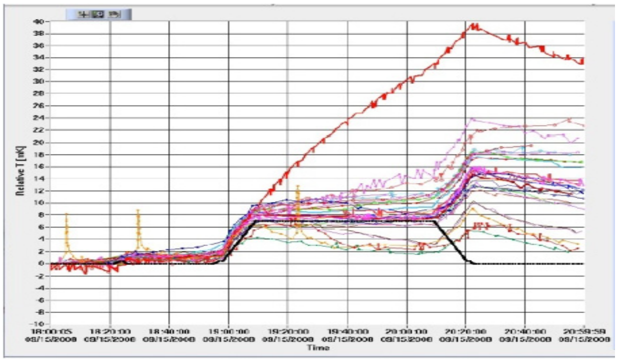


Figure 2 Temperature increase in sector 3-4 during a current plateau at 7 kA on September 15th. Each line represents a half-cell. The top curve corresponds to the half-cell 23R3 that reaches 40 mK increase with respect to its value before powering.

Following this finding, the data from the high current plateaux obtained during powering tests of the dipole and quadrupole circuits was analysed for signs of excessive heating in other sectors of the LHC machine. One should note that these tests were not meant to be accurate calorimetric measurements and cryogenic conditions were sometimes highly unstable. As an example, when powering is done right after a quench recovery, the cryogenic system is over-cooling and the temperature increase due to resistive heating cannot be detected.

From this first scan however, a suspicion arose for sector 1-2. During the final phase of the sector powering, all circuits are powered for an endurance test lasting eight hours at 8500 A. The temperature increase during this test in sector 1-2 is shown in Figure 3. The cryogenic subsector 15R1 registered a maximum variation of 40 mK and the Joule-Thomson valve that regulates the helium flow to cool the sub-sector was at its maximum value all the time. Three to five hours into the flat top, the temperature of the magnets starts to decrease.

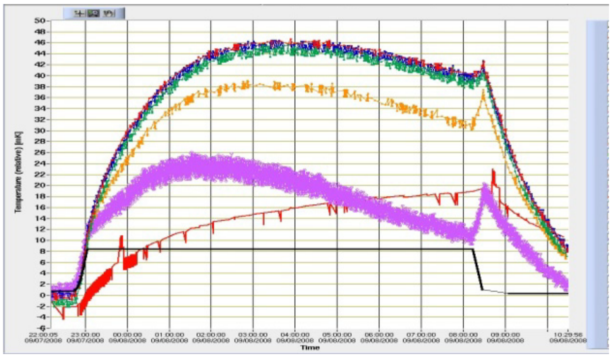


Figure 3. Evolution of the magnet temperatures in sector 1-2 during the endurance test. All circuits in the sectors were powered simultaneously.

A similar observation was done for sector 6-7 near the center of the arc. All other sectors did not show signs of excessive heating. These two locations received special attention in subsequent dedicated measurements.

DEDICATED MEASUREMENTS

During the last months of 2008, a campaign of dedicated measurements was launched to detect eventual resistive splices in the main dipole and quadrupole circuits. The detailed procedures for re-powering sector 1-2 can be found in EDMS [2] Sectors 5-6, 6-7, 7-8 and 8-1 were also powered. During these tests, long plateaux of increasing current are monitored and the relevant data analysed. The next current plateau is only launched after this analysis if no sign of a resistive splice is found. Two kinds of measurements are done: calorimetric and electrical.

Calorimetric measurements

Figure 4 shows the schematic of a cryogenic cell [3]. An optic cell (two SSS and six dipoles) shares a heat exchanger filled with saturated liquid helium that evaporates and cools the cold mass circuit through the heat exchanger. At least two optical cells are connected to each other by the cold mass circuit and separated from the next through hydraulic restrictions. The volume of two or three optical cells is filled by the same bath of static pressurized helium. This unit is called a cryogenic sub-sector and is cooled down via two Joule Thomson valves.

At least 72 hours prior to the test, one of the two valves in the cryogenic sub-sector is blocked at a constant value and only the second one controls the sector temperature. Two hours prior to powering, the second valve is also blocked at its average opening value in such a way as to compensate the static heat loads. During the current ramps, the temperature of the cryogenic sub-sector increases due to eddy currents. When the plateau is reached, the remaining heating is only due to the resistive splices. From the temperature increase during the plateau, we calculate the internal energy variation and the deposited energy assuming a mass of 26 l/m of helium. The method was calibrated using electrical heaters as a 10 W heat source.

One should note that if conditions are adiabatic, the heat generated in any location is transmitted to the entire sub-sector almost instantaneously by the super-fluid helium and thus it is not possible to localise the exact source of heat.

Calorimetric measurements required current plateaux of at least one hour and are only significant when the current is above 7 kA. At this current significant splices will produce a heat dissipation of about 4 W. The resolution of the temperature measurement and the cooling loop stability translates into a 2 W accuracy in the dissipated power. This means that we can, in practise, detect resistive splices above 40 nOhms.

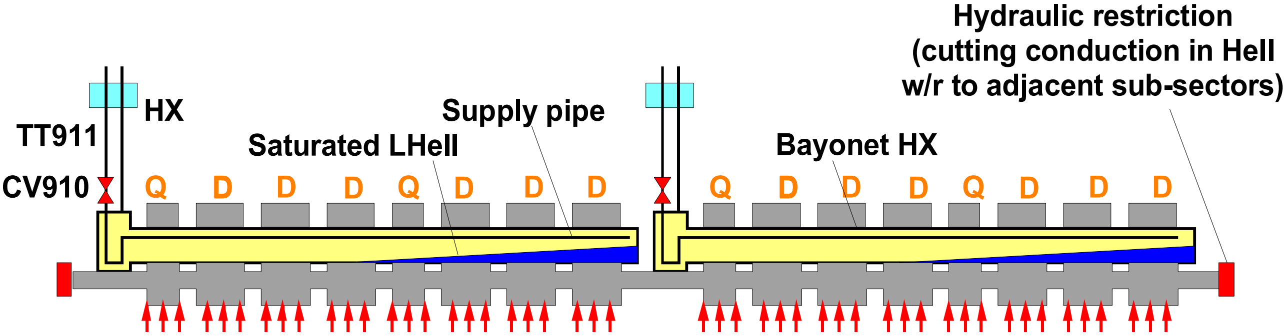


Figure 4 Schematic view of a cryogenic subsector. The two optics cells share the same volume of static helium and are cooled by two heat exchanger circuits. The supply of helium is regulated by a Joule-Thomson valve for each exchanger.

Electrical measurements

When the calorimetric measurements indicated excessive heating, high resolution voltmeters were dispatched to the tunnel at suspected cryogenic sub-sector and connected to the voltage taps between magnets. Eight channels were used to verify the resistance of all the interconnection splices in an optical cell (see Figure 5). The bus-bar segments measured in this way contain two or three bus-bar splices done during the interconnection work. Measurements of voltage versus current allow measuring the resistance up to the nOhm precision. As the eight channels are only sufficient to measure one optical cell, two or three measurements are necessary to scan the full suspected cryogenic subsector.

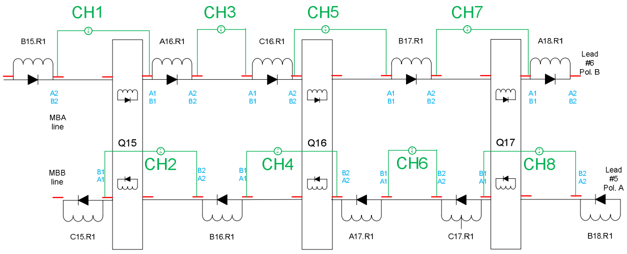
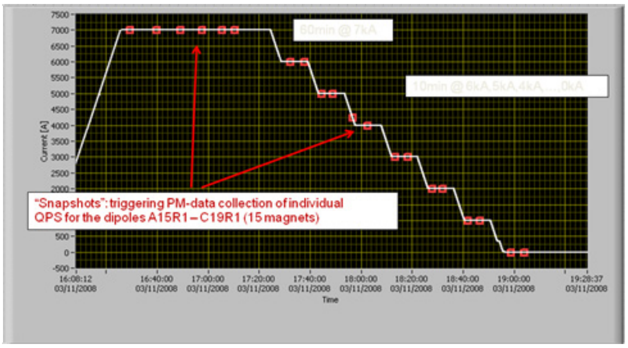


Figure 5: Connection of the voltmeter channels in an optical cell to measure bus-bar resistance.

The last method known as the "snapshot" is indeed an electrical measurement similar to the previous one. The only difference is that the signal measured against current is the difference of the voltage across the two apertures of a magnet. In this way, the resistance of the magnet internal splices is put into evidence. This signal is already used by the quench protection system and the measurement can be thus triggered via the QPS acquisition simultaneously for all the magnets in a circuit. Figure 6 shows the different snapshots taken for the cell A15R1 while ramping down the magnet. The acquisition lasts 13 seconds compatible to the QPS acquisition buffer. This gives a precision of 0.125 V and a total accuracy of about 3 nOhms.

This measurement was developed for the detection of unbalanced resistance between the two apertures of a magnet and was routinely used during the powering tests.



"Snapshots": triggering PM-data collection of individual QPS for the dipoles A15R1 – C19R1 (15 magnets)

Figure 6: Snaspshot principle. At least two voltage measurements are done at different current plateaux.

A general advantage of electrical measurements is that they can be done much faster (5-10 minutes) and do not require stable cryogenic conditions. Unlike calorimetric measurements, they also have enough resolution at low currents.

RESULTS

The main dipole circuit was tested for sectors 1-2, 5-6-6-7, 7-8, and 8-1. The main quadrupole circuit was tested in all these sectors except in sector 1-2 due to lack of time.

Sector 1-2

Sector 1-2 was the first sector to be tested, as it had to be warmed up to allow the transport of damaged dipoles coming from sector 3-4. As seen previously, the cryogenic sub-sector 15R1 showed an excessive heating already during hardware commissioning. This was confirmed by calorimetric measurements (see Figure 7) that indicated a resistance of 100 nOhms in that position.

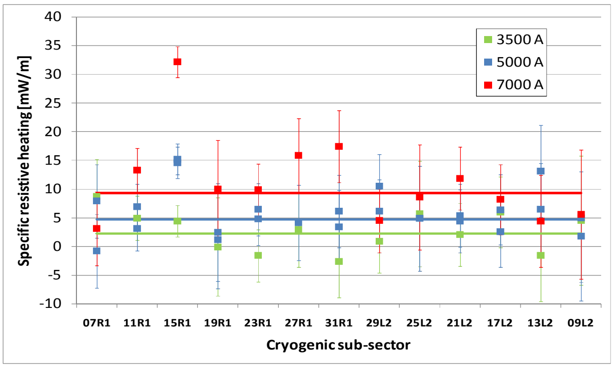
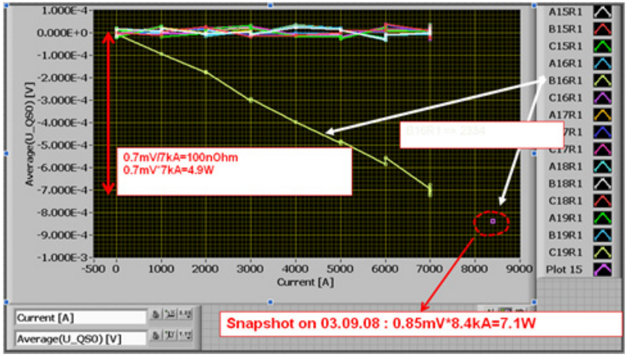


Figure 7: Measurement of resistive heating along sector 1-2. A net increase of heating with current indicates a significant resistance.

The voltmeters were installed in the tunnel to measure the resistance of all bus-bar segments in sub-sector 15R1. The measured resistance was in all cases bellow 1 nOhm. The snapshot tool was then used in the magnets of the cryogenic sub-sector 15R1.



0.7mV/7kA=100nOhm
0.7mV*7kA=4.9W

Snapshot on 03.09.08 : 0.85mV*8.4kA=7.1W

Figure 8: Resistance measurement of the intra-magnet splices for the magnets in the cryogenic subsector 15R1. One magnet shows a much higher resistance.

Figure 8 shows an unbalanced resistance of 100 nOhms in the dipole B16R1. This value is confirmed by a previous snapshot taken during the powering tests at 8.5 kA seen at the bottom of the graph. The analysis of data taken during the acceptance tests in SM18 of this magnet (MB2334) confirms a resistance of 105 nOhms and locates it in the inter-pole splice of aperture 1 (see Figure 9). After warming up the sector 1-2, the magnet 2334 was brought back to the surface and de-cryostated.

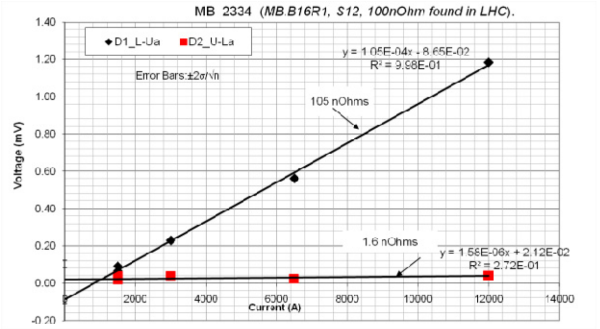
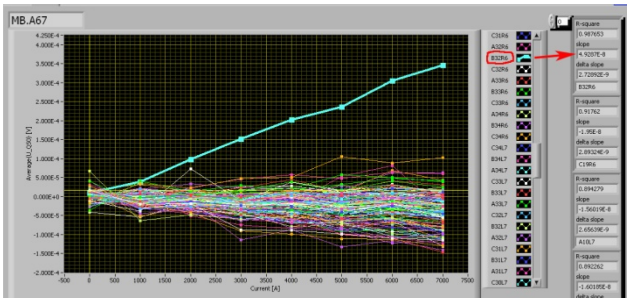


Figure 9: Resistance estimation of the internal splices in magnet 2334 from SM18 data.

Calorimetric measurements indicated also a possible heat source in sub-sector 31R1 but electrical measurements in the bus-bar splices were not performed due to lack of time. However, snapshots done during hardware commissioning exclude a resistive splice inside the dipoles. The presence of a resistive splice made during interconnection of the magnets in de tunnel has not been excluded. Further investigations are needed.

Sector 6-7

During the calorimetric measurements in this sector, anomalous heating was measured in the cryogenic subsector in the middle of the arc (33R6). As for sector 1-2, electrical measurements of the resistance across the bus-bar segments in the tunnel did not show any high resistance.



R-square
0.987653
slope
4.9287E-8
delta slope
2.72892E-9
B32R6

R-square
0.91762
slope
-1.95E-8
delta slope
2.89324E-9
C19R6

R-square
0.894279
slope
-1.56019E-8
delta slope
2.65639E-9
A10L7

R-square
0.892262
slope
-1.60185E-8

Figure 10: Resistance measurement of the internal magnet splices in sector 6-7

The snapshot method was then applied to all the dipoles in the sector in steps of 100A and the final result can be seen in Figure 10. Magnet B32R6 shows a resistance of 49 nOhms. The resistance measured in magnet B32R6 (MB 2303) was also confirmed by SM18 data recorded during acceptance tests. As in the previous case, the fault is located in the inter-pole splice this time in aperture 2 (Figure 11).

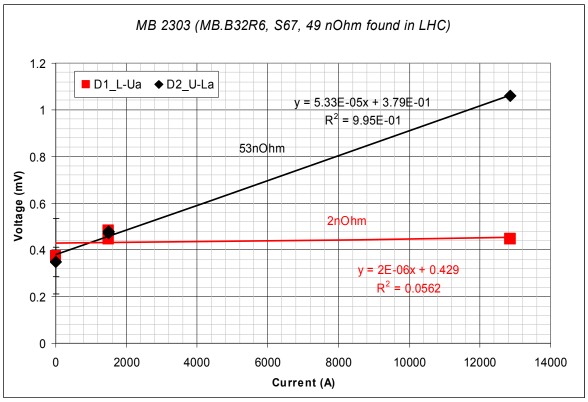


Figure 11: Resistance measurement of the inter-pole splices in magnet 2334 from data taken during cold test.

Other sectors

The summary of the calorimetric measurements done in the five available sectors is shown in Figure 12.

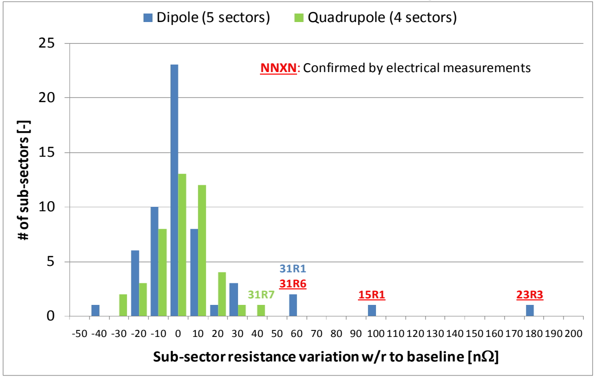


Figure 12: Distribution of resistance variation wrt. nominal for all cryogenic subsectors. Data estimated from calorimetric measurements

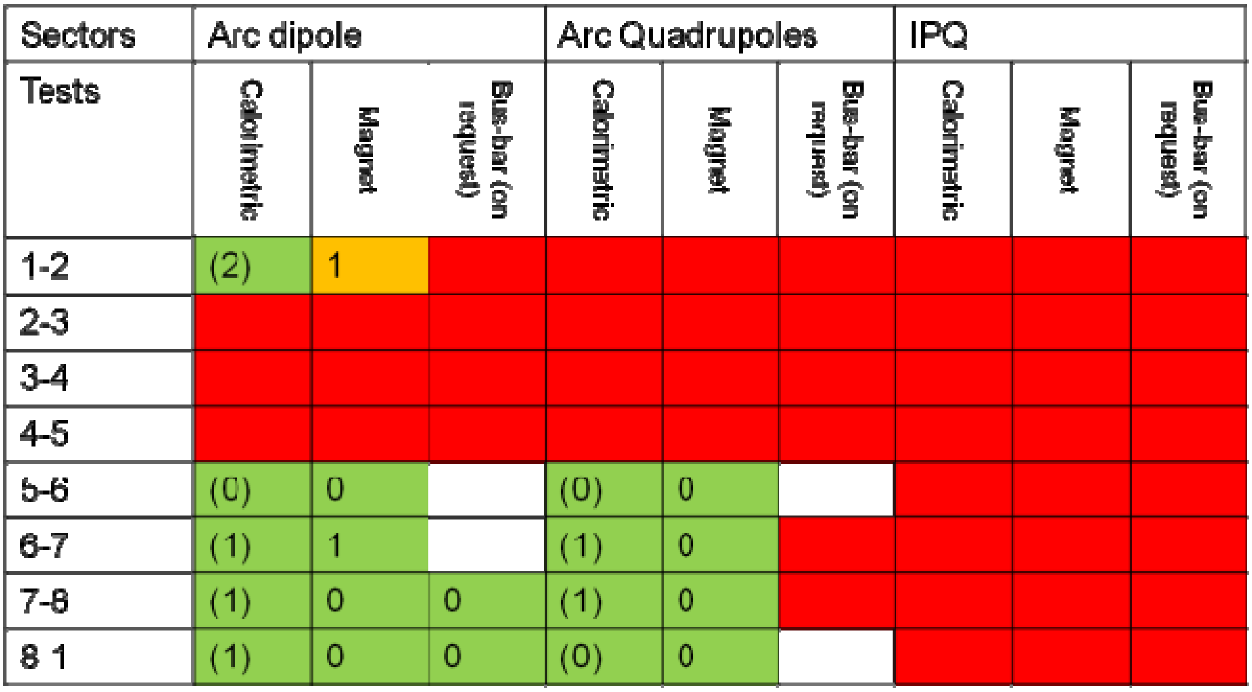
As expected, the calorimetric measurements can resolve resistances over 40 nOhms. Besides the case in sector 3-4, two other cases have been confirmed by electrical measurements.

CONCLUSIONS

A summary of the measurements done last year aiming to detect resistive splices is shown in Table 1.

The arc dipole circuit has been investigated in five sectors of LHC. The two arc quadrupole circuits have been investigation in four sectors. No resistive splice was found in the bus-bar splices signed out by calorimetric measurements with the exception of subsector 31R1 for which investigation is pending. Snapshot measurements confirmed the presence of resistive internal splices in two dipoles (B16R1 andB32R6).

Table 1: Summary of the measurement done by the end of the 2008 run per sector and circuit and with the number of (suspected) or confirmed cases indicated. Green boxes indicated circuits and sectors that were tested with each method. In red are not tested circuits. The case of the dipole circuit in sector 1-2 is shown in orange as the electrical measurement in the magnet (snapshot) was not done for all cells.



Sectors	Arc dipole			Arc Quadrupoles			IPQ		
Tests	Calorimetric	Magnet	Bus-bar (on request)	Calorimetric	Magnet	Bus-bar (on request)	Calorimetric	Magnet	Bus-bar (on request)
1-2	(2)	1	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2-3	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
3-4	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
4-5	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
5-6	(0)	0		(0)	0		🟥	🟥	🟥
6-7	(1)	1		(1)	0	🟥	🟥	🟥	🟥
7-8	(1)	0	0	(1)	0	🟥	🟥	🟥	🟥
8 1	(1)	0	0	(0)	0		🟥	🟥	🟥

Calorimetric and electrical measurements have shown their capacity to detect potentially dangerous resistive splices. Sub-sector 31R1 and the remaining three sectors in LHC need to be investigated by calorimetric and electrical measurements as soon as the quench protection system is updated. Investigations in individual powered quadrupoles and insertion magnets are not yet planned.

The new QPS system will be able to measure the resistance of individual magnets and bus-bar segments in the LHC during dedicated tests. Improved calorimetric measurements will also be available for next run. Both methods will be mandatory and included in the powering procedures for hardware commissioning.

REFERENCES

[1] Ph. Lebrun, The sector 3-4 incident. These proceedings

[2] Procedure for repowering sector 1-2 to assess the quality of the electrical joints of the main circuits. EDMS 973396

[3] LHC design report, http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html. Chapter 11, cryogenics.

[4] R. Denz, QPS upgrade and re-commissioning. These proceedings.