

LHC COMMISSIONING AT HIGHER ENERGY

P. Collier, F. Bordry, J. Wenninger, CERN, Geneva, Switzerland

Abstract

The LHC has just come to the end of its first Long Shutdown (LS1) and preparations are underway to prepare for Run 2 data taking at 13 TeV centre of mass energy. After briefly recalling the major work undertaken during the 2-year long LS1, details will be given of the cool-down and hardware commissioning phase where each individual superconducting circuit is individually qualified for operation at nominal current. For the main dipole circuits this phase was completed with a quench training campaign in order to operate reliably at the required field. In parallel to the training campaign a rigorous cold checkout has been used to qualify the machine as an ensemble and to establish the conditions necessary for beam operation. The details of this phase will be given together with associated dry runs and beam injection tests. Finally, the latest news will be presented concerning the beam commissioning of the machine in preparation for first physics operation, which will hopefully begin in June.

INTRODUCTION

Between 2009 and early 2013 the LHC was delivering beam to the experiments almost continuously, with only relatively short end of year technical stops to perform essential maintenance. This mode of operation was triggered by the need for a major shutdown to consolidate the inter-magnet bus-bar splices before operation at nominal energy could be considered [1]. The time required to plan, prepare and organize this long shutdown (LS1) allowed three years of operation of the LHC at an intermediate energy, first at 3.5 TeV, then, in 2012, at 4 TeV.

During this first run a total of 30 fb^{-1} were delivered to the large general purpose experiments, using ~ 1400 bunches spaced by 50 ns to deliver a peak luminosity of over $7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. During this period there were also highly successful runs with Pb^{82+} heavy ion collisions as well as proton-lead operation during the final month.

LS1 lasted almost 26 months, beam-to-beam, and involved a huge amount of activity in the machine tunnel. Most activities were planned, but some were unexpected and others were added later [2]. Some of these are described below.

LHC LONG SHUTDOWN 1

The main priorities in LS1 were to prepare the machine for high-energy operation and to perform maintenance and consolidation to ensure reliable operation through the second long run, i.e. up to the next long shutdown scheduled for 2018. In addition to these main themes there were many additional activities to repair and upgrade individual systems. Major modifications to the control system itself as well as the

operational software and databases were also foreseen. As a result it rapidly became clear that the LHC would be essentially a new machine when it restarted. Careful consideration was given from an early stage into the re-commissioning process and this was built into the overall planning.

Unfortunately only a few of the major planned and unexpected activities can be described here.

Super-Conducting Magnet and Circuit Consolidation (SMACC)

As soon as the machine was warm the SMACC activities could begin. Each interconnect in the machine was opened and the high-current bus-bars measured and inspected. Where necessary the joint was machined or repaired. Shunts were then applied across the joints and the whole junction encased in an insulating box. After suitable QA checks and measurements, the interconnect was re-closed [3]. With ~ 1700 interconnects and 10,170 high current splices this represented a huge workload over the shutdown, especially with an unexpectedly high number of splices (30%) needing to be completely re-made.

In addition to the splice repair a total of 18 cryo-magnets were removed from the machine and replaced by spares. These all had known unconformities: either showing high internal resistance, or having broken quench heaters. In total over 1 million hours were worked in the tunnel on these machine related activities.

Reliable Operation

During the first run of the LHC a problem with radiation-induced failures in electronic equipment was diagnosed and progressive mitigation measures used to keep single-event upsets at a reasonable level. During LS1 major works were undertaken to relocate, or shield electronics in several parts of the machine. The relocation often involved local civil engineering works, followed by major cabling campaigns to relocate the electronic equipment into more favourable locations. Over 100 control and power racks were moved. For the QPS system, which cannot be relocated, new cards were designed having a number of radiation-tolerant features and over 1000 cards in the tunnel were replaced [4].

To be reliable the major systems of the LHC needed maintenance. An example is the cryogenic system where some stations had been running for close to 5 years. A complete overhaul of the warm and cold compressors was undertaken as well as major interventions on the cryogenic lines and valve boxes. In addition, the opportunity was taken to repair several small leaks in the cryogenic feed lines (QRL).

An additional unexpected activity became apparent once the whole system had been warmed up. Several

cryogenic feed-boxes (DFB) were found to have leaks caused by faults in the manufacture of some multi-layer bellows. At cold, helium diffused through cracks in the welds and became trapped between the sheets forming the bellows. On warming up this helium expanded and ruptured the bellows. In some cases the repair involved removing the complete DFB from the tunnel and making the necessary repairs in the workshop.

Cool-Down

As sectors were completed and closed they were leak and pressure tested and minor non-conformities solved before cool-down could begin. The cool-down of the first sector began in May 2014 and the last in October. Over 10,000 tonnes of liquid Nitrogen were needed to pre-cool the whole machine before loading the 130 tonne liquid Helium inventory. The progression for the 8-sectors is shown in Fig. 1.

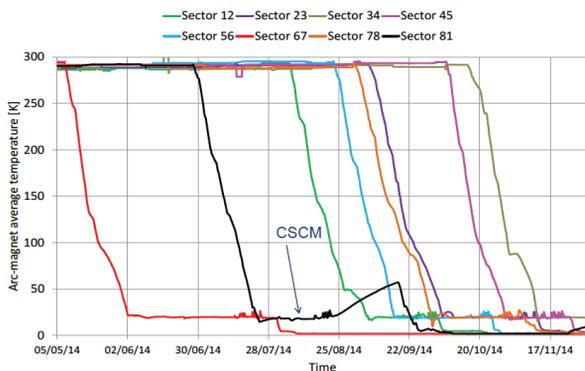


Figure 1: The Progressive cool-down of the LHC over six months.

Copper Stabiliser Continuity Measurement (CSCM)

The CSCM measurement was designed as a final check of the quality of the whole bus-bar chain in each sector. A type-test measurement was performed during the warm up at the beginning of LS1 and the decision was taken to add this as qualifying test of each sector even though it added several weeks to the overall schedule.

The test involved stabilizing the sector at 20 K. At this temperature the bus-bar cables are not superconducting and current in the circuit will flow through the copper stabiliser. To perform the test the power converter was reconfigured to provide up to 12kA and 400V. A voltage pulse was then applied to the complete circuit in order to fire all the magnet protection diodes. At this point all of the magnet coils are shorted out by the diodes and only the bus-bars (and diodes) remain in the circuit. A current pulse could then be applied to the circuit and allowed to decay away with the 100s time constant characteristic of the circuit in normal operation. Figure 2 shows the typical voltage and current applied over the circuit to make the test.

Observation of the voltage evolution across the bus-bar elements then allowed any anomalous resistances to be identified. With the very small stored energy in the circuit in this mode, the circuit connections could be tested up to nominal current with very little risk. All dipole circuits were tested and qualified for operation at 6.5 TeV.

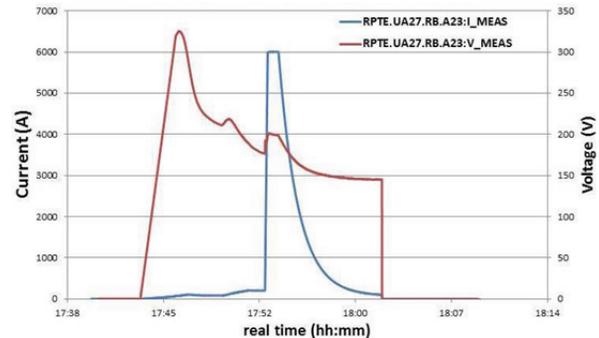


Figure 2: A CSCM Measurement showing the Voltage (Red) and Current (Blue) applied across the dipole circuit in an LHC sector.

HARDWARE COMMISSIONING

Powering Tests

After the CSCM measurement, each sector was cooled down to 1.9 K and prepared for powering. A long preparatory campaign of electrical checks, quench protection system (QPS) commissioning and quench heater circuit testing followed before the circuits in each sector were ready for hardware commissioning.

Hardware commissioning consisted of a series of predefined test steps to check out all aspects of the circuit including its interlocks, protection systems and the energy extraction system. Figure 3 illustrates the steps needed in the case of the main dipole circuits. Only in the last 2 steps was the circuit ramped to nominal operating current.

Each type of circuit had its own set of test steps associated with it. In some cases (such as the 60A arc orbit correctors) the test procedure is rather simple,

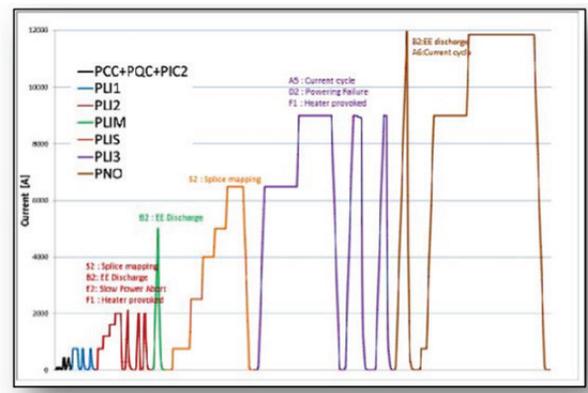


Figure 3: Hardware Commissioning steps for the main dipole circuits.

whereas for others (such as the main circuits) the complexity was high. With close to 1,600 superconducting circuits in the LHC the powering tests represent a large effort over 5 months, with a total of over 17,000 tests steps to be performed, checked and qualified.

Dipole Training Campaign

During the final hardware commissioning tests the dipole circuits were ramped to their nominal current, plus a margin of 100A for operational stability. To reach this current the dipoles required quench training. The training campaign is summarised in Fig. 4.

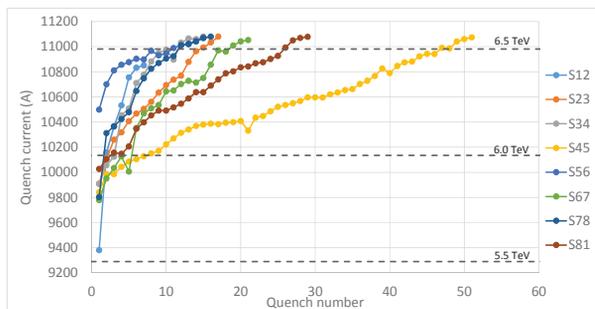


Figure 4: Quench Training of the main dipole circuits.

A large variation was observed in the number of training quenches needed in each sector: one sector (sector 1-2) required only 7, while another (sector 4-5) needed 51. It took a total of 142 training quenches to reach 6.5 TeV with a further 29 to establish the 100A margin. Analysis of this extensive training campaign is now underway in order to draw conclusions for the future.

Short to Ground

During the training of one of the last sectors a short to ground was detected. The fault was traced to a specific magnet and occurred after this magnet quenched. During the quench this short was intermittent, but afterwards settled down to give a consistent 1Ω resistance to ground. A careful series of measurements via the voltage taps of the circuit revealed that the short was in the cold part and was finally localized to the diode box of the magnet C19L4. The diagnosis pointed to a piece of metallic debris resting on the half-moon connectors of the diode and large enough to pass the insulating rings and touch the side of diode box. Such debris has been observed before and was probably produced during the magnet manufacture. Flushing of the circuits with Helium gas before cool-down is a systematic process that is used to try to remove debris from the magnets. Unfortunately, this piece remained inside the magnet and moved during the quench. By bad luck it settled in a new position where it was generating a short circuit.

A detailed analysis identified 3 methods to remove the short:

- Using the flow of helium, either liquid or gas, to try to move the object
- Making a controlled electrical discharge through the short to burn it away
- Warming up part of the sector to physically intervene and remove the debris.

The last option was kept as a last resort, since the warm-up and cool-down would take several weeks. Instead, after a careful risk analysis the electrical discharge method was tried. Using a modified quench heater supply a controlled amount of energy was deposited in the short. This method was successful and the short removed.

Figure 5 summarizes the observations made during the discharge with the curves plotted for the voltage, current, resistance and deposited energy throughout the 11.5 ms of the discharge. Part way through the discharge the resistance can clearly be seen increasing dramatically as the short was removed. A total of 500 J was deposited in the short during this process. Later, electrical quality checks of the circuit confirmed that the short was completely gone.

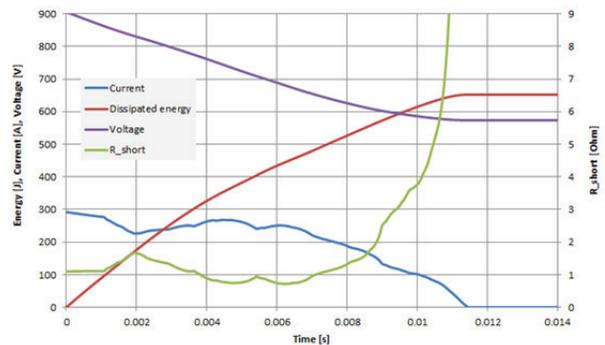


Figure 5: The voltage (Purple), Current (Blue), deposited energy (Red) and resistance to ground (Green) during the controlled burning of the short.

PREPARING FOR BEAM

Dry Runs

Powering tests and individual system tests check out the different machine elements as stand alone entities. However, for the LHC to operate with beam these different systems need to be integrated into operational processes and operated together. For this purpose dry runs were scheduled throughout the later part of LS1 and the power-testing period.

Dry runs involve driving a number of systems through their operational cycles as an ensemble, but also driving them with the ‘operational’ controls, databases and applications. Careful scheduling was therefore needed to ensure that all necessary ingredients were available. As a tool for debugging operational sequences

the dry runs were essential. Typical examples of dry runs include:

- RF synchronization
- Beam interlock system tests
- Experimental handshake
- Beam dump reliability run
- Injection preparation
- Machine modes
- Optimization procedures during stable beams

Sector Test

In the end, the best diagnostic tool is the beam itself. Around 1 month before the scheduled start of beam commissioning, sector tests were planned for both beams. During the sector test, beam was prepared in the injectors, transported through the transfer lines and injected into the LHC. It was then allowed to pass through part of the LHC, before being stopped. This test clearly requires the relevant sectors of the LHC machine to be commissioned at injection energy, but also requires the complete injector chain to be fully operational. On 7th March the first beam was injected at point 8 into the anti-clockwise ring of the LHC and passed through LHCb and one sector of the LHC machine (sector 8-7) before being stopped on collimators in the cleaning section of point 7. Figure 6 shows the trajectories of the beam on the first attempt. Later the beam was allowed to continue through the next sector before being extracted and dumped by the LHC beam dump. Further tests with the clockwise beam were also successfully completed with the beam transported through ALICE and sector 2-3 of the machine.

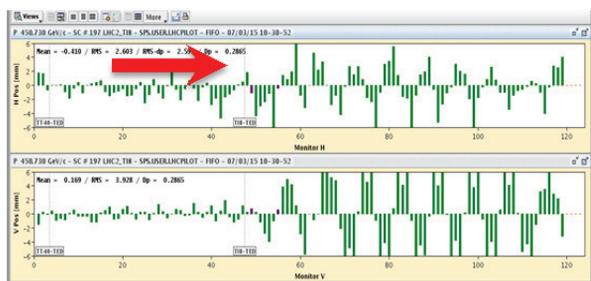


Figure 6: The first beam into the LHC after LS1. The first part is the transfer line, TI 8 from the SPS, followed by the straight section around LHCb and sector 7-8.

The Sector tests lasted 2-days. As well as testing the injection and synchronization systems, the beam was also used to perform initial pickup and corrector magnet polarity checks and even optics and dispersion matching.

Final Machine Checkout

During the Easter weekend final checkout of the machine was made. At this point, for the first time all magnet circuits were cycled together, all vacuum valves

were opened and the Beam Interlock System could be armed to allow injection into the machine.

INITIAL BEAM COMMISSIONING

First beam was injected and threaded on Sunday 5th April. It took about 40 minutes to thread the beam in each direction and within a few hours the beam had been captured by the RF system. At this point a very detailed plan of commissioning steps could be started.

Initially only a single pilot bunch was used (~5x10¹⁰ protons). However, after establishing a good reference orbit, aligning the collimators and commissioning the various machine protection systems, bunches having a nominal intensity (1.2x10¹¹) could be injected. Measurement and correction of the optics and detailed measurements of the decay on the injection plateau mean that the machine is in good shape at injection energy. As an example, Figure 7 shows the beta-beating measured in the machine at injection, before and after correction.

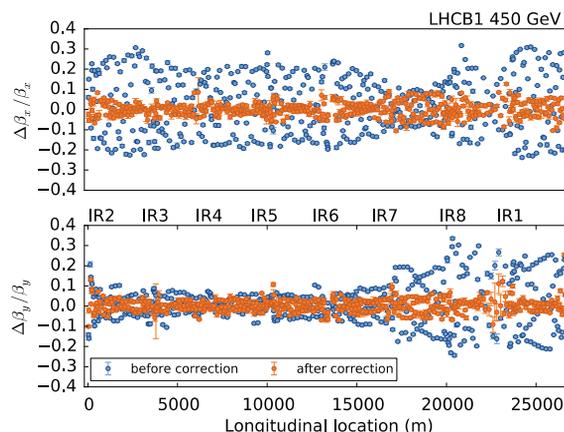


Figure 7: Beta Beating at injection before (Blue) and after (Orange) correction.

Ramping

The first energy ramp took place on 10th April with a single pilot bunch in each beam. Unfortunately the tune excursions were not controlled sufficiently well during snapback and beam 2 was lost. However Beam 1 made it all the way to 6.5 TeV. A second attempt the next day was successful in reaching 6.5 TeV with both beams. These beams were dumped after some minutes by a sharp loss spike on a Beam Loss Monitor, diagnosed as small objects falling into the beam and provoking losses. These, so-called, “UFO” events were also observed during Run 1, however, never with such small beam intensities in single bunches.

Over the next few days several ramps were made and most were terminated by UFOs in exactly the same region. On 2 occasions the beam loss was sufficient to provoke a quench in the downstream dipole (as a result the BLM thresholds in this region were lowered). The problem region has now been pinpointed to the middle

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of a dipole magnet (C15R8). Aperture scans at this point in time showed no restriction.

In order to eliminate the possibility of frozen air, the beam screen in this location was warmed and held for several hours at around 80 K. After this intervention the characteristics of the problem changed completely. UFO events seemed to diminish significantly. However a new aperture scan discovered an obstacle apparently lying on the bottom of the screen. Figure 8 sketches the approximate extent of the obstruction in the centre of the C15R8 dipole. The dashed lines correspond to the optically accessible region (since the dipole is sitting next to a QF quadrupole). It can be seen that the object sticks into the available aperture by a few mm. Clearly, intense studies are underway to characterize the obstruction and determine its stability.

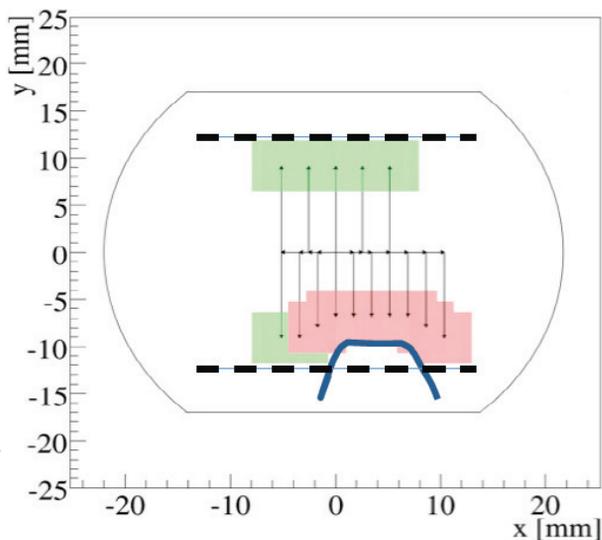


Figure 8: Sketch of the aperture in C15R8 showing the approximate position of the obstruction. The black dashed lines mark the approximate limit of the accessible aperture in this position.

FUTURE PLANNING

The schedule for the commissioning and operation of the LHC in 2015 has been elaborated in detail. In chronological order the steps are:

- Low intensity commissioning of the full operational cycle. 8 weeks is presently scheduled for this.
- First stable beams with a low number of bunches.
- Special physics runs for LHCf and Luminosity calibration (using higher β^*).
- A first scrubbing run using 50 ns bunch trains.

- Intensity ramp-up with 50 ns beams, delivery of $\sim 1\text{fb}^{-1}$ the experiments.
- A second scrubbing using 25 ns bunch trains
- Intensity ramp-up with 25ns bunch trains
- At the end of the year, operation with Pb-Pb collisions.

In spite of the difficulties outlined above, the machine is still more or less on track to deliver first physics beams during June.

CONCLUSIONS

After almost 2 years of shutdown and major repairs, consolidation and upgrades, the LHC is once more operating with beam. The cool-down, preparation and power testing of the circuits represented a major activity spread over several months. Beam commissioning started at the beginning of April and has made steady progress since.

The re-commissioning of the LHC has not been without incident. A short to ground in one magnet diode was successfully solved by a controlled electrical discharge. A more recent problem has appeared with another magnet, where there is apparently an object lodged deep inside one aperture. The impact of this on operation this year is still under intense study.

ACKNOWLEDGMENTS

The authors would like to acknowledge the tremendous efforts of the teams from CERN and collaborating institutes from around the world who worked on the LHC during LS1. In addition, we would like to thank all members of the LHC team that provided the material used to make this paper.

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