STATUS OF THE LHC AT CERN

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Abstract

For the LHC to provide particle physics with proton-proton collisions at the centre of mass energy of 14 TeV with a luminosity of 10^{34} cm^{-2}s^{-1}, the machine will operate with high-field dipole magnets using NbTi superconductors cooled to below the lambda point of helium. The construction, installation and commissioning follows a decade of intensive R&D and technical validation of major collider sub-systems. This paper will introduce the required LHC performance and discuss the status of the main subsystems. The systems for safe operation in presence of the unprecedented quantity of energy stored in both magnets and beams will be presented. A brief outlook to operation will be given.

INTRODUCTION

Addressing fundamental questions in particle physics requires colliding two proton beams of 7 TeV/c momentum in the 27 km long LEP tunnel with an unprecedented luminosity of 10^{34} cm^{-2}s^{-1}. A magnetic field of 8.33 Tesla is necessary to achieve the required deflection of 7 TeV/c protons that can only be generated with superconducting magnets. The machine is also designed for collisions of heavy ions (for example lead) at very high centre of mass energies. The LHC accelerator has been under preparation since the beginning of the eighties. Beam operation shall start in 2007. More details on the LHC are given in [1] and [2].

LUMINOSITY AND BEAM CURRENT

The luminosity L increases with the number of protons N in each bunch, with the number of bunches nb, with the revolution frequency f, and decreases with the beam size σ_x and σ_y at the collision points (assuming head-on collisions):

$$L = \frac{N^2 \cdot f \cdot nb}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y}$$

The most relevant parameters for the LHC are summarised in Table 1. In order to achieve the required luminosity of 10^{34} cm^{-2}s^{-1} with the nominal bunch intensity of $1.1 \cdot 10^{11}$, each beam will have 2808 bunches. Beams with high currents are accelerated to 7 TeV. The energy stored in each beam is 362 MJ. The energy of 10 GJ stored in the magnets is very high. For comparison, about 600 kJ are sufficient to heat and melt 1 kg of copper. Figure 1 compares the energy stored in LHC beam and magnets with the beam energy for other machines. A small fraction of the beam energy released into equipment could lead to damage, and a tiny fraction could quench a superconducting magnet.

Energy at collision	7	TeV
Energy at injection	0.45	TeV
Circumference	26658	m
Dipole field at 7 TeV	8.33	T
Luminosity	10^{34}	cm^{-2}s^{-1}
Protons per bunch	$1.15 \cdot 10^{11}$	
Number of bunches / beam	2808	
Nominal bunch spacing	25	ns
Beam size at IP / 7 TeV	15.9	μm
Total crossing angle	300	μrad
Typical beam size in arcs (rms) / 7 TeV	300	μm
Arc magnet coil inner diameter	56	mm
Distance between beams (arc)	194	mm
Stored energy per beam / 7 TeV	362	MJ
Stored energy in magnets / 7 TeV	10	GJ

Table I: LHC main parameters

LHC OVERVIEW

Beams for the LHC are prepared and accelerated by existing particle sources and pre-accelerators [3]. The injector complex includes Linacs, Booster, LEIR (Low Energy Ion Ring) as an ion accumulator, CPS and the SPS. The beams will be injected from the SPS into the LHC at 450 GeV/c, accelerated to 7 TeV/c, and then collide for many hours.

The pre-accelerators are operational and the modifications required to achieve the LHC beam parameters are essentially finished. During autumn 2004 beam has been extracted from the SPS and transported to the end on SPS-LHC transfer line with a length of 2.6 km.

The LHC has an eight-fold symmetry with eight arc sections, and eight straight sections for experiments and systems for machine operation (Figure 2). Two counter-rotating proton beams will circulate in separate beam pipes installed in the twin-aperture magnets and cross over at four points.

There will be four experimental insertions, for the main experiments ATLAS, CMS, ALICE and LHCb and one small experiment, TOTEM. The injection elements are installed in the insertions for ALICE and LHCb.

The other insertions are dedicated to machine operation, two for beam cleaning, one for the beam dumping systems, and one for RF and beam instrumentation.

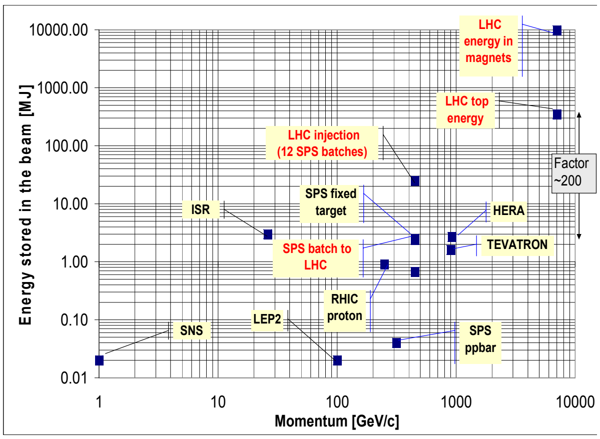

Figure 1. Energy stored in LHC beams and magnets compared with other accelerators

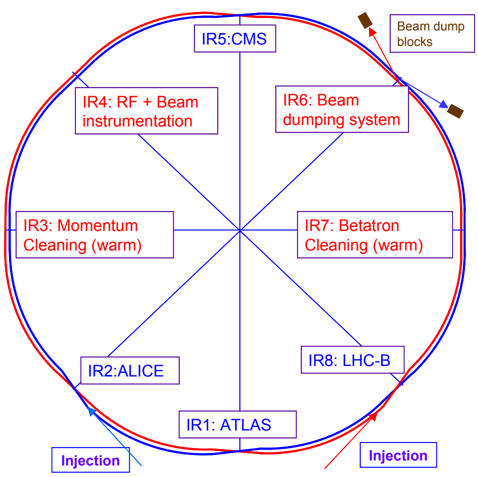

Figure 2: LHC layout

LHC MAIN SYSTEMS

For the regular arc, 1232 main dipole and 392 main quadrupoles are required [4]. About 150 additional main superconducting dipoles and quadrupoles will be installed in the long straight sections. Further, several thousand smaller superconducting magnets are required for beam steering, chromaticity compensation and correction of multipole field errors. About 140 normal conducting magnets will be installed in the LHC ring, mainly in the cleaning insertions. More than 600 normal conducting magnets are required for the SPS-LHC transfer lines, the majority is already installed.

The cryogenics system includes cryoplants at the surface and a 26 km long cryogenic distribution line in the tunnel for supply and recovery of helium [5]. Four vacuum systems are required: one for each beam, one insulation vacuum system for the magnets, and one insulation vacuum for the cryogenic distribution line.

The status of the equipment production is updated on dashboards of the LHC homepage [6]. Niobium-titanium cable production for the dipole magnets is finished. More than 90 % of all dipole magnets have been delivered to CERN. For other magnets, the advancement in the production is similar. The installation of the magnets is in full swing. More than 400 magnets have been installed in the tunnel. Most parts of the cryogenics system have been installed, and a large fraction has been commissioned. The installation of the cryogenics distribution line will finish soon.

To install all components in the 27 km long tunnel is time consuming. As an example, 1600 magnets need to be transported inside the tunnel from one point to their final location, with a vehicle that runs at 3 km/h.

HARDWARE COMMISSIONING

The unprecedented complexity of the LHC powering system includes 1700 magnet electrical circuits with their power converters (60 A to 13000 A). For safe operation the quench protection and powering interlock systems are required. In total, there are more than 10000 electronics crates for operation and protection.

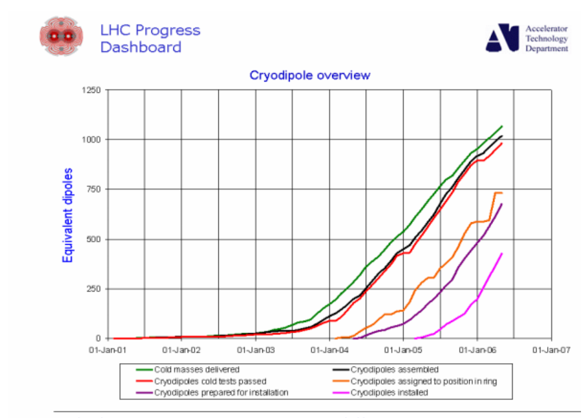

Figure 3: LHC dashboard - progress of construction and installation of cryodipole magnets

The commissioning of all technical systems that do not require beam has been carefully planned and started recently. Power converters are commissioning on short circuits, including a 24 h endurance test with 81 power converters providing a current of 156 kA and a dissipated power of 1.2 MW (Fig.4).

Commissioning of the cryoplants is close to completion. Commissioning of the tunnel cryogenics started with the cool-down of a stretch of the QRL (Fig.5).

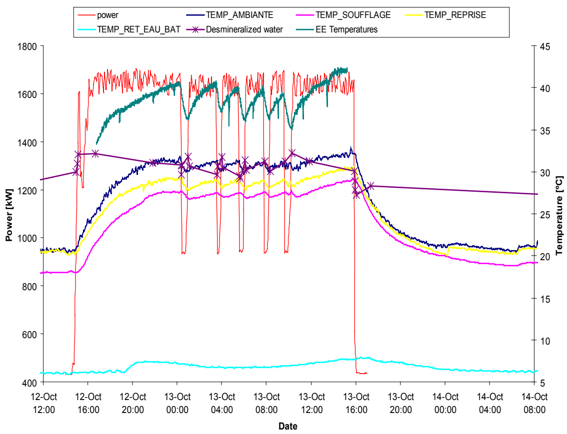

Figure 4: Power consumption during short circuit tests

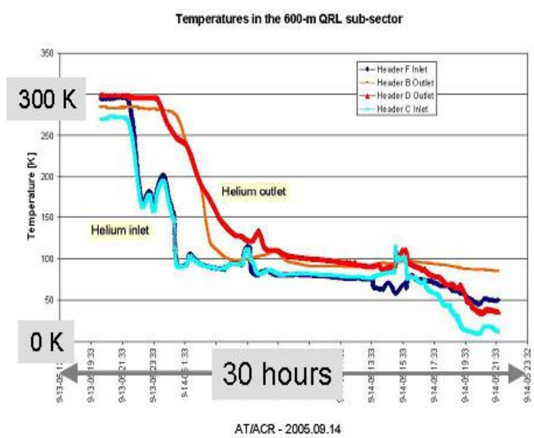

Figure 5: Cooling down of a 600 m long section of the cryogenic distribution line

MACHINE PROTECTION

BEAM LOSSES INTO MATERIAL

Very small beam losses into are sufficient to quench a superconducting magnets. Quench recovery to re-establish the conditions for beam operation will take several hours. For large beam impact the material could be damaged, leading to long and costly repairs. For example, the exchange of one superconducting magnet would take about 5 weeks.

In order to verify the damage calculations, an experiment has been performed with the 450 GeV proton beam extracted from the SPS, with intensities between $2{\cdot}10^{12}$ and $8{\cdot}10^{12}$ (0.1 % of the beam energy at LHC for 7 TeV). The beam was deflected into a 30 cm long target consisting of a stack of metal plates. The expected beam induced damage level from simulation programs was compared with the results from an experiment [7]. The result for a copper plate is shown in Figure 6: the beam with maximum intensity clearly damaged the plate. Damage is also visible for an intensity of $6{\cdot}10^{12}$, for lower intensity no damage was observed. The good agreement between simulations and experimental results suggest that calculations of the damage level are realistic.

PHASES OF PROTECTION

Operation of the LHC will be strongly constrained due to the risks from the large stored energy in the magnet system and in the beams. Three phases are considered:

- Beam transfer from SPS to LHC. The energy of a batch from SPS to LHC is 2.4 MJ.
- With circulating beams, both, the status of the hardware and beam parameters are monitored. A beam dump request is issued when a hardware failure is detected that could compromise beam operation, or if the beam becomes unstable and particle losses are observed. The energy of the LHC beam is between ~MJ (injection) up to 362 MJ (7 TeV).

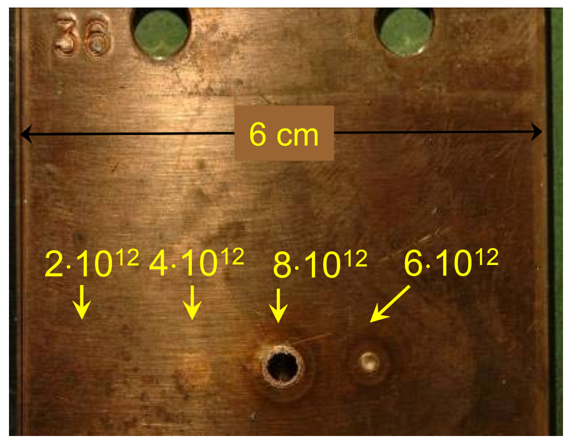

Figure 6: Controlled damage of a stack of metal plates with the SPS 450 GeV beam

- Extraction of the circulating beam into the beam dump blocks. This is always required, at the end of a fill, and in case of emergency. The beam dump block is the only component that can stand a loss of the full beam.

Before transferring beam from the SPS to LHC, the interlock system verifies that all critical parameters are inside a predefined window: beam position in SPS, magnet currents in SPS and in transfer line, position of movable elements and beam absorbers. The LHC must be ready to accept beam. If high intensity beam is transferred, some beam must already circulate in LHC. The interlock system is required for CNGS high intensity beam operation in 2006. This allows to get experience with such critical system for LHC.

With circulating beam in LHC, the beam dumping system must always be ready to safely extract the beams. This requires that orbit excursions in the beam dump insertion are below 3 mm, and magnet currents must be within tight tolerance. If these parameters change, the beams are extracted before the conditions are violated.

The status of the hardware and the circulating beams is monitored by a large number of systems:

- Quench Detection System
- Power converter monitoring
- Fast magnet current change monitors for normal conducting magnets (development with DESY [8])
- Temperature monitoring of normal conducting magnets
- Beam loss monitors at collimators and other aperture limitations [9]
- Beam loss monitors in the arcs [9]
- Beam position (change) monitors
- Fast beam current decay (“lifetime”) monitors

Several other systems can request a beam dump: personnel access, RF, vacuum, screens, experiments, etc. All beam dump requests is routed to the beam dumping system via the beam interlock system [10].

BEAM DUMPING SYSTEM

The only element in the LHC that can absorb the full energy of the 7 TeV beam without being damaged is the beam dump block [11]. At the end of a physics fill or in case of failure the beams are extracted into this block by fast kicker magnets. The extracted beam is further deflected by septum magnets towards the beam dump block. The beam size increases in the 700 m long extraction line. In addition, the beam is blown up by two additional sets of kicker magnets deflecting the beam in horizontal and vertical direction. The beam dump block has a graphite core and a concrete shielding. For nominal beam parameters, the maximum temperature in the beam dump block is expected to be in the order of 700 ^{0}C.

In the first phase only part of the dilution kickers will be installed. A second installation campaign completing the system is planned before the LHC will reach nominal intensity.

BEAM CLEANING

To avoid quenching a magnet, beam losses must be kept below the quench level. At injection energy, the magnet would quench after an instantaneous loss of about $5 \cdot 10^9$ protons, at top energy of only about $5 \cdot 10^6$ protons.

Collimators in the beam cleaning system are blocks of solid materials that should capture all particles with large amplitudes, to prevent particles losses around the accelerator, in particular in the superconducting magnets [12]. Below a lifetime of about 12 min, the heat load on the collimators would become unacceptable and the beams must be dumped.

The LHC will be the first accelerator requiring collimators to define the mechanical aperture throughout the entire cycle. For efficient beam cleaning, the collimators are adjusted to a position of 5-9 σ from the beam axis. For operating at 7 TeV with nominal beam parameters, more than 99.98 % of the protons in the beam halo should be captured in the cleaning insertions to minimise protons impacting on the cold magnets [12].

In case of equipment failures, collimators will be the first devices to intercept the beam and must absorb part of the energy until the beams are extracted. For the LHC start-up, most collimators will have graphite jaws. Graphite collimators are very robust, and in case of beam impact not easily damaged.

There are a large number of collimators of different types, for collimation and protection. The collimators are currently in fabrication, and the first completed units were delivered to CERN and installed in the tunnel.

OUTLOOK TO OPERATION

The experiments ATLAS and CMS expect proton collisions at the highest energy (7 TeV) with the nominal luminosity 10^{34} cm^{-2}s^{-1}. They will also take data when the LHC is operating to provide ion collisions [13].

LHCb is conceived for B physics with a luminosity of $\sim 5 \cdot 10^{32}$ cm^{-2}s^{-1}. ALICE is an experiment to observe ion collisions at various energies. The nominal luminosity is 10^{27} cm^{-2}s^{-1}. ALICE will also use proton collisions, with a luminosity of 10^{30} cm^{-2}s^{-1}. TOTEM will use proton collisions at various energies.

If the Higgs particle as predicted by the Standard Model decays into four leptons and its mass is in the range of some hundreds GeV, it can be discovered with an integrated luminosity ~4 fb^{-1}. Some super-symmetric particles can be discovered at more modest integrated luminosity of ~1 fb^{-1}. Potential for b-physics will be there soon after the startup. Operating the LHC for 300 hours with an average luminosity of 10^{34} cm^{-2}s^{-1} will result in an integrated luminosity of 1 fb^{-1}.

LHC CYCLE

The beams are accelerated in the SPS from 26 GeV/c to 450 GeV/c, and then transferred to the LHC. During the injection phase, 12 batches per beam (one batch has either 216 or 288 bunches) from the SPS are injected into the LHC (see Fig. 7). Injection of the two beams will take about 15 min. Then the field of the LHC dipole magnets is ramped within 28 min to 8.33 T corresponding to a momentum of 7 TeV/c. Normally, the beams will collide for several hours (physics fill). At the end of the fill, the beams will be dumped and the magnets will ramp down to prepare for the next injection.

LHC operation for physics will start with a pilot physics run with few bunches. There will be no crossing angle, the bunch current will be reduced, and operation is with 43 bunches. The performance will be pushed, filling more bunches, reducing the beam size in the interaction points, and increasing the bunch current. The second

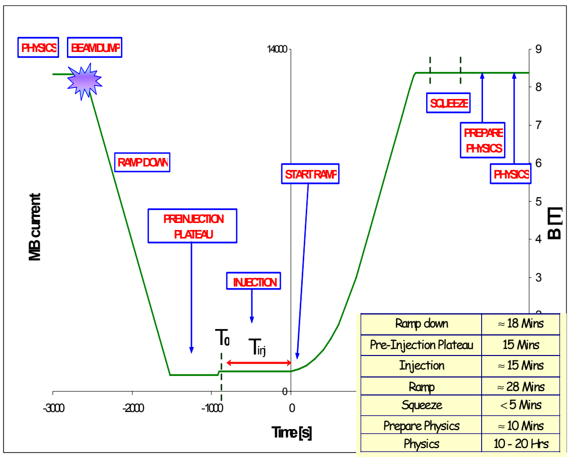

Figure 7: LHC operational cycle

phase is with bunches 75 ns apart.

The third phase is with bunches 25 ns apart below nominal intensity. This is the limit for the phase I collimator system, to increase the bunch intensity requires the second phase collimators.

CONCLUSIONS

Construction of the LHC is well advanced. Installation of the components into the former LEP tunnel is in full swing.

Before the first protons will be injected into the LHC, many of the technical systems will have been commissioned: cryogenics, vacuum, powering, quench protection and interlocks. Commissioning of individual systems has started. An extensive period is foreseen for commissioning the powering of the superconducting magnets up to nominal current. It is planned to finish machine installation and hardware commissioning and to start operation with beam in 2007. In 2006, the high energy CERN accelerators are restarted after 1.5 yr shutdown, in a new control centre for the operation of all accelerators and technical services. Experience with fast extraction of high intensity beam from the SPS will come from CNGS commissioning during summer 2006. The same interlock systems that will be deployed for the LHC will be used for these tests. SPS machine studies related to the LHC include test of intensity limits, commissioning of scrapers, collimator studies etc.

The LHC Machine Advisory Committee, chaired by Prof. M. Tigner, June 2005, concluded for the machine protection systems: “We recognize that the planned schedule is very aggressive, given the complexity and potential for damage involved in the initial phases of operation. It will be important to understand the performance of the machine protection system, the collimation system and the orbit feedback system as well as cycle repeatability and adequate beta-beat control before proceeding to run with significant stored beam energy. Pressure to take shortcuts must be resisted.”

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