SOLVED AND REMAINING NON-CONFORMITIES IN THE SUPERCONDUCTING CIRCUITS

A. Verweij, CERN, Geneva, Switzerland

Abstract

Before and during Run-1 several non-conformities (NC's) in the superconducting circuits of the LHC were identified. During the long shutdown 1 (LS1) the NC's that could give a strong impact on the machine performance have been solved whereas other, less critical, NC's still remain. In this paper and overview is presented of the status of the NC's on the superconducting circuits as of mid Sept 2014.

INTRODUCTION

This paper gives the status of the NC's of mid Sept 2014. At this moment 8 sectors have passed the Electrical Quality Assurance (ELQA) tests at warm (300 K), one sector has passed the ELQA tests at cold (1.9 K), whereas the powering tests have yet been performed. It is therefore possible that during the remaining ELQA tests and especially during the powering tests (foreseen for end 2014 and beginning of 2015), new NC's will come up. Therefore, please refer to the MP3 web site https://twiki.cern.ch/twiki/bin/view/MP3/SummaryIssues for an up-to-date overview of all issues in the circuits.

In previous HWC campaigns we had frequently quenches at flat-top, especially in the 600 A circuits. For the 2014/15 campaign all circuits will be commissioned to a slightly larger current than required for operation at 6.5 TeV beam energy, in order to guarantee as much as possible 'quench-free' operation. The additional current margin IDELTA varies per type of circuit, as shown in Table 1.

Table 1. Overview of I_{DELTA} values for the various circuits.

Circuit	Description	I_{DELTA} [A]
RB	Main dipole	100
RQD/F	Main (de)focussing quadrupoles	100
IT	Inner triplet	100
IPQ	Individually powered quadrupoles	50
IPD	Individually powered dipoles	50
600 A	600 A corrector circuits (including RCO)	10
80-120 A	80-120 A corrector circuits	5
60 A	60 A corrector circuits	5

In the next section the results of the consolidation campaign of the 13 kA joints will be presented. In the following sections the main issues and NC's will be presented per circuit type.

CONSOLIDATION OF THE 13 KA JOINTS

Insufficient contact between the superconducting cable and the stabiliser coinciding with a lack of longitudinal continuity of the stabiliser caused the incident in the main dipole circuit sector 34 in Sept. 2008 [1], and was later on shown to be also present in many other 13 kA busbar joints of all main dipole and quadrupole circuits of the machine. All these joints were therefore consolidated during LS1, adding as well additional copper shunts. The resistance R8 measured between the bus stabiliser and the splice stabiliser over a length of 8 cm turned out to be a good measurable to quantify the continuity of the bus. A perfectly soldered joint has a R8 value of about 5.6 μΩ for RB joints and 9.3 μΩ for RQ joints. The excess resistance is therefore defined as $R8_{excess}$=R8-5.6 μΩ for RB joints and $R8_{excess}$=R8-9.3 μΩ for RQ joints. Figure 1 shows the excess resistance on each side of the joints [2].

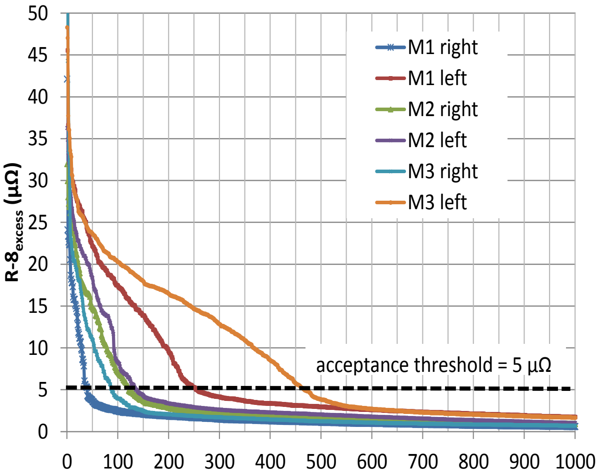

Figure 1. Excess joint resistance $R8_{excess}$ for the dipole (line M3) and quadrupole (line M1 and M2) busbars. Note that the two largest values (72 and 107 μΩ) are not shown [2].

Table 2 shows as well the maximum measured $R8_{excess}$ in each sector, and Table 3 shows the percentage of joints for which $R8_{excess}$ is larger than the acceptance criteria of 5 μΩ. These results led to the conclusion that the tooling on the M2 joints, which are better accessible from the tunnel side, was better centred.

Table 2. Overview of the maximum $R8_{excess}$ per sector [2].

Sector	RB max $R8_{excess}$ (μΩ)	RQ max $R8_{excess}$ (μΩ)
56	28.6	21.1
67	35.0	32.4
78	71.9	107
81	41.8	34.4
12	29.6	45.5
23	27.8	43.2
34	33.6	36.3
45	48.3	34.9

Table 3. Overview of the percentage of $R8_{excess}$ values exceeding the acceptance criteria [2].

Joint	$R8_{excess} > 5\ \mu\Omega$ (%)
M1-Left	8.2
M1-Right	1.3
M2-Left	4.4
M2-Right	3.8
M3-Left	15
M3-Right	2.7

About 30% of the splices needed to be machined before shunting due to high R8 value or due to geometrical imperfections. Shunts were then soldered on all splices. Figures 2 and 3 present the R8 values after machining and after shunting, showing a maximum excess resistance of only about 1 µΩ.

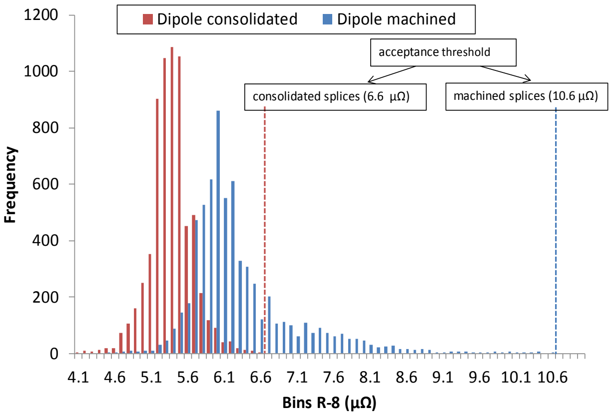

Figure 2. R8 distribution of all dipole busbar splices after machining and after shunting [2].

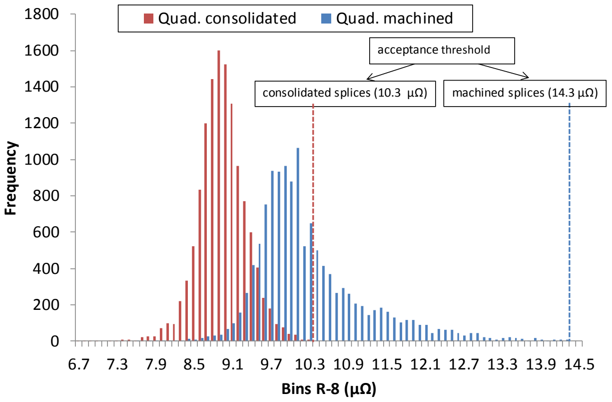

Figure 3. R8 distribution of all quadrupole busbar splices after machining and after shunting [2].

NC'S IN THE RB CIRCUITS

Besides the consolidation of the busbar joints, as described before, the main remarks to be made on the RB circuits are the following:

- ➢ 15 main dipole magnets (MB's) have been exchanged during LS1:
  - ▪ 1 magnet with high internal splice resistance (18 nΩ) and a quench heater issue.
  - ▪ 7 magnets with high internal splice resistances (>16 nΩ).
  - ▪ 4 magnets with quench heater issues.
  - ▪ 2 magnets with the wrong beam screen.
  - ▪ 1 magnet with limited High-Voltage Qualification during ELQA.
- ➢ Two shorts to ground in RB.A12 (discovered after warm-up before LS1) have been repaired. One on a diode and one at a lyra-MCS contact.
- ➢ The decay time constant is back to the design value of 104 s (30 s during Run-1).
- ➢ The diode leads have been measured at warm, and a 200 µΩ contact in a "half moon" has been repaired.

All MB's now have a full set of high-field and low-field quench heaters, and internal splices smaller than 16 nΩ. All RB circuits should be able to reach 6.5 TeV with probably considerable training. About 90-130 training quenches are expected, assuming that all sectors train in a similar way as the training of sector 56 in 2008 [3], [4].

There are no remaining issues limiting the operation.

NC'S IN THE RQ CIRCUITS

Besides the consolidation of the busbar joints, as described before, the main remarks to be made on the RQ circuits are the following:

- ➢ Two main quadrupole magnets (MQ's) have been exchanged during LS1 (Q23.R3 and Q27.R3), recovering the default configuration for the RQS circuits.
- ➢ The connections to the diodes are consolidated.
- ➢ The decay time constant is back to the design value of 30 s (9.2 s during Run-1).
- ➢ Some minor issues with open/loose voltage taps remain, but this has no effect on the quench detection and protection.

All MQ's have a full set of high-field and low-field quench heaters, and internal splices smallet than 27 nΩ. All RQ circuits should be able to reach 6.5 TeV with possibly some training quenches (much less than the MB's).

There are no remaining issues limiting the operation.

NC'S IN THE INNER TRIPLETS

Main quadrupoles:

All main quads of the IT's have a full set of 4 quench heater strips, wired into two independent redundant circuits. RQX.R1 has one circuit with reduced heater voltage and increased heater discharge capacitance, without impact on protection and operation.

All IT circuits should be able to reach 6.5 TeV equivalent with possibly a few training quenches.

There are no remaining issues limiting the operation.

MCBX circuits:

All 24 RCBXH/V pairs were limited to 350 A during Run-1, see the red square in Fig 4. After LS1 they will be commissioned ***individually*** to I_{PNO}=540 A, except RCBXH1.L5 (490 A).

During simultaneous powering they will be limited to $(I_V^2+I_H^2)<I_M^2$, with I_V the current in the MCBXV, I_H the current in the MCBXH, and I_M=540 A for 14 out of 24 circuits (see the green curve in Fig. 4). For ten RCBXH/V pairs I_M has a reduced value, between 400 A and 508 A (see the green surface).

For optics requirements, one could also foresee to operate these ten pairs on an ellipse with 540 A in either horizontal or vertical direction (see the blue curves)

Six RCBXH/V pairs also have combined MCSX-MCTX magnets, which unfortunately affect the quench behaviour of the MCBXH/V. The RCSX3 and RCTX3 circuits will be commissioned ***individually*** to 100 resp. 80 A, and then limited to 10 A for operation.

If needed for operation or for special MD's, the operational range will be optimized on an individual base.

Other triplet correctors:

The following four circuits are condemned:

- RCOSX3.L1
- RCOSX3.L2
- RCOX3.L2
- RCSSX3.L2

Circuit RCSSX3.L1 has a reduced nominal current (60 A instead of 100 A).

NC'S IN THE IPD CIRCUITS

The main remarks to be made on the IPD circuits are the following:

- The RD1.R8 circuit operates with one out of two quench heaters. This has no impact on the operating current.
- The RD3.L4 circuit show slow training behaviour. The nominal current is reduced from 5850 to 5600 A, which is sufficient for operation up to 6.74 TeV.

There are no remaining issues limiting the operation.

NC'S IN THE IPQ CIRCUITS

The main remarks to be made on the IPQ circuits are the following:

- In position RQ5.L8 the magnet SSS606 has been replaced by magnet SSS696 during LS1 in order to resolve a NC with the corrector RCBCHS5.L8B1.
- Circuit RQ4.L8 operates with 7 out of 8 quench heaters. This has no impact for operation and protection.
- Circuit RQ5.R2 shows a slow training behaviour. This has no impact for 6.5 TeV operation.
- The MQY magnets in positions RQ4.L5 and RQ4.R5 will be operated during Run-2 with a so called "4-lead" instead of "3-lead" configuration. From a converter point of view they can now be used with arbitrary ratio I_{B1}/I_{B2}. However, the two apertures have a very strong magnetic cross-talk.

There are no remaining issues limiting the operation.

NC'S IN THE 600 A CIRCUITS

The main remarks to be made on the 600 A circuits are the following:

- The acceleration in all RSD/F circuits is reduced from 0.25 to 0.15 A/s^2.
- The ramp rate in RU.R8 is reduced to 0.1 A/s.
- In circuit RQTF.A81B1 four out of eight magnets are bypassed.
- Circuit RCO.A12B2 will be operational after LS1; it was condemned during Run-1.
- In circuit RCO.A78B2 two out of 77 magnets are bypassed (in positions B20L8 and C19L8).
- In circuit RCO.A81B2 two out of 77 magnets are bypassed (in positions B11L1 and B12L1).
- Circuits ROD.A34B1 and ROF.A34B2 both contain only 11 MO magnets instead of 13. Exchange of the SSS's in Q28 and Q32 is required to solve this NC.
- Circuit RSS.A34B1 is condemned
- Circuit RSS.A81B1 will be operational after LS1; it was not operated during Run-1 for unknown reason.
- Circuit RQS.A34B2 will operate after LS1 with the design configuration of four MQS magnets in series; during Run-1 two magnets (out of four) were missing.
- Circuit RQS.R3B1 will operate aftger LS1 with the design configuration of two MQS magnets in series; during Run-1 this circuit contained no magnets.
- In circuit RCS.A34B2 four out of 154 magnets will be bypassed.

All 600 A circuits have a nominal current of 550 A, except:

- all ROD/F circuits for which the nominal current is 590 A, with $I_{DELTA}=0$ A.
- the RSD circuits in S12, S45, S56, S81 for which the nominal current is 590 A, with $I_{DELTA}=0$ A.
- the RQ6 circuits in points 3 and 7 which operate at 4.5 K with a nominal current of 400 A.
- 28 600-A circuits that have a nominal current between 300 and 500 A, see Table 4.

Table 4. Overview of 28 circuits with nominal current smaller than the default value of 550 A.

Circuit	I_{PNO}
RQTL8.L3B1	450 A
RQTL8.L3B2	450 A
RQTL8.L7B1	300 A
RQTL8.L7B2	300 A
RQTL9.L7B1	400 A
RQTL9.L7B2	400 A
RQTL9.R3B1	450 A
RQTL9.R3B2	425 A
RQTL9.R7B1	500 A
RQTL9.R7B2	500 A
RQTL10.L7B1	500 A
RQTL10.L7B2	500 A
RQTL10.R3B1	450 A
RQTL10.R3B2	450 A
RQTL11.L3B1	400 A
RQTL11.L3B2	400 A
RQTL11.L6B1	350 A
RQTL11.L6B2	400 A
RQTL11.L7B1	300 A
RQTL11.L7B2	300 A
RQTL11.R3B1	500 A
RQTL11.R3B2	500 A
RQTL11.R5B1	500 A
RQTL11.R5B2	500 A
RQTL11.R6B1	300 A
RQTL11.R6B2	300 A
RU.L4	400 A
RU.R4	400 A

NC’S IN THE 80-120 A CIRCUITS

The main remarks to be made on the 80-120 A circuits are the following:

- ➢ Circuit RCBCH6.L2B2 will be operational after LS1; the circuit was condemned during Run-1.
- ➢ A small reduction of the nominal current in circuit RCBCH7.R3B1 from 100 to 80-90 A might be needed.
- ➢ A reduction of the nominal current in circuit RCBCH10.R3B2 from 100 to 60 A might be needed.
- ➢ The magnet in circuit RCBCHS5.L8B1 was replaced during LS1 (as part of Q5.L8) and the circuit will be operational after LS1; the circuit was condemned during Run-1 since there was a high magnet resistance of 20 mΩ.
- ➢ The nominal current in circuit RCBYH4.R8B1 is limited to 50 A.
- ➢ The nominal current in circuit RCBYHS4.L5B1 is limited to 50 A.
- ➢ The nominal current in circuit RCBYHS5.R8B1 is limited to 40 A, with dI/dt reduced to 0.3 A/s.
- ➢ The nominal current in circuit RCBYV5.L4B2 is limited to 50 A.

NC’S IN THE 60 A CIRCUITS

All 60 A corrector circuits can be run up to nominal current after LS1 except for the circuits RCBH31.R7B1 and RCBV26.R5B1 which are condemned due to too high resistance.

CONCLUSIONS

During LS1 the most important limiting factor for operation at 6.5 TeV beam energy has been solved by consolidation of the 13 kA busbar joints. In the same period a certain number of NC’s have been resolved through exchange of magnets, or bypasses of parts of circuits. A number of NC’s still remain in the superconducting circuits after LS1. However, none of these NC’s limits the operation for 6.5 TeV beam energy. It is of course possible that during the 2014/15 HWC campaign new NC’s will come up. An up to date overview of all NC’s and issues can be found on: https://twiki.cern.ch/twiki/bin/view/MP3/SummaryIssues.

ACKNOWLEDGEMENTS

The author would like to thank all members from the MP3 (www.cern.ch/MP3), M. Pojer and M. Solfaroli Camillocci for their help in preparing and checking the data presented in the slides and the paper.

REFERENCES

[1] A. Verweij, “Busbar and Joints Stability and Protection”, https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/papers/AV_4_03.pdf .

[2] S. Heck, et al., “Non-destructive testing and quality control of the LHC main interconnection splices”, IEEE Trans. Appl. Supercond., Vol. 25(2), 2015.

[3] A. Verweij, “Training the dipoles”, https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/papers/AV_1_01.pdf .

[4] B. Bellesia, N. Catalan Lasheras, E. Todesco, “Magnet (re)training”, https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/papers/ET_8_06.pdf .