STATUS OF THE LHC

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Abstract

The Large Hadron Collider (LHC) will provide particle physics with a tool to access the energy frontier above 1 TeV. To deliver proton-proton collisions at the centre of mass energy of 14 TeV with a nominal luminosity of 10^{34} cm^{-2}s^{-1}, the LHC will operate with high-field dipole magnets using NbTi superconductors cooled below the λ-point of helium. Following a decade of R&D and technical validation of major collider sub-systems, the LHC main components are being built in industry and procured through world-wide collaboration. For final validation of the entire system and preparation of machine operation, a full-scale prototype of a lattice cell is being commissioned. The machine equipment and protection systems are being prepared to operate with about 3×10^{14} protons/beam. The energy stored in one beam is 350 MJ, more than seven orders of magnitude above the quench limit of a superconducting magnet. After briefly recalling the challenges and design choices of the machine, status and future prospects are discussed.

1 INTRODUCTION

As has been stated by the LHC Machine Advisory Committee recently [1], “the LHC is a global project with the world-wide high-energy physics community devoted to its progress and results. As a project, it is much more complex and diversified than SPS or LEP or any other large accelerator project constructed to date”.

The complexity of the LHC is unprecedented. Specific to the LHC is the large number of superconducting magnets operating in superfluid helium, in total about 8000, which will be powered in 1700 electrical circuits. The magnets are fed via service modules every 107 m from a separate 25 km long cryogenic distribution line (QRL) alongside the magnet cryostats. The vacuum system includes the cryogenic ultra-high vacuum systems for the beams and the insulation vacua for cryomagnets and QRL.

One challenge is the fabrication and assembly of a large number of demanding components, and their installation into the confined space of the existing tunnel formerly used for LEP.

Another challenge is the safe operation with beam parameters pushed to the extreme in order to achieve a luminosity of 10^{34} cm^{-2}s^{-1}. Whereas the proton energy is a factor of seven above other machines, the energy stored in the beams is more than a factor of 100 higher. The beams must be handled in an environment with superconducting magnets that could quench in case of a fast, localised beam loss of 10^6 to 10^7 protons when operating at 7 TeV. Any uncontrolled release of the beam energy could cause serious damage to equipment.

2 LAYOUT

The main parameters for the LHC as proton collider are given in Table 1. Two-in-one superconducting magnets guide the counter-rotating proton or ion beams in separate beam tubes through eight arc sectors. In four insertions the beams cross over and collide at a small angle in the centre of the experimental detectors. The other four insertions are dedicated to machine operation, two for beam cleaning, one for the beam dump system, and one for RF and beam instrumentation.

Table 1: Main parameters of the LHC

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}
Luminosity lifetime	10	h
Protons per bunch	$1.1\cdot10^{11}$	
Number of bunches / beam	2808	
Nominal bunch spacing	25	ns
DC beam current	0.56	A
Normalised emittance	3.75	μm
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
Energy loss per turn/proton / 7 TeV	6.7	keV
Radiated power per beam / 7 TeV	3.8	kW
Stored energy per beam / 7 TeV	350	MJ
Stored energy in magnets / 7 TeV	11	GJ

The design of the lattice has matured over the past years, both in robustness and flexibility. The FODO lattice is composed of 46 half-cells per arc, each with a length of 53.45 m. A half-cell includes three twin aperture dipoles with a magnetic length of 14.3 m and a “short straight section”. At the extremities of the dipoles several “spool piece” multipole corrector magnets are installed. The short straight sections include a 3.1 m long quadrupole, orbit correctors, chromaticity correcting sextupoles, and optionally other correctors (trim/skew quadrupoles, Landau damping octupoles, or skew sextupoles).

The insertions include dispersion suppressors, matching sections and dipoles for beam separation / recombination. In the experimental insertions a low-β quadrupole triplet focuses the beams onto the collision point.

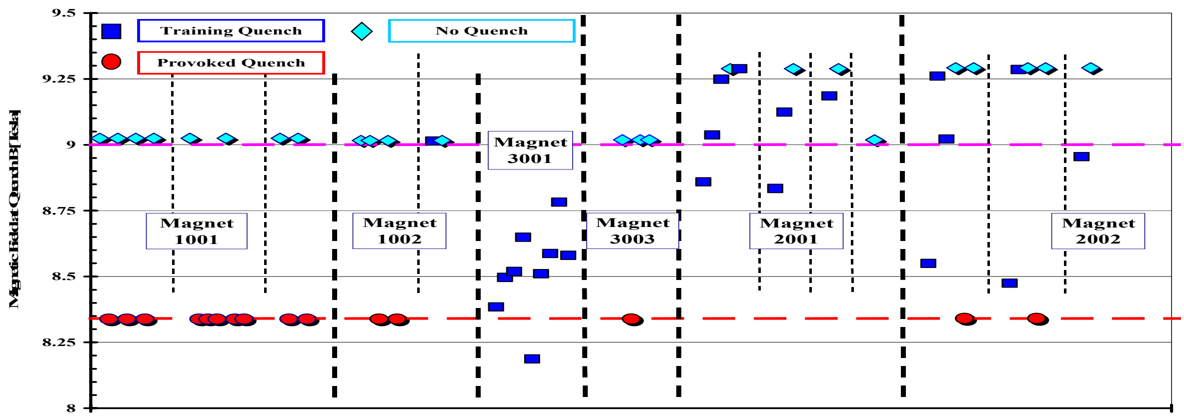

Figure 1: Preseries dipoles, training quenches at 1.8 K, second and further thermal cycles

3 INJECTION AND TRANSFER

The LHC pre-injector complex (Linac, PS Booster, PS) has achieved beam parameters that are required for the LHC after implementing a process based on a series of bunch splitting steps in the PS [2]. Variants of the method allow generating bunch trains with gaps of different lengths for machine studies and possible operation in the presence of electron cloud effects [3-6]. For the SPS as LHC injector, mobile RF shields were inserted into each inter-magnet vacuum pumping port to reduce the impedance. The result has been a significant reduction of the impedance. Consequently, the threshold of the microwave instability was increased to a value above nominal bunch intensity [7]. The civil engineering for two new transfer lines for the 450 GeV beams from the SPS to the LHC, each with a length of about 2.8 km, is being completed. Installation of magnets will start soon, and commissioning of the first line is foreseen for 2004.

4 MAGNET SYSTEM

A main technological challenge is the development and production of superconducting magnets [8]. For the arcs, 1232 main dipoles operating at 8.33 T and 392 main quadrupoles producing gradients of 223 T/m are required (Table 2). 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 errors. About 120 normal conducting magnets will be installed in the LHC ring, mainly in the cleaning insertions, and more than 600 in the SPS-LHC transfer lines. Field errors for all magnets must be kept below specified limits to ensure sufficient dynamic aperture [9]. Series production of the magnets has started in European industry, and in collaboration with institutes in Canada, India, Japan, Russia and the USA.

4.1 Superconducting cables

The production of 1200 tons of the superconducting cables required for the main dipole and quadrupole magnets is under way. The physical, electrical and mechanical properties of strands and cables are specified without defining manufacturing processes. Facilities for high precision measurements of wire and cable properties at 4.2 K and 1.9 K have been implemented at CERN and BNL, to measure strand and cable critical current, copper to superconductor ratio, magnetisation, interstrand resistance and RRR value. The production shows that the highly demanding specification can be fulfilled. Initial difficulties to achieve the required production rate are being overcome [10].

Table 2: Magnets to be installed in the LHC machine

Name	Quantity	Purpose
MB	1232	Arc dipoles
MQ	392	Arc quadrupoles
MBX/MBR	16	Separation dipoles
MSCB	376	Arc combined chromaticity – dipole orbit correctors
MQX	32	Low-b-insertion quadrupoles
MQY	24	Enlarged-aperture quadrupoles in insertions
MQM/MQML/ MQMC	86	Dispersion-suppressor / matching quadrupoles
MO	168	Landau damping octupoles
MQT/MQTL	248	Quadrupoles for lattice and tune corrections
MCB…	~190	Orbit correction dipoles
MCDO	1232	Correction of static / dynamic dipole field errors (sextupoles, octupoles and decapoles)
MCS	2464	
MBW/MQW/ MBXW/…	about 120	Normal conducting magnets in insertions (quadrupoles and dipoles)

4.2 Dipole magnets

After an R&D phase, six full-scale dipole prototypes of final design were built in collaboration between industry and CERN. Before launching the manufacture of the series, 90 pre-series dipoles were ordered. Five prototypes and several pre-series magnets have been tested at CERN. The training quenches for the magnets that passed the nominal field of 8.33 T at 1.9 K are shown in Figure 1 [11] [12]. Results show that the first pre-series magnets have on average better training behaviour, better memory effect between thermal cycles, and a coil structure less sensitive to detraining effects than the prototypes.

Concerning field quality for pre-series dipoles, the a2 and b2 harmonic components were significantly reduced [13]. Fine-tuning of the coil structure is in progress, demonstrating already beneficial effects for b3 and b5, although the origin of b5 is not fully understood. Experience with one magnet that was rejected after tests at 1.9 K shows that the transfer of technology from CERN to industry for cold mass assembly procedures needs to be improved, and rigorous quality control needs to be strictly implemented and followed. The CERN facilities for cryostating and for qualification measurements at 1.9 K are being prepared to absorb the full production rate.

4.3 Lattice quadrupole magnets

After the development and construction of superconducting quadrupole prototypes by CEA/Saclay and CNRS, production was launched and technology is being transferred to industry [14]. The tooling for the fabrication is operational and fabrication of the coils has started. As for the dipoles, CERN supplies a number of components, such as superconducting cables, quench protection heaters and diodes, steel of different grades, etc. After fabrication, the cold masses are installed into cryostats in industry. Delivery of the first series quadrupole is expected for the second half of 2002.

4.4 Insertion main magnets

Two types of quadrupoles are used in the low-β triplet. The two central 5.7 m long MQXB magnets are designed and built as a single cold mass by FNAL (USA). The 6.6 m long MQXA magnets, located on either side of the central quadrupole, come from KEK (Japan). Completion of the cold masses and assembly of the magnets into the cryostats is done by FNAL, while their feed boxes are designed and manufactured by LBNL (USA). Following full-scale prototypes, first production magnets are under test [15] [16]. Most of the separation dipoles, using the same coil design as for RHIC, have been completed and are being tested [17]. Special quadrupoles for the matching sections (MQM and MQY) are produced by European industry. First pre-series magnets are expected by the end of 2002.

4.5 Corrector magnets

Contracts have been awarded for all types of superconducting corrector magnets, and the construction has started [18]. The challenge is the low cost fabrication of 11 different types, in total about 6000 magnets, with high field strength and good field quality. Magnets are produced in European industry and in India. Corrector magnets are assembled together with the cold mass of the main dipole and quadrupole magnets. The schedule is tight since the delivery must precede the main magnet fabrication.

4.6 Normal conducting magnets

The fabrication of 360 dipoles and 185 quadrupoles in BINP/Novosibirsk for the transfer lines from SPS to LHC has been completed. The magnets have been delivered to CERN and installation starts soon [19]. For the LHC, dipoles, quadrupoles and septum magnets are required [20]. Separation dipoles and corrector magnets are produced by BINP and first prototypes are expected for this summer. Quadrupoles for the cleaning insertions were developed in collaboration with TRIUMF/Canada and about one third of the magnets has been produced.

5 OTHER SYSTEMS

5.1 Cryogenic system

The LHC magnets operate in a static bath of pressurised superfluid helium at 1.9 K, cooled by continuous heat exchange with flowing saturated superfluid helium [21]. One cryogenic loop extends along a lattice cell of 107 m, supplying the magnets in one cell. In each sector, many loops are connected to the 3.3 km cryogenic distribution line (QRL) that is fed from one of the eight cryogenic plants. Qualification tests of three 110 m long pre-series QRLs delivered by three European firms were done before final specification and ordering from one supplier. In addition to the four existing cryogenic plants from LEP (each with a cooling power of 18 kW at 4.5 K), four new plants with the same cooling power are being installed. The first plant starts to be operational. For the production of saturated superfluid helium, the compression of high flow-rates of helium vapour over a pressure ratio of 80 is achieved by means of multi-stage cold hydrodynamic compressors that were developed for this purpose. The first set of compressors made by industry are under test and results are promising.

5.2 Vacuum system

Vacuum stability has to be ensured in the beam vacuum of the arcs with a cold bore at 1.9 K and in the insertions with sections at 1.9 K, 4.2 K and 300 K. A beam screen operating between 5 and 20 K will be inserted in the cold bore around most of the circumference, to intercept the heat load from synchrotron radiation. The screen has a copper layer to reduce the impedance, and is also required to avoid any ion-induced instability. A critical factor is the electron cloud instability that has been observed in several accelerators [3,4]. Depending on bunch intensity and spacing, a resonant build-up of secondary electrons could produce heating of the chamber wall and can cause even beam instabilities. In the SPS, a dynamic pressure rise with 3 batches of $3 \cdot 10^{10}$ p/bunch has limited the intensities last year. Beam scrubbing for 10 days in 2002 reduced the secondary emission yield (SEY). Beams above nominal intensity can now be injected in the SPS with acceptable vacuum pressure. The transverse and longitudinal parameters are kept within the nominal values along the injection plateau [5,7]. For the LHC, the heat load due to the electron cloud is expected to exceed the cooling capacity for nominal beam parameters, if the SEY is larger than about 1.2. Various cures have been devised, such as minimising the beam screen reflectivity and lowering the production yield for secondary electrons [6]. After an initial time of operation the accumulated dose of electrons should have sufficiently scrubbed the surfaces thus reducing the SEY to the required value. Increasing the bunch spacing from 25 ns to 75 ns is expected to suppress the resonance.

5.3 Powering and quench protection systems

In order to handle the large energy of 11 GJ in the magnet system, the LHC is powered in several independent powering sectors (arcs, triplets, matching sections). There are eight power converters for the main dipoles, each powering 154 dipoles in one arc. Control of the current with an accuracy of about one ppm is required. Several types of converters with nominal current in the range between 60 A to 13 kA have been developed and are being evaluated.

Individual protection for each main magnet, each current lead, and each circuit with corrector magnets requires a complex system to detect quenches and react accordingly. A large fraction of the current leads use High Temperature Superconducting (HTS) material. After a quench in a main magnet, an uncontrolled release of the energy stored in the superconducting magnets (1.4 GJ per sector for the dipoles) is prevented by firing heaters for the quenched magnet and by switching resistors into the circuit. The energy is safely absorbed in the resistors, heating eight tons of steel to about 300 °C [22]. The components for the system (quench diodes, quench heaters, ..) have been validated and production started. The reliability of the entire system is being addressed [23].

A large number of electronic crates will be installed in the tunnel, not only for quench protection and powering, but also for vacuum and cryogenics. Systematic tests are being performed in a facility providing an LHC like radiation environment to qualify the equipment [24].

5.4 RF system

The RF operates at 400.8 MHz, the second harmonic of the SPS frequency, with a relatively modest RF voltage of 16 MV/beam to accelerate and keep the proton beams bunched. The high beam currents led to the choice of low impedance (R/Q) superconducting copper cavities sputtered with a thin film of niobium. The cavities are located in a region of enlarged 420 mm beam separation. The second beam can pass outside the first beam cavities. Sixteen single-cell wide-aperture cavities (2 MV/cavity) have been manufactured and assembled into four cavity modules, two per beam. The decision to install an additional system at 200.4 MHz to ease injection tolerances and to provide increased injection oscillation damping will be taken in 2004. The first 330 kW klystron from industry has been delivered and is under test.

6 ACCELERATOR PHYSICS AND LHC OPERATION

The permissible beam losses are very low. Accurate modelling the beam dynamics throughout the cycle takes into account magnetic multipoles, dynamic effects in the superconducting magnets, and head-on/parasitic beam-beam collisions. Successful operation will rely on accurate monitoring and control of the beams, including slow tune, chromaticity and orbit feedback based on signals from beam and magnetic measurements from reference magnets [25]. Chromaticity diagnostics with high time resolution is of paramount importance for the control of the dynamic events [26]. A prototype system measuring the machine chromaticity via RF phase modulation and continuous tune tracking is being implemented for the SPS. The possibility of adjusting the powering of correction circuits via beam based measurements is being studied [27].

6.1 Beam cleaning and protection

The LHC will be the first machine requiring collimators to define the mechanical aperture through the entire cycle. For very efficient beam cleaning, the collimators are adjusted between 5-9 σ. For operating at 7 TeV, more than 99.9% of the protons in the beam halo should be captured in the cleaning insertions to minimise protons impacting on the cold magnets [28]. In case of equipment failures, collimators will be first to intercept the beam and must absorb part of the energy until the beams are extracted. Two insertions are reserved for beam cleaning. In one insertion, collimators in locations with non-zero dispersion catch protons with too large momentum deviation. In a second insertion, collimators capture protons with large betatron amplitudes. Downstream from a primary collimator that is closest to the beam, four secondary collimators catch the scattered protons. If the beam lifetime would exceptionally drop to 0.2 h, power deposition in the cleaning section could be up to 0.5 MW.

Ionisation chambers installed close to collimators and other aperture limitations will monitor the flux of secondary particles continuously [29]. Although failures of magnets (quenches) or power converters could lead to fast beam losses within ten turns [30], enough time is available for detection, and sending the beams through the dedicated 300 m long tunnel to beam absorbers [31]. In the unlikely case of the asynchronous firing of one of the 15 dump kicker modules, followed by the firing of all other modules 1.3 μs later, about 20 bunches would impact on the collimators. To stand such an event without being damaged, the material for the collimators, originally Al and Cu, is being reconsidered.

7 STRING 2

String 2 is a full-size model of a regular cell in the LHC. The facility was built to assess installation, tooling and assembly procedures, to validate the LHC systems and to investigate their collective behaviour. In 2001, three dipole magnets and two quadrupole magnets were assembled [32]. Six HTS prototype current leads for 13 kA and 26 HTS leads for 600 A were integrated in the feedbox. Commissioning started with two weeks cool down from 300 K to 1.9 K. After verification of the integrity of the electrical circuits and of the instrumentation and protection systems, the magnets were gradually powered from minimum stable current, through injection current up to nominal current. With a new method of digital regulation together with an ultra high precision current measurement system the objective for powering with an accuracy of about one ppm was achieved [33]. Three pre-series dipole magnets were added in 2002 to complete the cell and the test programme has started.

8 FROM BUILDING COMPONENTS TO COLLIDING BEAMS

A large quantity of complex equipment will be installed in the limited space of tunnel and underground service areas. Detailed studies are performed of how to integrate the equipment without interference. Digital models of the different tunnel sections including the equipment to be installed are being provided for the entire machine. The procedures for transport, installation, making the interconnections etc. have been taken into account. LHC installation is sector-by-sector and started already in March 2002. General services such as piping, electrical equipment, control cables and optical fibres are installed first. The installation and commissioning of the cryogenic ring line starting by mid 2003 is expected to take until the end of 2005. When the commissioning of the cryoline in one sector is finished, the cryomagnets and other equipment will be installed, including the delicate procedure of interconnecting the magnets. The installation of superconducting magnets in the first sector will start in March 2004, and the last magnet will be installed in September 2006.

The LHC layout with eight independent sectors allows step-by-step commissioning of each sector, starting in 2005. Thorough commissioning of the hardware systems is a prerequisite for fast start of beam operation. This includes pump-down of vacuum enclosures, cool-down, commissioning of the protection systems and powering of all electrical circuits up to nominal current.

9 CONCLUSIONS

Civil engineering underground is nearly completed and most major industrial contracts have been awarded. The fabrication of equipment as part of special contributions from non-member states is advancing well. Production of superconducting cables is in full swing, and magnet production started. In the years to come several types of activities need to be carried out in parallel: construction of equipment, installation of ready components, and commissioning of completed machine sectors during 2005 and 2006. Confidence for a smooth commissioning of the hardware systems comes from the encouraging experience with String 2. With respect to the number of electrical circuits, instrumentation and the complexity of the processes, String 2 is similar to an LHC Sector. The first injection of one beam and transport across two sectors is envisaged for 2006, in order to be well prepared for the start-up with two beams in 2007.

10 ACKNOWLEDGEMENTS

The report has been written on behalf of all CERN staff participating to the LHC Project, as well as all those involved in external collaborations for the construction of the machine.

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