The Status of the LHC Machine.

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Abstract

The construction of the LHC is proceeding well. The problems encountered with civil engineering work last year which are now resolved, and the letting of contracts for machine components is on schedule. Although the initial deliveries of equipment are up to a few months behind those planned, suppliers are confident they will be able to make good on this once the full-scale production is running. The machine layout is stable as is the expected performance, and we can look forward with confidence to the first physics run in 2006.

I. INTRODUCTION

The LHC (Large Hadron Collider)[1], under construction at CERN, is designed to provide proton-proton collisions at a center-of-mass energy of 14 TeV and luminosity of 10^{34} $cm^2.s^{-1}$. This machine is a major advanced engineering venture. It consists of two synchrotron rings, interleaved horizontally, the main elements of which are the two-in-one superconducting dipole and quadrupole magnets operating in superfluid helium at 1.9 K. The collider will be installed in the existing tunnel of 26.7 km in circumference which until recently housed the LEP collider. This has constrained the layout to resemble closely that of LEP, with eight identical 2.8 km long arcs, separated by eight 540 m long straight sections, the centres of which are referred to as “Points”. At four of these points the beams are brought into collision. Points 1 and 5 will house the high luminosity multipurpose experiments ATLAS and CMS, for which considerable civil engineering is required. The more specialized experiments ALICE and LHCb will be installed in the existing caverns, which previously housed LEP experiments, at Points 2 and 8. Major systems of the collider itself will be installed in the remaining four straight sections. Points 3 and 7 are dedicated to beam cleaning, Point 4 to beam acceleration, and Point 6 to beam extraction. The general layout of the LHC is shown in Figure 1, and a simulated view of the installed machine is shown in Figure 2.

Following a decade of R&D and technical validation of the major systems of the collider at CERN, at collaborating institutes and with industry, construction of the LHC is now underway. Contracts have been awarded to industry for the supply of superconducting magnets, cryogenic refrigeration plants and other machine equipment, and manufacture has begun. The components of some systems, such as those of the injection lines and the superconducting RF are nearing completion. The upgrading of the injector complex of existing CERN accelerators is practically finished. Civil engineering is now advancing well after some setbacks associated with the terrain, but not before leading to a review of the schedule. It is now planned to start installation in autumn 2003, to commission the first sector (Point 8 to Point 7) in summer 2004, and to complete installation by the end of 2005. After an initial set-up test with beam in spring 2006, it is foreseen to start a seven-month physics programme in autumn 2006.

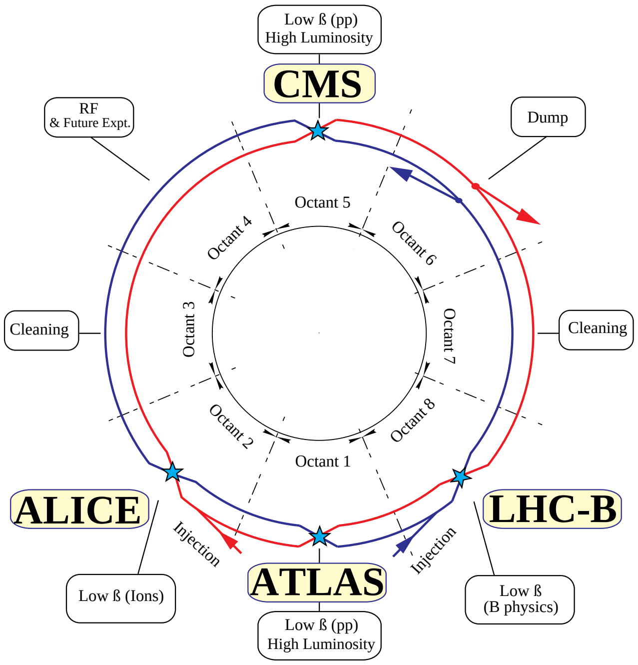


Figure 1: General layout of the LHC

Figure 2: Simulated view of the LHC in its tunnel

II. THE LATTICE

The main parameters of the LHC as a proton collider are listed in Table 1.

The design of the lattice has matured over the past years both in terms of robustness and flexibility, and critical technologies and engineering solutions have been validated, while nevertheless maintaining the initially declared performance of the machine. The FODO lattice is composed of 46 half-cells per arc; each half-cell is 53.45 m long and consists of three twin-aperture dipoles having a magnetic length of 14.3 m, and one twin aperture quadrupole, 3.1 m in length.

Table 1: Main parameters of the LHC

Energy at collision	7	TeV
Energy at injection	450	GeV
Dipole field at 7 TeV	8.33	T
Coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Luminosity	10^{34}	$cm^{-2}s^{-1}$
Beam current	0.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Number of particles per bunch	1.1×10^{11}	
Normalized transverse emittance (r.m.s.)	3.75	µm
Total crossing angle	300	µrad
Luminosity lifetime	10	h
Energy loss per turn	6.7	keV
Critical photon energy	44.1	eV
Total radiated power per beam	3.8	kW
Stored energy per beam	350	MJ

III. THE SUPERCONDUCTING MAGNETS

A major technological challenge of the LHC is the industrial production of 1232 superconducting main dipoles [2] operating at 8.3 T, 400 superconducting main quadrupoles [3] producing gradients of 223 T m^{-1}, and several thousand other superconducting magnets [4], for correcting multipole errors, steering and colliding the beams, and increasing luminosity in collision. All these magnets (Table 2), which must produce a controlled field with a precision of 10^{-4}, are presently being manufactured by industry in Europe, India, Japan and the USA.

A specific feature of the main dipoles, a cross-section of which appears in Figure 3, is their twin-aperture design. To produce the fields required for bending the counter-rotating beams, two sets of windings are combined in a common mechanical and magnetic structure to constitute twin-aperture magnets. This design is more compact and efficient than two separate strings of magnets, as the return flux of one aperture contributes to increasing the field in the other. The high quality field in the magnet apertures is produced by winding flat multi-strand cables, in a two-layer cos θ geometry. The large electromagnetic forces acting on the conductors are reacted by non-magnetic collars resting against the iron yoke, contained in a welded cylinder which also act as a helium enclosure.

Table 2: Superconducting magnets in the LHC

Type	Quantity	Purpose
MB	1232	Main dipole
MQ	400	Main quadrupole
MSCB	376	Combined chromaticity and closed-orbit corrector
MCS	2464	Sextupole for correcting dipole persistent currents
MCDO	1232	Octupole/decapole for correcting dipole persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quadrupole for lattice correction
MCB	266	Orbit correction dipole
MQM	100	Dispersion suppressor quadrupole
MQX	32	Low-β insertion quadrupole
MQY	20	Enlarged-aperture quadrupole

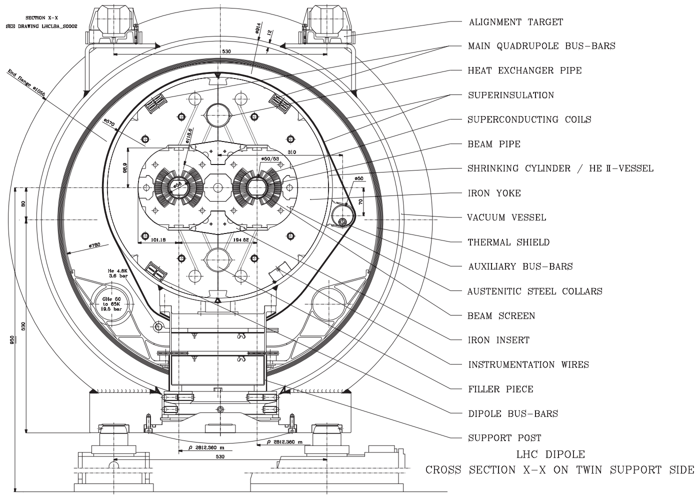
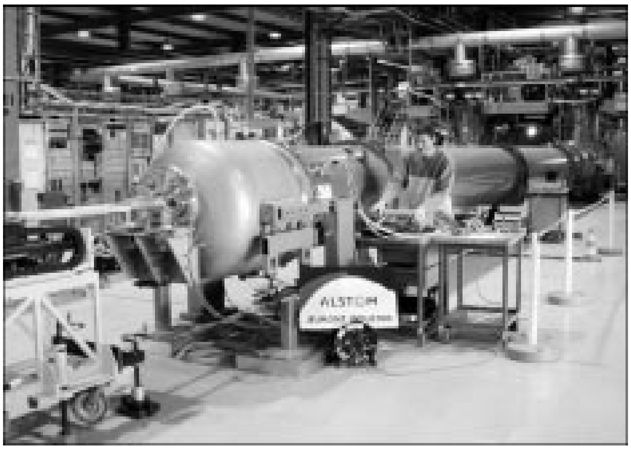


Figure 3: Transverse cross-section of the dipole in its cryostat

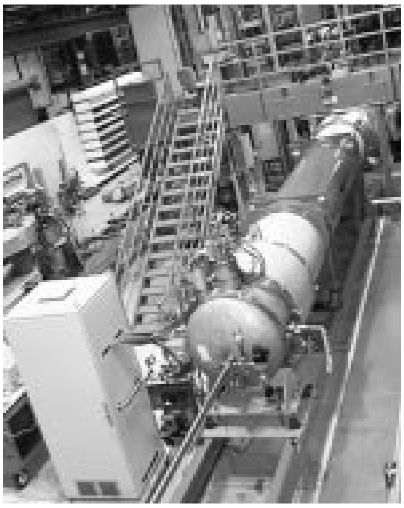
CERN supplies the superconducting cable to the companies assembling the magnets. In view of the quantity of cable required (~1250 tonnes), all European wire manufacturers (together with one in the USA and one in Japan) are involved in this production.

The LHC magnets must preserve their field quality over a large dynamic range, in particular at low levels when persistent currents in the superconductor give rise to remanent field effects. This requires a small diameter of the Nb-Ti filaments in the cable strands. The chosen diameter of ~7µm represents a compromise that also takes into account the requirement to maximize overall current density in the strand. It is also necessary to apply a uniform resistive coating to the strands to control inter-strand currents. Together with the tight dimensional tolerances, these constraints have presented quite a challenge to the manufacturers, but after a difficult start most companies are now producing satisfactory material. However, with present delays of about 12 months we shall require a large increase in throughput to satisfy the needs of magnet production as it accelerates in the next months.

Following a decade of development and model work, final prototypes magnets built in industry have permitted the validation of technical design choices and manufacturing techniques, thus leading the way for the adjudication of pre-series and series contracts for the dipoles, quadrupoles and correctors, the production of which has now started and will continue over the next four years (Figure 4). The first three magnets of the dipole series have been tested and are acceptable for installation in the machine. Preparations for the production of the quadrupoles are advancing well, and deliveries of corrector magnets have already started.



a)



b)

Figure 4: First pre-series superconducting magnets under test. a) Main dipole at CERN; b) Low-β quadrupole at Fermilab

IV. CRYOGENICS

The LHC uses superfluid helium for cooling the magnets [5]. The main reason for this is the lower operating temperature, with corresponding increased working field of the superconductor. The low viscosity of superfluid helium enables it to permeate the magnet windings, thereby smoothing thermal disturbances, thanks to its very large specific heat (~2000 times that of the cable per unit volume), and conducting heat away, thanks to its exceptional thermal conductivity (1000 times that of OFHC copper, peaking at 1.9 K).

The LHC magnets operate in static baths of pressurized superfluid helium, cooled by continuous heat exchange with flowing saturated superfluid helium. This cooling scheme, which requires two-phase flow of superfluid helium in nearly horizontal tubes, has been intensively studied on test loops and validated on a full-scale prototype magnet string [6]. Individual cryogenic loops extend over 107 m, the length of a lattice cell, and these loops are fed in parallel from each cryogenic plant over the 3.3 km sector length through a compound cryogenic distribution line [7] running along the cryo-magnets in the tunnel.

The high thermodynamic cost of refrigeration at low temperature requires careful management of the system heat loads. This has been achieved by the combined use of intermediate shielding, multi-layer insulation and conduction intercepts in the design of the cryostats (see Figure 3), and by the installation of beam screens cooled at between 5 and 20 K by supercritical helium, for absorbing a large fraction of the beam-induced heat loads [8]. To cope with its heat load, the LHC will employ eight large helium cryogenic plants, each producing a mix of liquefaction and refrigeration at different temperatures, with an equivalent capacity of 18 kW @ 4.5 K and a coefficient of performance of 230 W/W [9]. The cold box of the first LHC cryogenic plant, presently undergoing reception tests at CERN, is shown in Figure 5.

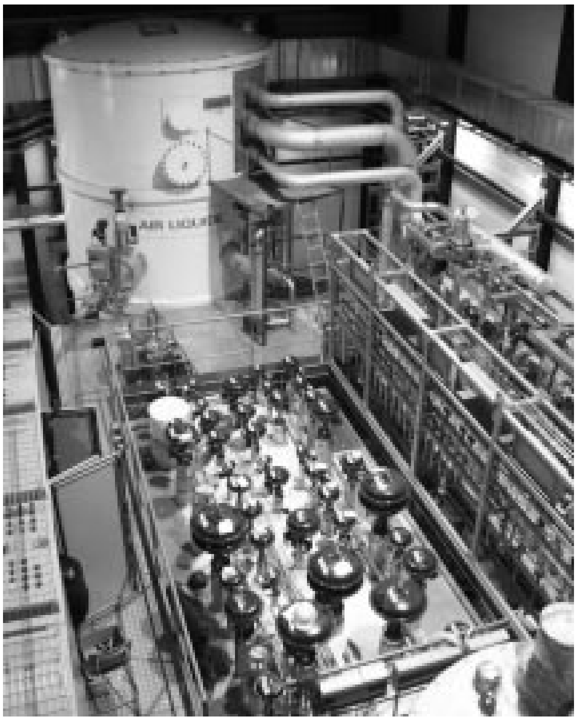


Figure 5: Coldbox of first 18 kW @ 4.5 K helium refrigerator

In view of the low saturation pressure of helium at 1.8 K, the compression of high flow-rates of helium vapour over a pressure ratio of 80 requires multi-stage cold hydrodynamic compressors (Figure 6). This technology, together with that of low-pressure heat exchangers, was developed specifically for this purpose. Following detailed thermodynamic studies and prototyping conducted in partnership with industry, eight 2400 W @ 1.8 K refrigeration units have been ordered from two companies, and the first one has been delivered to CERN for reception tests. The overall coefficient of performance of these units, when connected to the conventional 4.5 K helium refrigerators, is about 900 W/W.

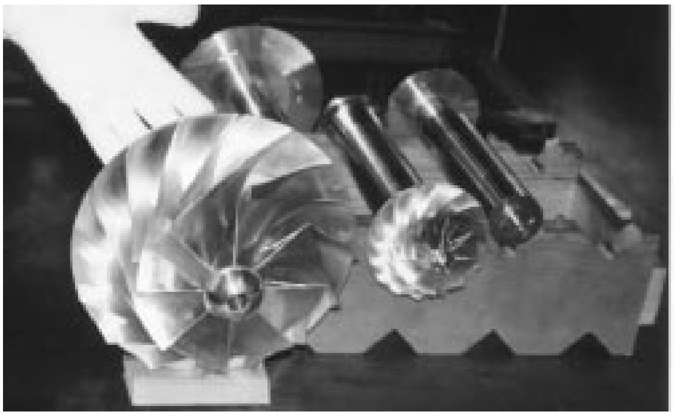


Figure 6: Impellers of cold compressors for the first 2.4 kW @ 1.8 K refrigeration unit

V. HIGH TEMPERATURE SUPERCONDUCTOR CURRENT LEADS

Powering the magnet circuits in the LHC will require feeding up to 3.4 MA into the cryogenic environment. Using resistive vapour-cooled current leads for this purpose would result in a heavy liquefaction load. The favourable cooling conditions provided by 20 K gaseous helium available in the LHC cryogenic system make the use of HTS-based current leads in this system particularly attractive. With a comfortable temperature difference to extract the heat from the resistive section in a compact heat exchanger, this allows operation of the upper end of the HTS section below 50 K, at which the presently available materials, e.g., BSCCO 2223 in a silver/gold matrix, exhibit much higher critical current density than at the usual 77 K provided by liquid nitrogen cooling. The thermodynamic appeal of such HTS-based current leads is presented in Table 3.

Table 3: Performance of HTS-based current leads for the LHC, compared to resistive vapour-cooled leads

Lead type		**Resistive, vapour-cooled (4 to 300 K)**	**HTS (4 to 50 K) Resistive, gas cooled (50 to 300 K)**
Heat into LHe	[W/kA]	1.1	0.1
Total exergy	[W/kA]	430	150
Electrical	[W/kA]	1430	500

After conducting tests on material samples, CERN procured from industry and tested extensively prototypes of HTS-based current leads for 13 kA and 0.6 kA. This has enabled us to demonstrate feasibility and performance of this solution, to identify potential construction problems, to address transient behaviour and control issues, and to prepare the way for procurement of series units [10].

VI. INSTALLATION AND TEST STRING 2

The tight constraints of the LHC tunnel, the large quantity of equipment to be transported and installed, and the limited time for installation require detailed preparation, including both CAD simulation and full-scale modeling. Using the information from verifications of the tunnel geometry that were performed in 1999, 3D mock-ups have been developed for critical tunnel sections. As a result of these studies areas of interference have been identified, and transport and installation scenarios have been confirmed. The recent experience gained in the assembly of the first half of Test String 2 [11], featuring a full 107 m long cell comprising dipoles and quadrupoles, has been of great value in validating the techniques and tooling developed for the installation and interconnection of the lattice magnets. The Test String is shown in Figure 7.

Figure 7: Test String 2.

VII. PERFORMANCE AND UPGRADE POTENTIAL

It is confidently expected that in the first year of running a luminosity of 10^{33} cm^{-2}s^{-1} will be achieved at the nominal centre-of-mass energy of 7+7 TeV, and that the machine will provide an integrated luminosity of 10 fb^{-1} during the first 6-month period of physics data-taking. It will probably then take another two to three years to ramp up to the nominal peak luminosity of 10^{34} cm^{-2}s^{-1} in the high luminosity experiments. As concerns upgrade potential, the accelerator is being engineered so as to allow the possibility of achieving up to about 7.5 TeV per beam, but this may require changing some of the weaker dipoles. It can also be envisaged to further increase the luminosity by up to a factor of two by reducing the β−function at the interaction point from 0.5 m to 0.25 m, but this will call for the replacement of the inner triplet quadrupoles with larger aperture magnets. This new generation of high field superconducting magnets, based on the use of Nb_3Sn or Nb_3Al material, is presently the subject of R&D in several laboratories; we expect that in 5-7 years it should be possible to embark on the production of a small series suitable for the low-β insertions. Studies are also underway regarding more radical upgrading of the machine, such as increasing the luminosity by another factor of five, or replacing the main lattice magnets with more powerful magnets to take the beam energy up to 10-12 TeV. But this will be for a far more distant future.

VIII. CONCLUSION

After a decade of comprehensive R&D, the LHC construction is now in full swing [12]. Industrial contracts have been awarded for the procurement of most of the 7000 superconducting magnets and for the largest helium cryogenic system ever built, and the production of this equipment is underway. Although located at CERN and basically funded by its twenty member states, the project, which will serve the world's high-energy physics community, is supported by a global collaboration, with special contributions from Canada, India, Japan, Russia and the USA. A full-scale test of the first sector is planned for 2004, and colliding beams for physics are expected to be available from 2006 onwards.

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