OPTIMISATION OF THE POWERING TESTS OF THE LHC SUPERCONDUCTING CIRCUITS

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Abstract

The Large Hadron Collider has (LHC) 1572 superconducting circuits which are distributed along the eight 3.5 km LHC sectors [1]. Time and resources during the commissioning of the LHC technical systems were mostly consumed by the powering tests of each circuit. The tests consisted in carrying out several powering cycles at different current levels for each superconducting circuit. The Hardware Commissioning Coordination was in charge of planning, following up and piloting the execution of the test program. The first powering test campaign was carried out in summer 2007 for sector 7-8 with an expected duration of 12 weeks. The experience gained during these tests was used by the commissioning team for minimising the duration of the following powering campaigns to comply with the stringent LHC project deadlines. Improvements concerned several areas: strategy, procedures, control tools, automatization, and resource allocation led to an average daily test rate increase from 25 to 200 tests per day. This paper describes these improvements and details their impact on the operation during the last months of LHC Hardware Commissioning.

THE COMMISSIONING OF THE LHC SUPERCONDUCTING CIRCUITS

Each one of the 1572 superconducting circuits (sc) forming the LHC collider was commissioned before injecting beam into the accelerator.

The powering tests of the LHC superconducting circuits start as soon as the cryogenic conditions for powering the circuits of each of the eight sectors are met: [2]:

- a temperature or 1.9 K and 4.5 K for the circuits in the arc and the long straight sections respectively;
- the correct liquid helium levels and temperatures in the distribution feeding boxes – DFB, linking the warm part of the circuit to the cold part;
- no condensation on the current leads, etc.

During the cool-down, all the circuits will have gone through different electrical quality assurance tests (ElQA) [3] at several temperature levels. Moreover, before the cryogenic conditions for powering are met, all the corrector circuits in the sector will have gone through their first interlock tests for validating the correct communication between the Quench Protection System, the power converters and the Powering Interlock System.

The LHC superconducting circuit system is divided in 28 powering sub-sectors. With the exception of the AC electrical distribution, each sub-sector is totally independent from the others. From the electrical protection as well as the powering point of view, the LHC can be considered as 28 independent parts. Each of the 8 LHC sectors is subdivided into a maximum of 5 powering sub-sectors: the arc, two matching sections and two inner triplets.

THE LHC SUPERCONDUCTING CIRCUIT TYPES

The superconducting circuits of the LHC have been divided in eight different circuit types (nine with the inner triplet circuit) [1]:

- 13kA Main circuits: main dipole and quadrupole circuits
- Individually powered dipoles (IPD)
- Individually powered quadrupoles (IPQ)
- 600A corrector circuits with external energy extraction (600AEE)
- 600A corrector circuits with energy extraction inside of the converter the so called crow-bar (600Acb)
- 600A corrector circuits without energy extraction (600AnoEE)
- 120A corrector circuits powered from the DFBs or the short straight sections
- 60A closed orbit corrector circuits.

The inner triplet circuits, 8 in the whole machine, containing the nested power converters, are considered as a combination of circuits of different types.

Table 1 gives the inventory all circuits of the LHC by circuit type: 1564 in total.

The circuits of Table 1 are powered via the DFBs; only a few 120A and the 60A are powered directly from current leads attached to the magnets cryostats.

Table 1: LHC sc circuits divided w.r.t. the 8 Sectors

	S12	S23	S34	S45	S56	S67	S78	S81
13KA	3	3	3	3	3	3	3	3
IPD	3	2	2	3	1	0	2	3
IPQ	14	7	6	13	12	5	7	14
600AEE	23	27	28	24	23	27	27	23
600Acb	14	20	20	14	14	20	20	14
600AnoE	16	9	2	9	9	2	9	16
120A	50	37	22	33	33	22	37	50
60A	94	94	94	94	94	94	94	94
TOT	217	199	177	193	189	173	199	217

POWERING TEST PHASES

The powering tests are divided in two phases. The first phase is devoted to those activities meant to prepare and configure all the systems [4]:

- Electrical quality assurance at cold (continuity of instrumentation wires, transfer function measurement, insulation tests up to 1.9 kV)
- Individual system tests of the Quench Protection System at cold (individual discharge of all the quench heater power supplies)
- Interlock tests without current in the magnets for all electrical circuits (PIC1)
- Connection of the DC cables to the power converters and to the current leads
- Cryogenic commissioning of the without current (liquid He levels, condensation, temperature of the current lead ends, lead head heater system, etc.)

The second phase is the proper *powering test phase* where the following tests are carried-out [4]:

- Interlock tests with the magnets connected to the power converter at their minimum operational current, I_min_op, (PIC2 and configuration of the Power converter)
- Powering to nominal (P2N) which includes, per circuits, all test at different current level to qualify the circuits for the operation of the machine.

POWERING TO NOMINAL IN STEPS AT DIFFERENT CURRENT LEVELS

Once all the circuits of the powering sub-sector have successfully passed the preparation phases listed above and the interlock tests with current in the magnets, they go through the different steps of the powering to nominal procedure at different current levels. In general, the current levels are:

- I_min_op
- First Intermediate Current: Injection current
- Second Intermediate Current: 50% of nominal current
- Third Intermediate Current: 70% of nominal current
- Nominal Current

The number of current levels applied for each circuit type is driven by the need of validating the energy extraction and the quench heater performance. Circuits with energy extraction facility and quench heaters will need to go through all the levels, while those protected internally by the power converter will be tested directly at nominal current.

At each current level the circuit will go through different test steps, depending on its type:

- Ramp up to the test current (mono- or bi-polar)
- Verification of the current leads performance
- Forced energy extraction
- Provoked quench
- Simulation of a Fast Power Abort from the powering interlock
- Simulation of a Powering Failure of the converter
- Simulation of a Slow Power Abort from the powering interlock

The aim of these tests is the validation of the protection strategies under the different failure scenarios and the evaluation of the proper behaviour of the magnet chain, the current leads and the power converters during a normal LHC ramp and steady state.

Even for the most complex circuits the tests are not repeated at the different current levels; on contrary, the level at which these tests are carried out has been carefully optimised along the hardware commissioning period in order to minimise number of current cycles, quenches and therefore total commissioning time. Table 2 indicates the number of tests planned for each circuit type together with the total time needed for the commissioning expressed in working days considering two shifts (15 hours per day). The time reported in the table is a total time for the qualification of the circuit including the analysis of the results by the competent experts.

Table 2: Number of test planned per circuit type. Time/ circuit given in day, 15 working-hours/day

	Number of test					Time/ circuit
	I_min op	In1	In2	In3	Nom	
13KA	10	3	2	3	2	10
IPD	9	1	1	-	1	2
IPQ	9	1	2	-	2	1.5
600AEE	7	1	-	2	3	1
600Acb	7	1	-	1	2	1
600AnoE	7	1	-	1	2	0.5
120A	5	1	-	-	3	0.2
60A	-	1	-	-	2	0.2

TIME FOR THE POWERING TESTS

After the DFBs are commissioned, the time needed for carrying out the preparation for the powering tests (i.e. ElQA at cold, QPS individual system tests, PIC1 and connection of the DC cables to the current leads) is 2.5 weeks for the arcs and one week for the matching sections and the triplets [5].

The total time needed for carrying out the powering test steps for all the circuits in one sector depends on the number and types of the circuits: tests in sector 8-1 and 1-2, with two inner triplet regions each, take longer than in sector 6-7 and 3-4 without inner triplets.

THE POWERING TESTS

The powering test of the sc circuits of the LHC started in March 2007 with the sector 7-8 which was not fully completed because of a short to ground of a quadrupole circuit. The sector was consequently warmed up and the magnet replaced. In November 2007 sector 4-5 was partially commissioned and then warmed up to connect the inner triplet magnets to the cooling plant in March 2008. The commissioning of sector 4-5 can be considered as the first full commissioning campaign. The average successful test rate was of 60 tests per working-day, see Figure 1. The full sector including the two matching sections and the arc was commissioned in 7 weeks.

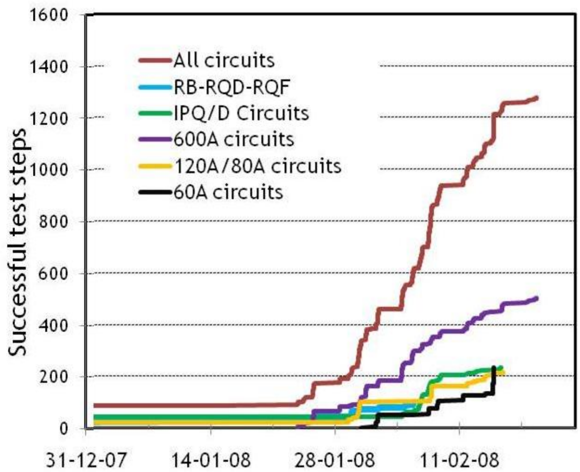

Figure 1: Test rate of the first commissioning of S4-5.

After sector 4-5 campaign a review of the organization and of the procedures was done. The outcome was a set of reduced procedures, improved tools and optimised organisation which had a positive impact on the commissioning of the following sectors.

The full commissioning campaign of all the sectors in parallel started with sector 5-6 in March 2008 and ended on September 19th when an incident in sector 3-4 occurred while the main dipole circuit was ramping to nominal current [6]. By that day, proton beams had circulated already in both LHC beam pipes. A first considerable improvement of the test rate was achieved in summer 2008: up to 110 successful test per working day with peaks of 300 in the last part of the commissioning.

This improvement was for several reasons, most of them linked to a better knowledge of the circuits and their systems but also thanks to a better organisation and a high automation of the commissioning process. Reliable tools have been developed for:

- Execute the tests
- Gather and analysis information resulting from the tests
- Accept or reject the test results by the different system experts and the hardware commissioning coordinators
- Store and visualize the test result and history
- Track online the test progress
- Prepare and optimise the testing schedule

This tools, together with a the experience gathered during the three years of hardware commissioning allowed CERN to celebrate the successful injection of rotating beams into the LHC on the 10th of September 2008.

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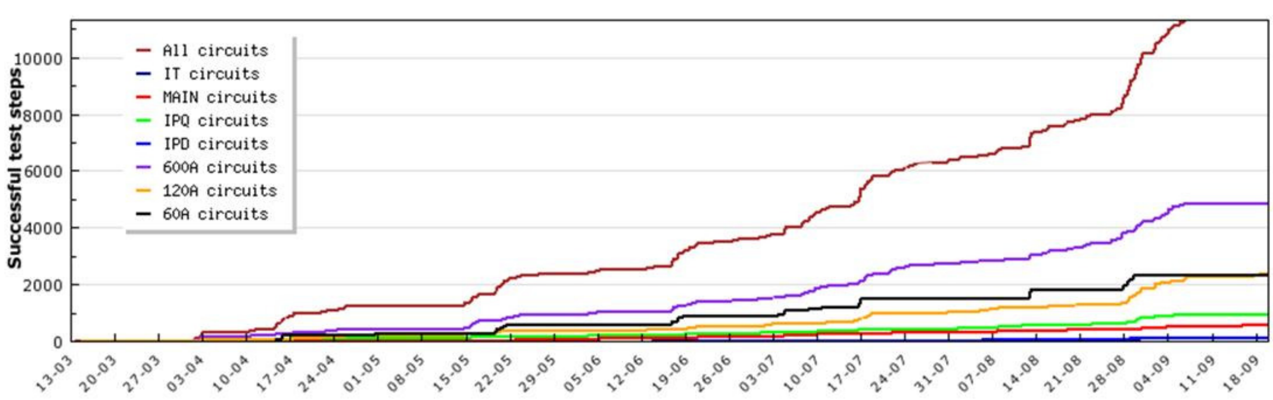

Figure 2: Test step rate during the powering tests of the sc circuit of the LHC in 2008.