# LHC COMMISSIONING AND FIRST OPERATION

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### (On behalf of the LHC team and international collaborators)

### Abstract

A description is given of the repair of the LHC after the accident of September 2008. The LHC hardware and beam commissioning and initial operation are reviewed both in terms of beam and hardware performance. The implemented machine protection measures and their impact on LHC operation are presented.

### LHC TECHNICAL CHALLENGES

The design of the LHC [1] involved many technical challenges and innovations. Table 1 gives a short list of some of the most notable challenges.

The magnetic system is the highest superconducting field ever used (8.4 Tesla) for an accelerator and in addition employs "double-barrel" magnets where the apertures of both beams are within the same cold mass. The cryogenic system [2] is the largest ever built and operates at 1.9K, and the power converters [3] have a resolution of less than 1ppm, and use a powering circuit for each octant of the machine.

Of constant major concern is the stored energy in the magnets and in the beam. For this reason the protection systems [4], including the collimation system [5], are crucial in the operation of the collider.

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Circumference (km)	26.7	100-150m underground
Number of superconducting Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K) (cryogenics	1.9	Superconducting magnets needed for the high magnetic field
system)		Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field
		1ppm resolution
Beam Intensity (A)	0.5	2.2.10 <sup>-6</sup> loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current
		1MJ melts 1.5kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

Table1: Table of Technical Challenges of LHC.

**ACCIDENT OF SEPTEMBER 19, 2008** 

The scheduled start-up with beam on September 10, 2008 could not have gone better. Both beams made a full machine turn within hours and one beam was captured by the RF system. Following this impressive beginning, a technical problem arose with an electrical transformer which necessitated stopping commissioning for several days. During this stop it was decided to test the last octant (sector 34) up to 9.3kA, the dipole current required for operation at 5TeV per beam. At 8.7kA a resistive zone

hnical
There was an absence of solder on the offending magnet interconnect giving a contact resistance of 220nΩ (design ~1nΩ)
There was poor electrical contact between the sc cable and the copper stabilizing bus-bar
The fault detection of the interconnect was not sensitive enough
The pressure relief ports were under-dimensioned

The pressure relief ports were under-dimensioned for an accident of this magnitude
The anchorage of the magnets to the tunnel floor

developed in the dipole bus bar magnet interconnects.

This led to thermal runaway in the interconnect followed

by meltdown and the development of an electrical arc,

initially across the interconnect and later puncturing the

helium enclosure. The release of the helium caused a

pressure wave over a region of more than 400 metres and

damage to magnets, interconnects and pollution of the

An inquiry by specialists [6] indicated several causes of

ultra-high vacuum system.

the substantial damage to the machine:

• The anchorage of the magnets to the tunnel floor was inadequate.

Figure 1 shows the first page of a three page fault tree describing in detail the evolution of events immediately following the thermal runaway.



Figure 1: Fault Tree following Investigation.

# THE REPAIR

Following the initial investigation of the resulting damage, a crash programme was set up to deal with the repair and consolidation of the LHC. The teams included many CERN partners, collaborators, detector people as well as the accelerator sector. The task was enormous and required not only repairing the damaged components but equally importantly re-engineering many elements so that such an accident would always be avoided in the future.

Figure 2 shows a schematic of the main elements of the repair in the damaged part of the tunnel. A total of 39 dipole magnets (marked 2 in diagram) were required to be

01 Circular Colliders A01 Hadron Colliders replaced. This of course used up all available spares. In addition 14 quadrupole magnets needed to be replaced (1) and a total of 54 damaged magnet interconnects needed full repair (3) with around 150 extra (3) needing partial repair. More than 4km of ultra high vacuum beam tube (4) required removal of pieces of super-insulation and black soot followed by careful cleaning [7]. A new longitudinal restraining system (5) was designed and installed on 50 quadrupole magnets. All existing flanges on the magnets were equipped with additional pressure relief ports (typically 10cm diameter) and 20 cm flanges were cut on dipoles and equipped with double size pressure relief ports. In total 900 helium pressure relief ports were added (6).



Figure 2: Schematic of the main elements of the repair.

A major task was the upgrade [8] of the magnet protection system which had proved too insensitive to fully protect the interconnect splices. The new design is now 3000 times more sensitive than the older system and involved 6500 new detectors (7) and the installation of more than 250km of cable. A major added advantage of the new magnet protection system was that it gives the possibility of measuring [9], to sub n $\Omega$  precision, the resistance of all inter-magnet splices in the machine (see Figure 3 for results).



Figure 3: Measurements of the resistance of the sc intermagnet splice resistances (white lines are the calculated resistances of the splices).

## THE COPPER STABILIZER BUS-BARS

The completed inter-magnet bus-bar splice is designed for two separate functions. Firstly, at sc temperatures, to provide perfect electrical contact between the joined sc cable braids. And secondly, at non sc temperatures (in the event of a quench for example) to ensure electrical continuity across the copper sheath. Hence in the event of a quench and the sc cable has a finite resistance, the copper sheath "shunts" the current away from the sc cable while the stored energy is being extracted from the magnet. In this way the sc cable is protected in case of a quench by the large cross-section of the copper stabilizer.



Figure 4: Exploded Diagram of an inter-magnet bus-bar.

The procedure for producing an inter-magnet bus-bar is depicted in Figure 4. The solder has two important functions, firstly to ensure good electrical contact between the two sc cable braids and secondly to ensure electrical continuity between the 2 copper profiles and the left copper sheath (bus-bar), and the right copper sheath. A little thought should indicate that if there is not electrical continuity across the copper stabilizer then the decaying current following a quench will flow through the sc cable which is no longer superconducting and possibly cause thermal runaway.

The quality of a splice is therefore determined by the resistance across the splice measured both at superconducting temperatures and at non-sc temperatures.

Figure 5 shows a photograph of a completed busbar as installed in the LHC.

The enhanced quality assurance introduced during the repair of sector 3-4 revealed new concerns about the copper bus bar in which the superconductor is embedded.

Tests demonstrated that the soldering process can cause discontinuities in the copper part of the busbars and produce voids which prevent contact between the superconducting cable and the copper stabilizer.

Consequently, in 2009, a campaign was started to measure the splice resistance [9] at room temperature. The "in-situ" measurement technique had a limited precision corresponding to about a factor of three higher than the resistance of a perfect splice. Consequently this technique could only be used to identify "outliers" which

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had a significant fault. On identification of outliers a much more precise measurement (which involved the overhead of opening the interconnect) could be performed. In this way all significant outliers were identified and repaired. However the limited precision of the "in-situ" measurement implied that some splices may have resistances significantly above the optimum. Calculations, simulations and experimentation revealed that the maximum current that can flow in the interconnects without causing thermal runaway was less that the currents needed for maximum beam energy. Consequently it was decided to operate LHC (for a limited period) at a safe energy compatible with the existing situation of the already installed splices.

The decision was taken to operate for data taking at 3.5TeV per beam until the end of 2011 and then in a shutdown in 2012 to repair and consolidate the splices [10] in such a way that they would be safe for maximum LHC energy and for the lifetime of the machine.



Figure 5: Bus-bar as installed.

#### FIRST BEAM IN NOVEMBER 2009

Following the repair and the hardware commissioning in 2009, there was a time slot of 26 days remaining before the end of the year. It was decided to use this time to operate with beam at a maximum dipole current of 2000A which is equivalent to 1.18TeV per beam.

During this short test period, beams were injected in both rings, stable beams were performed at 450GeV and beams were accelerated to1.18TeV per beam where a limited amount of physics data taking was performed (see Figure 6 which gives the highlights of this period).

# FIRST 7TEV COLLISIONS IN MARCH 2010

A special media day was organised for March 30, 2010 when the first collisions at 7TeV centre of mass energy was planned. Collisions were optimistically planned to occur at 09:17 precisely! In reality the first two attempts resulted in beam losses for minor technical reasons. On the third attempt at around 13:00 the beams were successfully brought into collision [11] to much applause and cheering. Figure 7 shows the first (and second) physics run at the new record collision energy.

Date	Day	Achieved
Nov 20	1	Each beam circulating. Key beam instrumentation working.
Nov 23	4	First collisions at 450 GeV. First ramp (reached 560 GeV).
Nov 26	7	Magnetic cycling established (reproducibility).
Nov 27	8	Energy matching.
Nov 29	10	Ramp to 1.18 TeV.
Nov 30	11	Experiment solenoids on.
Dec 04	15	Aperture measurement campaign finished. LHCb and ALICE dipoles on.
Dec 05	16	Machine protection (Injection, Beam dump, Collimators) ready for safe operation with pilots.
Dec 06	17	First collisions with STABLE BEAMS, 4 on 4 pilots at 450 GeV, rates around 1Hz.
Dec 08	19	Ramp colliding bunches to 1.18 TeV
Dec 11	22	Collisions with STABLE BEAMS, 4 on 4 at 450 GeV, > 10 <sup>10</sup> per bunch, rates around 10Hz.
Dec 13	24	Ramp 2 bunches per beam to 1.18 TeV. Collisions for 90mins.
Dec 14	25	Collisions with STABLE BEAMS, 16 on 16 at 450 GeV, > 10 <sup>10</sup> per bunch, rates around 50Hz.
Dec 16	27	Ramp 4 on 4 to 1.18 TeV. Squeeze to 7 m.

Figure 6: Highlights of First 26 days of LHC operation with beam in 2009.



Figure 7: First Physics Runs at 7TeV cm (blue/red plot is intensity of: beam 1/2 resp; black is the beam energy).

## **PROGRESS IN APRIL AND MAY 2010**

During the months of April and May, operation has been split between machine studies to increase the luminosity and physics data taking. The luminosity increase has been concentrated on increasing the current per bunch, the number of bunches and reducing the  $\beta^*$  in the collision points. The rate of progress has been impressive, nevertheless before each step is taken in increasing the intensity and hence the stored beam energy, all machine protection systems are brought up to the necessary level.

The LHC machine protection system [4] is probably one of the most intricate accelerator systems ever operated. It relies on very stringent control of the optics of the machine, both locally and globally. For all protection devices there are closed orbit constraints as well as  $\beta$ value constraints. Hence, any effects which are intensity dependent (e.g. closed orbit measurement,  $\beta^*$ measurement...) complicate the procedure for finalizing the protection.

The details of the machine protection system are presented elsewhere in this conference [4].

The collimation system [5] is part of the machine protection system and the collimators must intercept almost the totality of any beam losses if they are to protect the rest of the machine. The hierarchy of the collimation system (primary, secondary, and tertiary) must be respected. This implies a stringent control of the  $\beta$  functions and the closed orbits at the collimators at all beam energies and throughout the "squeeze" of the low  $\beta$  insertions. The  $\beta$  functions are measured and corrected [12] and the orbits are subjected to a feedback control with threshold limits. There is a watch-dog monitoring the orbit deviations at the locations of the collimators and if the limits are violated, the beam is dumped. A similar system is employed at the location of the beam dump extraction kicker. The tolerances set on the  $\beta$  "beating" is around 20% and Figure 8 shows measurements made at beam energies between 1.5 and 3.5TeV.



Figure 8: Measurement of the  $\beta$  beating at different energies.

In order to measure the cleaning efficiency of the collimation system, "loss maps" are made by provoking beam losses around the circumference. When the collimators are well set up and the hierarchy of losses is correct, the vast majority of all losses should be localised at the collimator. Figure 9 shows one such plot where it can be seen that the ratio between the losses at the collimators and the worst cold location is a factor of 10,000. It has been found that the settings of the collimators remain constant [13] for periods of at least weeks.



Figure 9: Loss Maps for Collimation.

From a technical point of view, the very fast progress being made so far in commissioning the LHC is due to many factors. To mention just a few;

- The excellent performance of the diagnostics and feedback systems [14];
- The quality of the optics settings stemming from the quality of the magnetic fields, the magnetic modelling and the optics modelling [15], [16], [17]. This has allowed fast changes to new conditions with high degrees of confidence;
- The robust applications software which been well tested in the other CERN accelerators;
- And last but certainly not least, the reliability of all the technical components (e.g. the RF system [18]) of the LHC as well as the injectors.

There are numerous examples of the high quality of the diagnostics and its implementation into the controls applications. Figure 10 shows one such example. In order to measure the chromaticity during the energy ramp, the beam momentum is modulated by varying the RF frequency and the transverse tunes are measured by a phase lock loop.



Figure 10: Tune and Chromaticity Measurements, (the upper blue plot shows the modulation of the tune and from the peak to peak of the modulation the chromaticity is calculated and shown in the lower red plot).

Another example is shown in Figure 11, which shows the operation of orbit feedback during the energy ramp. The three plots show the mean, rms orbit distortion and the momentum deviation. The maximum rms orbit change during the ramp is 0.08mm.



Figure 11: Orbit Feedback in Operation.

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## **BEAM OPERATION AT 7TEV CM**

As previously stated LHC has been operating in shared mode between beam commissioning and physics data taking during the months of April and May. The peak luminosity has been increased by almost 2 orders of magnitude during this period. However there are still another few orders of magnitude to be increased before the goal for the end of 2010 is reached  $(2x10^{32} \text{ cm}^{-2}\text{s}^{-1})$ 



Figure 12: Integrated Luminosity delivered to the experiments during first 2 months of shared operation between commissioning and physics data taking.

## PLANS FOR THE FUTURE

The present goals for the LHC, as set by the experimenters are for an integrated luminosity (with protons) of around 1fb-1 by the end of 2010. In addition there will be 2 periods of operation with colliding lead ions, each for about one month. The ion running periods are foreseen towards the end of 2010 and 2011.

In 2012 LHC will be stopped for a long shutdown of duration of about one year in order to complete the consolidation of the intermagnet connectors. Several other consolidation programmes are foreseen during this shutdown both for the LHC and the injectors. Following this shutdown the goal is to operate close to 7TeV per beam with high intensity beams.

## ACKNOWLEDGEMENTS

This paper summarizes the work carried out by hundreds if not thousands of scientists, engineers and technicians both employed by CERN and very importantly by the many institutes that collaborate with CERN. It is a great personal pleasure to acknowledge the incredible contributions and dedication of such a wonderful team.

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