WHICH SYSTEMS (EXCEPT MAIN CIRCUITS) SHOULD BE COMMISSIONED/TESTED FOR 7 TEV OPERATION BEFORE THE LONG SHUTDOWN?

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Abstract

The key driver of the long 2012/13 shutdown is the consolidation of the 13 kA splices. Once the machine will be back to operation, the increase of energy to 7 TeV should be possible. Are all circuits and systems ready for 7 TeV operation? This paper focuses on what else could limit LHC high energy operation and how we can know that in advance. A period of dedicated testing at the end of operation and before the long shutdown could give a precious knowledge on the status of the machine.

INTRODUCTION

The energy at which the LHC is operated has been progressively reduced since 2008. This is the result of the evidence of the long training required to reach 7 TeV in the main dipoles and, above all, because of the problem with the splices between main magnets: at the origin of September 08 incident, it will require a long shutdown to repair all splices. Following the simulations performed on a safe energy level without splice consolidation [1], the machine energy (and therefore the main dipole current) was halved with respect to the design value, leading to a scaling of the current needed for all circuits around the ring.

Because of the gradual current reduction, there might be limits in the machine that we have not yet discovered. A series of tests could be envisaged in order to highlight these limits (if any) and avoid restarting operation after the long shutdown without fixing them.

STATUS OF COMMISSIONING IN 2008

After the first commissioning campaign, at the end of 2008, the preparation of the machine for operation at 7 TeV was well advanced. The long training required to bring the main dipoles to high current in the first sector (a maximum of 6.6 TeV equivalent current had been achieved in sector 56 [2]) had brought to a short period objective of 5.5 TeV, even if most of the circuits had been already commissioned for 7 TeV operation. Excluding sector 34 (where all circuits had to be considered as brand new after September 08 incident), all circuits in the machine were indeed commissioned to the design value, excluding [3 to 9]:

- the main circuits were commissioned to 5.5 TeV, with the exception of RB.A78 (which was stopped to less than 5 TeV due to training below 9.3 kA), RB.A56 (commissioned to 6.6 TeV) and RQD/F.A56 (commissioned to 7 TeV);
- RQX.L5 was commissioned to less than 5 TeV, as a result of an *a posteriori* change of the nominal current;
- RD3.R4 and RD4.R4 were commissioned to 6.6 and 6.3 TeV, respectively, as a result of an *a posteriori* change of the nominal current;
- RD2.R8 quenched four times (at 5816, 5788, 5856 and 5854 A) at less than 6.8 TeV (this probably constitutes a real limitation for the 7 TeV operation);
- few 120 A magnets showed problems and had to be limited in current;
- the 600 A circuits were somehow jeopardized, due to the reduction of the nominal current and the change of specifications.

For completeness, all Inner Triplets (excluded RQX.L5, as mentioned above) and all the individually powered quadrupoles reached the design value for 7 TeV operation.

According to this status, a first suggestion to discovered hidden machine limitations in circuits different from main dipoles and quadrupoles would be to try and push to their nominal current all 600 A circuits, plus the three IPDs and the IT in L5.

STATUS OF COMMISSIONING IN 2010

After September ‘08 incident, investigations were carried out to establish a safe current value for operation of the main circuits without re-machining all splices. In particular, simulations were performed [1] that showed that the LHC could safely run to 3.5 TeV. This is why the machine was re-commissioned in 2009/10 for this energy level. The details of the commissioning parameters used for all circuits can be found in [10-17].

During the preparation of all circuits for powering, few non-conformities were discovered during the Electrical Quality Assurance tests, which will be treated during the long shutdown: a weak insulation on sector 78 dipole line, in position B30.R7 (the circuit was ElQA-tested up to 1.6 kV instead of 1.9 kV); a badly insulated quench heater on the circuit RQ4.L8; a weak electrical insulation to coil and/or ground for a quench heater on RQX.R1.

Quench and training

To speed up the commissioning, a new *modus operandi* was adopted: the high current circuits were all commissioned to 3.5 TeV; for the low current circuits, the agreed plan was to commission them up to 5 TeV (for the 600 A circuits) or 7 TeV (120 A and 60 A circuits). Once a circuit was quenching twice, its nominal current was reduced (compatibly with the 3.5 TeV operation). This two-quench criterion resulted in a limitation of current for a number of 600 A and 120 A circuits, for which non-conformity reports were created. These circuits are listed in Table 1, which contains the name of the circuit, the quench currents, the non-conformity number and the nominal current value used in 2008 and in 2009/10.

Some of the circuits of the table were already limited in 2008, but most of them were successfully powered up to 7 TeV equivalent current. To confirm whether real limitations exist and if important detraining is present in some cases, it is necessary, before entering the long shutdown, to power all circuits up to 7 TeV equivalent current. In case of quench, the circuit has to be re-powered, up to a maximum number of quenches (number to be defined by magnet protection experts). If, after this training campaign, the circuit has not reached 7 TeV, then diagnostics have to be carried out to identify the problem; in case of a serious problem, a decision must be taken:

- lowering the nominal current in agreement with the reviewed machine parameters or if there is the possibility of a new optics;
- performing a repair, whenever possible;
- replacing, as a last solution, the superconducting circuit with a warm magnet, as already done at point 8 (RCBCHS5.L8B1 - NC 831927).

Table 1: Circuits with current limitation in 2009/10

Circuit	Quench currents [A]	NC report	I_nom '08/'10 [A]
RCD.A45B1	300, 391	1035252	550 / 400
RCD.A56B2	479, 496	1026728	550 / 450
RCD.A81B1	351, 484	1043522	550 / 450
RQTL11.L2B2	544.85	1020622	550 / 500
RQTL11.R5B1	501, 492	1027448	400 / 450
RQTL11.R5B2	550, 533	1027413	400 / 450
RQTL11.L6B1	353, 292, 340, 350, 384	1026809	300 / 300
RQTL11.L6B2	267, 348, 384, 354, 382	1026747	400 / 300
RQTL8.L7B1	240, 257	1046464	300 / 200
RQTL9.R3B2	359, 400, 396	1046992	200 / 400
RQT13.L5B1	-	1060679	550 / 400
RCBCV5.R5B2	69.4, 76.9	1029792	80 / 72
RCBCH7.R3B1	98, 95	1046994	100 / 80
RCBYH4.R8B1	55.6	1051795	72 / 50
RCBYV5.L4B2	63.3, 65.7, 64.7	1049055	- / 50
RCSSX3.L1	62.9(4 times)	1053719	locked
RCBYHS5.R8B1	quench-back	1063839	72 / 20
RCBYHS4.L5B1	weak magnet	1053709	72 / 50

Splices, shorts and open circuits

There are three circuits in the LHC which were in 2008 condemned due to suspicious connections: RCBCHS5.L8B1 (NC831927, shows high resistance on the cold side and was replaced by warm magnet installed in the vicinity), RCO.A81B2 (NC 955048, current leads and coil resistance too high) and RCOSX3.L1 (NC 948545, cold taps of current lead found open and circuit isolated from ground and from the other circuits).

Other circuits showed, during 2009/10 powering tests, high splice resistance and non-conformities were created:

RQT12.R7B1 - NC 1027412
RQTL10.R7B1 - NC 1026729
RCBCH6.L2B2 - NC 1020424
RCBCV6.L2B1 - NC 1020423
RCBCH7.L2B1 - NC 1084848
RCBCV7.L2B2 - NC 1084849
RCBH31.R7B1 - NC 1017094

The last one of the circuits above was condemned, together with another circuit (RCO.A78B2 - NC 1029807) which quenched three times while ramping up the current from 55 A and it is as well probably affected by a splice problem.

Very important for the circuits where a splice issue was evidenced, it will be to perform dedicated ElQA diagnostics, narrowing (wherever possible) the fault localization to provide extremely useful information to the people in charge of carrying out the repair; also specific transfer functions could be executed to better understand their strange behaviour. Moreover, specific powering cycles (i.e. with modified parameters) could be done.

As already stressed by K.H. Meβ in 2009 [18], the strange behaviour of some other circuits might also hide some real problem, as it is the case of RQT13.L5B1 and RQTF.A45B2: the circuits reached their design current value, but quenched several times at the flat-top. These two circuits might contain a bad splice. For the same reason, before the long shut-down all circuits will have to be as well submitted to a stress test (a long heat run) to the design current value to emphasize weak splices.

QPS and other issues

Some other issues were identified during the 2009/10 campaign, which will have to be addressed possibly before the long shutdown. It is the case of a QPS hardware problem on the circuit RCBXH3.L5 or the limitation in ramp rate of the circuits RQ6.L7B1 and the RSD/F-1/2, or the new protection of the Inner Triplet correctors RCBXH/RCBXV, to be set to limit the cross-powering of the nested horizontal and vertical corrector to 550 A total. All these problems should be possibly addressed before the shutdown to check whether an easy solution can be found or a hardware modification is required.

WHAT ELSE CAN WE TEST WITHOUT BEAM?

Another important matter to be verified is the adaptation of the energy extraction for the main circuits for the operation at 7 TeV: the consequences on the n-QPS will have to be demonstrated.

Other specific tests were required by the QPS responsible: dedicated powering of few 600 A circuits where we might get problems with quench detection settings if going to higher energy (e.g. trim quads, IT correctors) and the test of the n-QPS for IPQ configuration (installation, re-commissioning of the circuit plus specific tests will be needed) and the validation of the earth voltage measurement system for the main circuits.

If not completed before the shutdown, we will have as well to carry on with the validation of the splices inside the individually-powered quadrupoles (in the dispersion suppression region plus stand-alone regions) and individually-powered dipoles.

As a final validation of all circuits, a heat run with the whole machine (excluding Mains) powered to 7 TeV equivalent current plus the Mains to half current, will have to be carried out, followed by the execution (in the same current conditions) of operational cycles, including the squeeze to nominal β^*.

Recently, it has been noticed that the ElQA tests are presently executed with a "reduced" voltage on the RQD/F and the 600 A circuits: the actual value does not take in fact into account the simultaneous powering of circuits routing through the same line. A re-test to higher voltage level (i.e. 480 V instead of 240 V for RQD/F) will be needed before entering the long machine stop, to highlight non-conformities.

The last verification we could carry on without beam concerns the cryogenic system and the LHC vacuum: for the first one, the quench lines between QUI and helium tank in all even points were never tested and important information could come from a stress test; the vacuum group required, on the other side, leak detection investigation before ventilation of the insulation vacuum in all the sectors, to identify weak points to repair.

WHAT CAN WE TEST WITH BEAM?

Before switching off the beams for the shutdown, there is as well a serious of investigation which could be performed. What listed below certainly constitutes a preliminary catalogue, but it is an exemplification of what we could do, to check other machine limitations.

Wire scanner tests could be performed in two setup conditions: with a proton beam at injection, 900 bunches, wire speeds between 1 and 0.3 m/s, to break the wire and test why we had breaking at different conditions in SPS and in LHC in 2010; with an ion beam at injection, 150 nominal bunches, wire speeds of 1-0.2 m/s, to break the wire with ions and see if it agrees with models.

A *quench test*, with 900 bunches at top energy was also suggested, to repeat the test from last year with a quench provoked in 1-5 ms scale instead of 30 ms. It is the only way to provide data about the quench level for the losses in ms timescale.

A problem was recently identified on the *BLMs*, where the change of threshold for high energy may result in a noise-to-signal ratio too high; verification and test of possible improvement will have to be carried out.

To compensate for the loss of one *orbit dipole corrector*, a solution applying real time trims on the others correctors could then be possibly tested.

From the *collimation* point of view, the stability and impedance with closed collimators (at nominal gaps) could be tested, together with combining the betatron and momentum cleaning in IR3.

The *injection and dump* responsible also formulated some hypothesis of tests before the end of beam operation:

- injection of full intensity trains of 288 bunches
- squeezing to 0.5 m beta* and checking the protection hierarchy there
- quench tests with beam at different time scale losses
- deliberate asynchronous dump tests with high intensity and also with 25ns (asynch dump of all MKDs synchronous, but asynchronous to the abort gap or a real pre-trigger with 1 or 2 MKDs being asynchronous to the other MKDs and also synchronous to the abort gap)
- with small intensity beam force a power abort of the dipoles in one octant but not dump the beam and see where it ends up (could be part of a study to install another big TCDQ like absorber in the machine).

TIME ESTIMATE

Summing up the different requests, we could imagine the following timeline for the period preceding the long shutdown:

- 1 week of dedicated tests with beam;
- minimum 1 week for Mains extraction reconfiguration and all kind of dedicated powering tests;
- about 4 days per sector, for a massive ElQA campaign to qualify all circuits to the nominal voltage level and to better identify all non-conformities;
- 2 days of cryogenics verification plus 4 days for vacuum leak test;
- additional 2 days/sector at warm for ElQA investigation.

It is important, for completeness, to remind that once the splices will be consolidated and the machine cooled back to 1.9 K, another massive ElQA campaign will have to be carried out, followed by several weeks of powering tests (the length of which will depend as well by the energy level to attain).

CONCLUSIONS

Before going into the long shutdown, all limits of the machine will have to be highlighted. The main point of the proposed strategy is to try and push all circuits (Mains excluded) to 7 TeV equivalent current, also by performing heat runs and nominal powering cycles. Many special tests will be performed to exclude or cope with anomalies and a massive ElQA campaign will be carried out.

For the present time, the circuit RD2.R8 constitutes the (second) most important problem in the machine, after the splices on the main circuits. A replacement could be envisaged, but tests could also be performed before the shutdown.

Special setups with beam can be as well figured out, and many other systems will have to be tested, even if most of them can be tested at any time, also with a warm machine.

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