STATUS OF LHC COMMISSIONING

J. Wenninger, CERN, Geneva

Abstract

Beam commissioning of the LHC started with injection tests in August 2008, and a circulating beam was obtained in little over 3 days in September 2008. Unfortunately a powering incident in one the eight LHC sectors set an abrupt end to the beam commissioning in 2008. This talk will review the LHC beam commissioning achievements. It will describe the repair the LHC sector affected by the incident and present the measures that have been taken to avoid similar incidents in the future. The commissioning steps foreseen for the 2009 run and towards LHC design performance will be outlined.

MACHINE PREPARATION FOR BEAM

During spring and summer 2008 the eight LHC sectors were cooled down one after the other to 1.9 K. All sectors reached the nominal temperature in the week before the official startup date. During the same period the Hardware Commissioning of the LHC super-conducting magnets and electrical circuits was performed [1]. Approximately 1’700 circuits with around 10’000 mostly super-conducting magnets were commissioned. A total of 11122 test steps were performed. Due to a pronounced retraining of the dipole magnets it was decided to commission the LHC to 5.5 TeV to gain time and avoid a large number of high field quenches. The onset of the retraining was observed between fields equivalent to 6-6.5 TeV.

INJECTION TESTS

Three injection tests were performed in the month preceding the official LHC start-up on Sept. 10th 2008: 3 sectors (1 sector corresponds to 1/8th of the ring) of ring 1 and 2 sectors of ring 2 were probed with beam [2].

The first injection test took place one month before the LHC start-up on the weekend of August 8th. Beam was injected into sector 23 of ring 1 and stopped by the momentum cleaning collimators in point 3. The beam went all the way to point 3 without requiring any threading. The first beam arrived in the LHC ring 2 on the August 22nd. Again the beam crossed sector 78 to point 7 without threading.

During the injection tests dispersion and kick response measurements were used to probe the optics, the quality of the beam position monitors (BPMs) and the polarity of dipole correctors. The BPM performance was impressive, with only $\approx$ 1% of the monitors unavailable [3]. A sensitivity test of beam position monitor (BPM) auto-trigger showed that the BPM system can be run without losing any triggers with an intensity down to about $\sim 1.5 \times 10^9$ protons per bunch which corresponds to 2% of the nominal intensity.

No polarity error of any dipole corrector was detected. The kick response measurement revealed however a number of issues with trim quadrupole polarity conventions that were fixed before the LHC startup on Sept. 10th. The polarities of higher-order correctors (sextupoles and octupoles) were also probed using off-momentum trajectories [4]. Some polarity issues were uncovered. It was demonstrated that the polarity and the strength (at the level of 10%) of higher order corrector circuits - sextpoles, b3 spool pieces, skew sextupoles, Landau octupoles - can easily be measured at injection energy for each individual sector.

The aperture was measured in the injection regions and the arcs and was found to be as expected as shown in Fig. 1. While the vertical aperture was probed during the first injection test, a 12 mm vertical oscillation triggered the first beam induced quench in the LHC with a fas local loss of $\sim 4 \times 10^9$ protons.

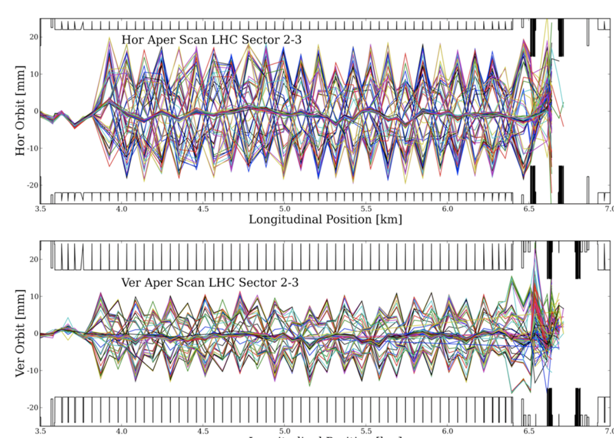

Figure 1: Trajectory envelopes recorded during an aperture scan of sector 23 compared to the expected mechanical aperture.

The injection tests were crucial as a check-out exercise for hardware, software and beam instrumentation. Due to intense preparation the tests took had minimal impact and achieved invaluable results within a minimum of time. More details on the test are described in Ref [2].

BEAM COMMISSIONING

The beam commissioning was carried out with single bunches of $2 - 4 \times 10^9$ protons to minimize the risk of quenches. Contrary to what happened during the injection tests, no quench was induced during this phase. Beam threading started with ring 1 on the morning of Sep. 10th and continued with ring 2 after having established the first turn for beam 1. Within one shift the first turn was achieved for both beams. From that point onwards the commissioning proceeded for beam 2.

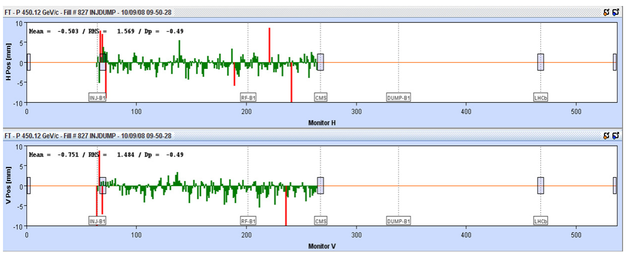

Figure 2: Beam 1 threading to the CMS experiment (IR5). The beam is stopped on a collimator in front of the experiment.

During threading the collimators in each insertion region (IR) were closed wherever possible to stop the beam and give the possibility of optimizing the trajectory steering before sending the beam into next sector(s) as shown in Fig. 2. This strategy proved to be very effective and both beams went through all sectors at the first shot with small losses. The beam loss monitoring (BLM) and beam position monitoring (BPM) systems worked reliably [3]. When the beams reached IR1 and IR5, several shots where intentionally dumped on tertiary collimators upstream of the IP to provide to ATLAS and CMS the first chance to record "beam-induced events" in their detectors. Within a few shots both detectors were timed in on the beam signals and recorded events as shown in Fig. 3.

The main milestones of the beam commissioning: threading and first turn closure for both beams during the morning shift on Sep. 10th; circulating, un-captured beam (300+ turns) in the evening of Sep. 10th; captured beam with good lifetime (first beam circulated for more than 10 minutes) on Sep. 11th; establishment of closed-orbit almost within tolerance in the afternoon of Sep. 12th and with a lifetime of more than 1 hour.

The following activities were performed as part beam commissioning: beta-beat measurements; commissioning of BPM acquisitions and tune measurements with chirp excitation; beam commissioning of RF measurements and of the hardware needed for the beam capture; initial commissioning of beam dump system [6]; initial commissioning of beam instrumentation [3].

The settings of all circuits were obtained from a full model of the main field and fields errors of all magnet types. The beam energy was determined to be $450.5 \pm$ 0.2 GeV/c at injection (nominal value 450 GeV/c). First estimates of the length of the ring 2 agree with the nominal value within 10 mm.

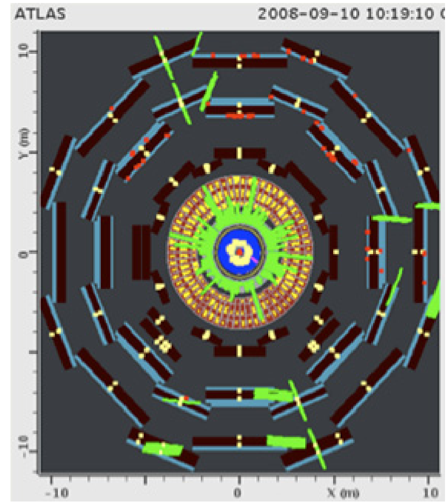

Figure 3: One of the first ATLAS events from beam impact on a collimator (courtesy ATLAS collaboration).

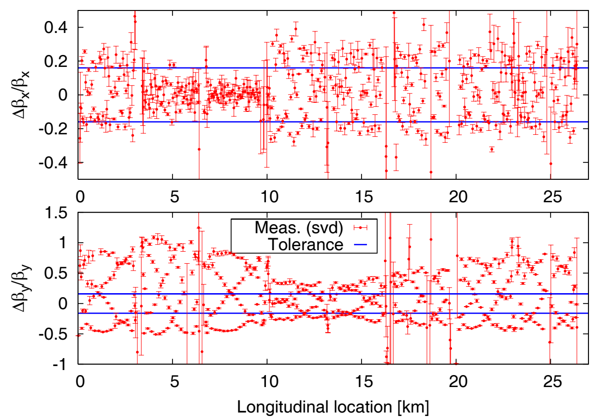

Figure 4: First beta-beat measurement for beam 2 at injection.

The beam 2 optics measurement was performed using turn-by-turn BPM data acquisition during injection [7]. The optics is probed through the phase advance between BPMs as this provides a robust and calibration independent observable. The beta functions are extracted from the phase advances between 3 BPMs. The beta-beating is the relative deviation of the measured betas from the design betas. Fig. 4 compares the measured LHC beam 2 beta-beating to the tolerance of $\pm 20\%$. While the horizontal beta-beating is is not far from tolerances, a large vertical beta-beating of $\sim 90\%$ is observed. The localization of optics correction was obtained from a segment-by segment approach and an iterative correction. The application of the segment-by-segment approach led to the identification of the dominant optics error in beam 2. Evidence from previous hardware tests supported the hypothesis that this error was caused by a cable swapping between the beam 2 and beam 1 trim quadrupole magnets. The comparison of the fit model and the data is presented in Fig. 5

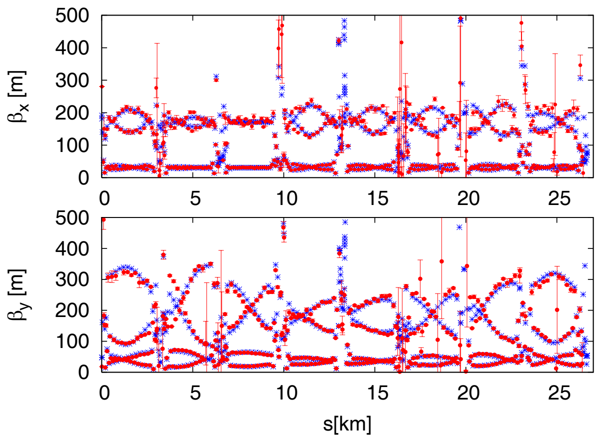

Figure 5: Beta-beat measurement and fit model for beam 2.

SECTOR 34 INCIDENT

Beam commissioning had to be stopped in the evening of Sept. 12th due to a high voltage transformer failure feeding among other major components the cryogenic system of LHC point 8. In the following days the powering tests of the few circuits that had not been fully commissioned for Sept. 10th were resumed. Most of those circuits concerned magnets in sector 34 of the LHC, including the main dipole circuit.

In the morning of Sept. 19th the last commissioning step of the main dipole circuit (154 magnets) of sector 34 was started, a ramp to 9.3 kA which corresponds to a beam energy of 5.5 TeV. During the ramp an electrical fault developed in the powering bus-bar between a dipole and a quadrupole at a current of 8.7 kA. A resistive voltage appeared and increased to 1 V after less than 0.5 s, leading to the power converter trip. The current started to decrease in the circuit and the energy discharge switch opened, inserting dump resistors in the circuit. In this sequence of events, the quench detection, power converter and energy discharge systems behaved as expected. No resistive voltage appeared on the dipoles of the circuit, individually equipped with quench detectors, and the quench of a magnet has been excluded as initial event.

Within the first second, a main electrical arc and multiple smaller secondary arcs developed and punctured the helium enclosure, leading to release of helium into the insulation vacuum of the cryostat. After a few seconds the beam vacuum also degraded. The spring-loaded relief discs on the insulation vacuum enclosure opened when the pressure exceeded atmospheric, thus relieving the helium to the tunnel. They were however unable to maintain the pressure rise below the nominal 0.15 MPa absolute, thus resulting in large pressure forces acting on the vacuum barriers separating neighboring sub-sectors (a sub-sector corresponds to two 107 m long cells) which damaged them as can be seen in Fig. 6. The forces displaced dipoles in the affected zone from their cold internal supports, and knocked the Short Straight Section (SSS) cryostats housing the quadrupoles and vacuum barriers from their external support jacks at tree positions, in some locations breaking the anchors in the concrete floor of the tunnel. The displacement also damaged the connections to the cryogenic distribution line. The main damage zone extends over approximately 700 m.

About 2 tons of helium were rapidly released to the tunnel, producing a cloud which triggered oxygen deficiency hazard detectors and tripped an emergency stop, thus switching off all electrical power from sector 34. Before restoration of electrical power enabled to actuate cryogenic valves, another 4 tons of helium were lost at lower flow rates. The total loss of inventory thus amounts to about 6 tons out of 15 tons initially in the sector.

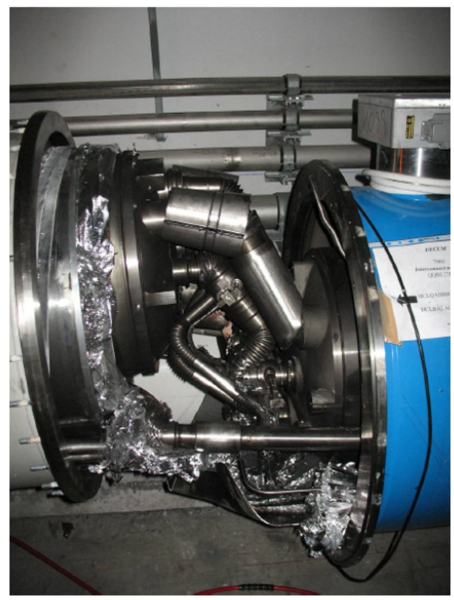

Figure 6: A damage interconnect between a quadrupole and a dipole.

Joint Resistances

A post-mortem analysis of cryogenic temperature data revealed a significant temperature anomaly in sector 34 during a powering step to 7 kA perform a few days before the incident. A steady temperature increase of up to 40 mK visible in Fig. 7 occured in the cryogenic cell of the incident. The excess power in the incident cell corresponds to an unaccounted resistance of around 220 nΩ. Given the location of the primary electrical arc, the most likely hypothesis for the cause of the incident is a problem of the busbar joint. The structure of such a joint is shown in Fig 8. The joints are brazed but not clamped, and the nominal joint resistance is 0.35 nΩ. The incident could be reproduced in simulation assuming a bad electrical and thermal contact of the copper stabilizer at the joint due to lack of solder or poor quality brazing [8].

Following the discovery of another smaller anomaly in sector 12 after inspection of the data of other LHC sec-

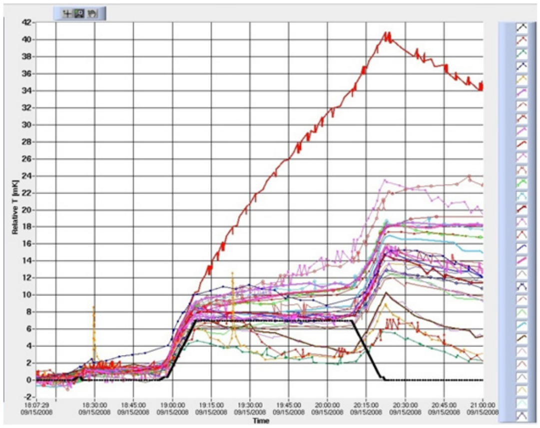

Figure 7: Temperature increase in mK during a powering cycle of sector 34. The current in the dipoles is indicated by the black line and corresponds to a 1 hour operation at 7 kA. An anomalous temperature rise of 40 mK is visible in the cell of the incident.

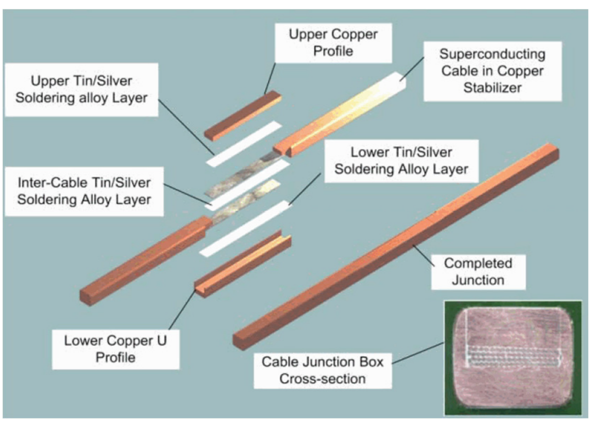

Figure 8: Schematic of the main dipole busbar joint. The superconducting cable is embedded in a Copper stabilizer. At the joint the two busbar ends are inserted with solder into a Copper profile and welded.

tors, controlled calorimetric measurement techniques with a resolution of around 40 nΩ were developed and applied in November and December 2008 to all available sectors. A few suspicious cells were localized in sectors 12 and 67 by calorimetry. Detailed high precision measurements of the busbar and joint resistances between magnets were performed for all suspected cells, but no anomaly was observed. All interconnection resistances were consistent with the expected value of 0.35 nΩ. Measurements of the internal magnet resistances using the quench protection system (QPS) data with massive averaging of the voltage measurements finally allowed to identify 2 dipole magnets with abnormal internal resistances of 47 (sector 67) and 100 nΩ (sector 12) [9]. The two magnets were replaced. Inspection of the 100 nΩ magnet revealed a lack of solder and bad quality brazing of an internal joint.

By the end 2008 approximately 60% of all joints of the main dipole and arc quadrupole circuits had been tested with a resolution varying between less than 1 and 40 nΩ [9]. Joint resistance measurements of the remaining magnets and sectors is the highest priority of the 2009 hardware commissioning. It must however be noted that the remaining joints all belong to sectors that have already been operated at 5.5 TeV.

REPAIR AND CONSOLIDATION

A total of 53 magnets, 39 dipoles and 14 quadrupole SSS have been removed from the tunnel and brought to ground level for cleaning and repair. Most of them were replaced with spare magnets. All magnets have been thoroughly retested before re-installation in the tunnel.

Both arc beam vacuum chambers were contaminated by soot from electrical arcs and chips of multilayer insulation over roughly 80% of their length as can be seen in Fig 9. Contamination by chips of multilayer insulation has been found over long distances away from the position of the original incident. These chips are deposited mostly on the beam screen surface, from where they are removed by in situ cleaning.

Damage to the cryogenic distribution line is limited to mechanical deformations of four jumper connections.

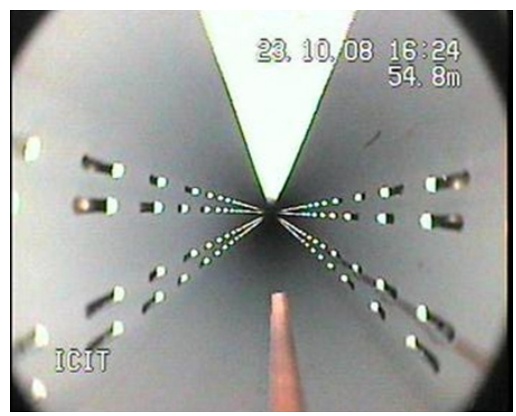

Figure 9: Example of a vacuum chamber beam screen covered with sooth from the incident.

Following the incident and a review of the QPS, a QPS upgrade was launched to protect all bus-bar joints of the arc main dipole and main quadrupole circuits. The required voltage tabs are available, but a large volume of electronics had to be developed. Production of the electronic cards and cabling work is ongoing at the time of writing. The new system will reduce the threshold for protection of the busbar from a 1 V global threshold (covering all joints of a circuit) to 0.3 mV for each interconnection. The new signals and electronics will provide a continuous online monitoring of all joint resistances with a resolution in the nΩ range.

In parallel to the improved protection of the busbar an improved pressure relief system for the insulation vacuum is installed on all cryostats. The four LHC sectors that are at room temperature are equipped with 200 mm diameter relief discs installed in situ on each dipole cryostat. This reduces the maximum pressure in case of helium release by a factor 40. On the four sectors that remain cold, existing diagnostics ports on the SSS are equipped with a spring relief system which reduces the maximum pressure by a factor 10. Those sectors will be equipped with the 200 mm relief valves in a future shutdown. All cryostats in the long straight sections will be equipped with 200 mm pressure relief valves.

Repair and re-commissioning of the LHC magnets and circuits is expected to be finished in September 2009.

LHC RUN 2009/2010

The aims of the first LHC physics run as seen from the LHC experiments depend on the integrated luminosity that can be delivered. With 50-100 pb^{-1} of good data at 5 TeV beam energy many new limits may be set on hypothetical particles. With 200-300 pb^{-1} of good data at 5 TeV the LHC experiments start competing with Tevatron on Higgs masses around 160 GeV/c^2. With 1 fb^{-1} of good data at 5 TeV a discovery of the Higgs for a mass around 160 GeV/c^2 becomes possible.

The present phase 1 four-stage collimation system can only handle a beam intensity corresponding to 10% of the nominal LHC intensity [10]. The flexibility of the LHC bunch filling scheme must be used to achieve the highest possible luminosity while respecting intensity limits set by collimation and possibly machine protection [11]. To reduce the complexity of the beam setup the LHC will initially run without crossing angle which limits the number of bunches to 156. It is expected that during the first run β^* will be limited to 2 m (design 0.55 m), although a reduction to 1 m may be feasible.

First collisions will be provided with 43 and later 156 bunches without crossing angle. The most flexible early running collisions scheme in bunch-train mode is the 50 ns bunch separation mode (twice the nominal separation). With this scheme the number of long-range beam-beam collisions is strongly reduced and the crossing angle can also be reduced. A estimate for the luminosity performance is given in Table 1.

Table 1: Expected LHC Luminosity and Running Conditions During the First Year of Operation for a β^* of 2 m.

No. bunches	**Intensity/bunch** (protons)	**L** ($cm^{-2}s^{-1}$)
43	5×10^{10}	6.9×10^{30}
156	5×10^{10}	2.5×10^{31}
156	1×10^{11}	1.0×10^{32}
720 (50 ns)	5×10^{10}	1.1×10^{32}

A short lead ion run is foreseen in the fall of 2010. At the LHC the differences between ions and protons are rather small and the setup for ions should not pose any problems.

CONCLUSION

The LHC beam commissioning was unfortunately a very short, but incredibly successful time. A beam with good lifetime was circulated after less than 3 days, and all the base beam instrumentation was commissioned. The incident on Sept. 19th caused damage in one LHC sector. It is most likely due to a poor quality busbar joint. The incident revealed a weakness of the busbar and busbar joint protection, and the pressure relief system was not designed for the large mass flows observed during the incident. Repair of the sector and consolidation of the machine, which includes a major upgrade of the quench protection system is ongoing. The new quench protection system will provide online diagnostics of all joint resistances of the main dipoles and quadrupoles of the LHC arc sectors. Beam commissioning is expected to resume in October of 2009.

ACKNOWLEDGEMENTS

The author would like to thank all CERN colleagues for help and information.

REFERENCES

[1] R. Schmidt et al., *Optimization of the powering tests of the LHC superconducting circuits*, these proceedings.

[2] M. Lamont et al., *The LHC injection tests*, these proceedings.

[3] R. Jones et al., *The LHC beam instrumentation*, these proceedings.

[4] F. Zimmermann et al.,*Linear and nonlinear optics checks during LHC injection tests*, these proceedings.

[5] M. Lamont et al., *Operational experience with first circulating beam in the LHC*, these proceedings.

[6] B, Goddard et al., *Initial results from the commissioning of the LHC dump system*, these proceedings.

[7] R. Tomas et al., *First beta-beating measurements in the LHC*, these proceedings.

[8] M. Bajko et al., *Report of the Task Force on the Incident of 19th September 2008 at the LHC*, CERN-LHC-PROJECT-Report-1168.

[9] M. Koratzinos et al., *A method to detect faulty splices in the superconducting magnet system of the LHC*, these proceedings.

[10] R. Assmann et al., *Collimation system*, these proceedings.

[11] R. Schmidt et al., *Protection of the CERN Large Hadron Collider*, New Journal of Physics 8 (2006) 290.