

WHAT NEEDS TO BE DONE TO REACH BEAM ENERGY ABOVE 3.5TeV? COMMISSIONING OF ESSENTIAL MAGNET POWERING AND MACHINE PROTECTION SYSTEMS.

N. Catalan Lasheras CERN, Geneva, Switzerland.

Abstract

After the initial plans in 2007 to run the LHC at 7 TeV, a number of unexpected events, and the extended knowledge of the machine that came after them, have convinced us to gradually reduce the beam energy to the current 3.5 TeV. As a consequence of this, some circuits have been commissioned to different energy levels. Some systems, as the quench protection system, are working at a reduced level of accuracy based on less demanding conditions. Non-conformities that were unacceptable for higher energy have no consequences at the current energy and are thus accepted. In this contribution, we will review the current status of commissioning of all the circuits and estimate the time and effort necessary to make all circuits operational at higher energies. All existing nonconformities that need to be solved before increasing the energy will be reviewed.

INTRODUCTION

During the different stages of installation and commissioning, a number of non-conformities or performance issues have been revealed since 2007. The paper will be divided between the most critical non-conformities revealed during the electrical quality assurance (EIQA) campaigns, and the performance issues revealed during both EIQA and hardware commissioning. While the first two cases limit very clearly the current in the circuits and thus the beam energy, performance issues, unsolved mostly in corrector circuits, have a less clear impact on the beam energy.

The last part of this review deals with a series of measurements that have not yet been done in the superconducting circuits, but that are deemed necessary to go to higher energies. The energy to which we can go without them is not defined precisely.

ELECTRICAL NON CONFORMITIES

During the first phase of hardware commissioning, a campaign of electrical qualification of all LHC superconducting circuits is done in the tunnel [1]. At this stage, the continuity of circuits, the proper functioning of the current leads and the insulation of each circuit and of the quench heater circuits are checked. The most serious electrical problems are revealed at this time. Two main non-conformities have been found that limit the use of circuits during operation:

MQXA quench heater insulation [2]. The insulation of one out of the two quench heater circuits inside the

RQX1.R1 did not fulfil the acceptance criteria. It broke down consistently around 1100V which is the qualification voltage for this component. As the maximum voltage is defined by the quench heater discharge capacitor, this value is independent from the beam energy. For operation at 3.5 TeV, working with the remaining quench heater circuit was judged sufficient and the faulty circuit was simply disconnected. For increasing the energy, the full protection has to be restored. Two solutions were discussed:

1. Limit the charging voltage of the capacitor to 400V. The energy delivered to the magnet during a quench will be lower and the protection less effective. However, simulations and extrapolation from prototype measurements done in KEK indicate that this situation would be sufficient even for nominal beam energy [3].
2. Increase the capacitor value in order to lower the charging voltage by discharging the same energy into the quench heaters. This solution is the preferred option and will require a rather simple change of hardware. The lead time for the procurement of the capacitor is however rather long and this cannot be implemented during the present Christmas break.

Both solutions will allow going to nominal current and energy. The required intervention can be done at any time as soon as the hardware is ready.

B30R7 insulation weakness [4]. During the qualification of the RB.A78 circuit, a breakdown appeared around 1.6 kV instead of the nominal qualification voltage of 1.9 kV. The insulation breakdown was localized inside the B30R7 dipole (MB1007) by the use of oscilloscopes [5]. The fault being inside the cold mass, there is no possibility to repair in-situ.

The qualification voltage is defined as the maximum operating voltage that the circuit might experience and has, for the case of the dipole circuit, two components. The first part (600 V) comes from the energy extraction resistance and the common mode voltage in the converter in case of short. This contribution is not energy dependent and cannot be reduced. Only a change in the energy extraction resistors and thus in the decay time for the RB circuit during a fast power abort will decrease the maximum voltage. This solution is however not considered safe until the splice consolidation has been done. The second part (1300 V) comes from the quench

development inside the coil and scales down with current and beam energy.

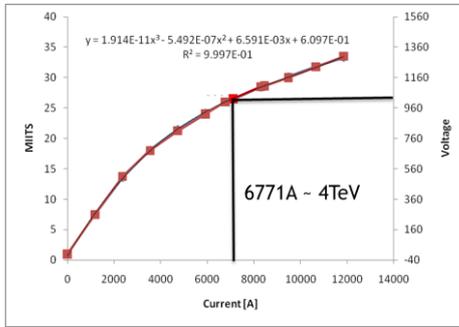


Figure 1: Simulated MIITS (A. Verweij) for the main arc dipole in LHC against current and the equivalent voltage developed in the coil.

Extrapolating from MIITS measurements in the main dipole (see Figure 1), a reduction of 300V in the voltage developed during a quench will mean a reduction of 3TeV. The maximum beam energy for which the use of this magnet is still safe is 4 TeV. Above that energy, the magnet should be replaced.

PERFORMANCE ISSUES

During the hardware commissioning, a number of NC have been revealed during the years [6]. These problems affect mostly the performance of the circuit and the maximum current at which it can be routinely operated. As they affect mostly corrector circuits, the performance loss did not impact the operation in 2010. Their impact at higher energies should nevertheless be taken into account.

Training non-conformities. A number of circuits have experienced quenches during hardware commissioning. At the time of commissioning in 2009/2010, the training was stopped and the nominal current decreased to save time. There is however no reason why the circuits will not go to higher currents. Figure 2 shows the training of RCD circuits both in 2008 and 2009. In this particular case, every circuit containing 77 magnets experienced one to seven training quenches before reaching 550A. Still all of them reached nominal during the 2008 campaign.

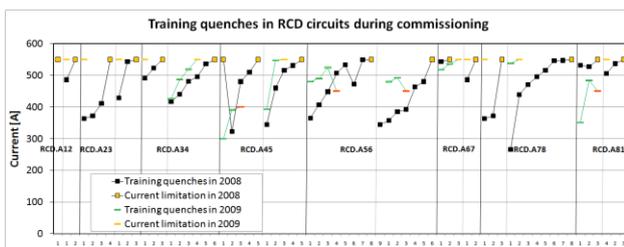


Figure 2 Quench history of all RCD circuits during the hardware campaigns 2008 and 2009. (S. Le Naour)

Similar results were observed for RQT/RQTL circuits in which several training quenches should be needed before reaching nominal. Only the case of

RQTL8.L7B1 should be considered anomalous as the circuit is showing detraining (quenches at 300 A, 245 A in 2008 and 240 A and 257 A in 2009). The circuit is currently limited to 200A and further studies will be necessary if this limit is insufficient.

Inner triplet 600 A corrector circuits. For these circuits, the present cooling scheme of the current leads may become unstable at current higher than 400A [7]. There are plans to consolidate the cooling procedure during the last long shutdown but, until then, the current in the circuits is limited to 400 A. Besides, the horizontal and vertical orbit corrector of the same module are nested which means that the voltage developed in one coil, while the other is ramping, will trigger the QPS detector. As a consequence, even if single circuits have been commissioned to 400A, the synchronous powering of the horizontal and vertical corrector in the same module cannot exceed 300 A.

RSD/RSF circuits. The QPS protection is unable to distinguish between a resistive transition and an inductive voltage in very short time. This limits the maximum ramp rate for circuits with high inductance like RSD/RSF circuits or RQ6 in IP3 and IP7. Future development of the QPS detectors and software will improve the situation but for the moment, the ramp rate of RSD/RSF circuits is limited to 0.15A/s.

Orbit corrector problem. It affects mostly MCBY and fewer MCBC magnets. The problem shows as instability on the control by the power converter. A parallel resistance needs to be added to the model of the load in order to stabilize the current. However, some of these circuits quench when decreasing the absolute current in the circuit. In other cases, they sustain the nominal cycle but quench as soon as a fast power abort is started. The limiting current stays constant without apparent degradation.

Table 1: Orbit dipole circuits affected by a performance problem. The parameters at which they were commissioned and the NC number in EDMS.

Circuit name	Commissioned parameters	NC number
RCBYHS5.R8B1	20A, 0.6A/s	1063839
RCBYV5.L4B2	50A, 0.5A/s	1049055
RCBYH4.R8B1	50 A, 0.67A/s	1051795
RCBYHS4.L5B1	50 A, 0.67A/s	1053709
RCBCV8.L1B2	-	NA
RCBCV8.L1B2	-	NA
RCBYH4.L2B2	-	NA
RCBCV7.L2B2	-	1084849
RCBYHS4.R2B1	-	1028324

The full list of affected magnets is shown in Table 1. The first four circuits are limited either in current or in ramp rate and five more show this behaviour only after a fast power abort, which generates very high ramp rates.

Two more circuits have recently been identified as showing similar behaviour and are presently under investigation.

A possible explanation for this observation is a resistive short circuit between two layers in the coil. Figure 3 shows the schematic shorted circuit. Simulations with such model seem to confirm the observed behaviour. A test using a modified magnet with a set of extended instrumentation is scheduled for April in the new SM18 vertical cryostat facility. This will allow verifying this hypothesis.

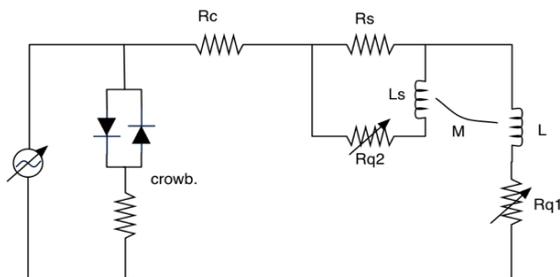


Figure 3: Electrical schematic of a dipole corrector in which one group of coils will be short-circuited. The final configuration would include two independent coils with a mutual inductance.

Unfortunately, the current in these circuits cannot be raised. If stronger correction is needed at any beam energy, new cryo-magnets should be put in the machine or additional warm correctors should be added. Both solutions will only be possible during a long shut-down period.

Open or resistive circuits. A number of circuits have been condemned during the EIQA and hardware commissioning campaigns (see Table 2). In the first two cases, the circuit is open. For RCO.A81B2 circuit, the discontinuity was localized by the EIQA team in the tunnel between B12L1 and B11L1. The last two circuits in Table 2 were found too resistive during EIQA and powering tests and have been condemned and the converter removed. Localization of the resistive segment for the RCO circuit should be possible using high precision voltmeters in the tunnel.

Table 2: Condemned superconducting circuits in the LHC due to serious non conformities.

Circuit name	NC number	Comment
RCOSX3.L1	948545	Open circuit
RCO.A81B2	955048	Open circuit
RCO.A78B2	1029807	Resistive splice
RCBH31.R7B1	1017094	1 mOhm

Reconfigured QPS protection. Quench heaters are a very important element for the integrity of the magnet. If the QH circuit is damaged, the activation of the heater stripe and protection of the magnet against quench cannot be ensured. Besides, if the QH strip itself is damaged,

discharging the capacitors in it could damage the magnet itself and have serious consequences. For this reason, quench heaters integrity is evaluated often during operation. During the EIQA campaign and during individual system tests of the QPS, a number of QH circuits have been found defective, (bad insulation, too resistive, open or not discharging smoothly). In these cases, after verification of the insulation between heater and coil, the protection scheme has been reconfigured in order to use the available spare quench heaters. Up to now, the QPS protection has been reconfigured in eight dipole magnets, and two insertion quadrupoles. The new protection scheme is redundant in all cases, except the RQX1 mentioned earlier, and allows operating the magnet up to nominal current of 7 TeV equivalent. Nevertheless, some of these magnets, for which the QH circuit fault is suspected to be inside the cold mass, will be changed during the next long technical stop for in-depth investigation. No case has been revealed yet during operation.

ADDITIONAL DIAGNOSTICS

In addition to the faults found during the standard electrical and powering tests, a number of potential risks have been identified for which additional or modified tests will be required. The energy at which we can drive the LHC beam is not clearly defined in this case, but the measurements should be done as soon as possible or, at the latest, before the next long technical shutdown to have the chance to repair in case of confirmed fault.

Bus-Bar resistance measurements in the insertion magnets. During the international reviews following the 2008 incident, it was recommended to measure all the splices in the machine done during interconnection. A new QPS system was deployed in 2009 to monitor and protect the main quadrupoles and dipoles in the arc. The insertion magnets individually powered are not as critical because the bus-bar and interconnection splices are protected at the same level as the internal coil by the current QPS system. However, no monitoring of the bus-bar resistance is done, as for the arc magnets. A campaign of electrical measurements started in 2010 to characterise every bus-bar of the individual powered quadrupoles in the dispersion suppressor and matching section. Up to now, all the circuits in the continuous cryostat have been measured and no evidence of a resistive splice has been found. The measurements are done during technical stops using mobile equipment and the test in one circuit takes about one hour. The rest of the circuits in the matching section, separation dipoles, and inner triplet, need to be measured before the beginning of the long shutdown so that eventual faults can be repaired. Measuring them all during technical stops in the next two years seems feasible.

Improved high voltage testing. During the recent investigations of the splice consolidation task force [8], it

was noticed that the withstand voltage at which every circuit is tested in the tunnel during electrical qualification, might not be adapted to the real conditions in the machine. Indeed, this voltage had been defined for individual testing of the insulation of each circuit versus ground [9]. However, the worse voltage conditions happen simultaneously for all the circuits in a powering sector during a global power abort triggered by an emergency dump. In these conditions, the relative voltage between circuits is, in some cases, higher than the specified one. The reference documents used for the electrical quality assurance are being updated. However, stressing the circuits to new values has a certain risk and should be avoided. A campaign of testing at this new voltage values should be planned at the end of the present run or before the long shutdown, in order to identify possible weakness of the insulation and have a chance to repair them. The time required to perform this campaign together with the localization of faults already known is estimated to two weeks.

CONCLUSIONS

Two electrical non-conformities limit the current beam energy in LHC. While the quench heater systems in RQX1.R1 can be recovered quite quickly, the voltage breakdown in dipole B30R7 is more serious and no other solution than changing the magnet seems feasible to go above 4TeV. Several performance issues in corrector magnets have been described and their limitation given in terms of current in the circuit. The impact on the beam energy has to be evaluated by the BE/ABP group.

Finally, some diagnostics are recommended before increasing the beam energy. The list is not exhaustive and

will be improved before the next long shutdown. However, they do not seem to be limiting the energy below 4TeV.

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