PROGRESS IN CONSTRUCTION OF THE LHC

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ABSTRACT

The Large Hadron Collider (LHC) project, approved by the CERN Council in December 1994, has now fully entered its construction phase, with the detailed technical definition of the major systems, and the adjudication of a number of large procurement contracts. We first recall the main features and characteristics of the LHC, report on the advances in definition of the layout and optics as well as on preparation of the injector complex, and review recent progress in the key technical systems of the main ring: magnets, cryogenics and vacuum, as well as civil construction, which has started following acceptance by authorities in the Host States.

INTRODUCTION

The Large Hadron Collider (LHC), approved in December 1994, is now in construction at CERN, the European Laboratory for Particle Physics near Geneva, Switzerland [1]. This large-diameter circular particle accelerator will bring into collision intense beams of protons at high energy and luminosity, as well as heavy (Pb) ions at more modest luminosity. The two counter-rotating beams will be guided and focused by high-field superconducting magnets operating in pressurised superfluid helium, installed in the 26.7 km circumference tunnel of the existing LEP collider. The main parameters of the machine, some of which are unprecedented in accelerator physics and technology [2], are recalled in Table 1.

We first review the status of machine layout and optics, briefly report on the preparation of the injector complex, and then focus on recent progress in the key technical systems of the project.

LAYOUT AND OPTICS

The LHC layout essentially mirrors that of LEP, with eight identical arcs, each 2.9 km in length, separated by long straight sections which house the so-called insertions for experiments or utilities (Figure 1). The diametrically opposite Points 1 and 5, equipped with high-luminosity insertions, will house the two large multi-purpose experimental detectors ATLAS and CMS.

Table 1: Main parameters of the LHC

Energy	(TeV)	7.0
Dipole field	(T)	8.3
Coil aperture	(mm)	56
Distance between apertures	(mm)	194
Luminosity	($cm^{-2}\,s^{-1}$)	10^{34}
Beam-beam parameter		0.0032
Injection energy	(GeV)	450
Circulating current/beam	(A)	0.530
Bunch spacing	(ns)	24.95
Particles per bunch		1×10^{11}
Stored beam energy	(MJ)	332
Normalized transverse emittance	(μm)	3.75
R.m.s. bunch length	(m)	0.075
Beta values at I.P.	(m)	0.5
Full crossing angle	(μrad)	300
Beam lifetime	(h)	22
Luminosity lifetime	(h)	10
Energy loss per turn	(keV)	6.9
Critical photon energy	(eV)	45.6
Total radiated power per beam	(kW)	3.7

Two other, more specialised experiments, ALICE and LHCb – the latter in the process of being approved – will occupy the existing experimental caverns at Points 2 and 8, respectively. The insertions at these locations also contain the injection systems for the two rings. The circulating beams only cross at the four experimental Points. The long straight sections at Points 3 and 7 are devoted to collimation of the beam halo, in order to limit background in the experiments and particle losses in the superconducting magnets. Consequently, these two insertions are equipped with resistive magnets, insensitive to "quenches" induced by beam losses. The long straight section at Point 4 also houses the RF acceleration cavities, separate for the two rings, which requires to increase beam separation from 194 to 420 mm. The insertion at Point 6 houses the system for extraction and external dumping of the spent beams. The optics of the LHC has recently undergone refinements towards more flexibility – particularly as concerns adaptation of the insertions - and robustness to changes in parameters or layout. The regular arc cell, 106.9 m in length, contains six dipoles, each with a magnetic length of 14.3 m, and two quadrupoles, 3.1 m in length. The "short straight sections" housing the quadrupoles also contain a combined orbit correction dipole and chromaticity sextupole, as well as another short corrector. The non-linear errors in the dipoles are locally corrected by sets of sextupole and decapole spool pieces attached to the ends of the dipole cold mass. The dipoles and two types of quadrupoles are powered independently, which allows separate adjustment of horizontal and vertical tune.

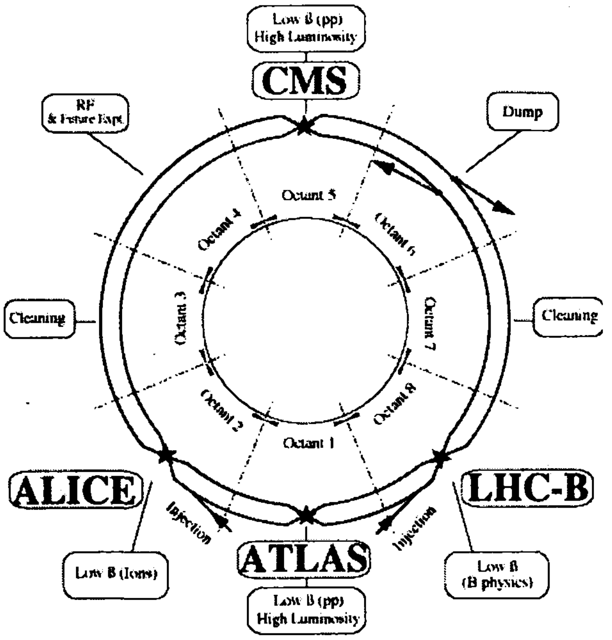

Figure 1: Overall layout of the LHC

The experimental insertions have similar layouts. The two beams, crossing with a small angle of 300 μrad at the interaction point, first pass through a single-aperture, high-gradient quadrupole triplet, the first component of which is located 23 m away from the interaction point. The beams are then separated by separation dipoles, either resistive in Points 1 and 5 to withstand the high flux of stray particules from the high-luminosity collisions, or superconducting in Points 2 and 8 to make space for the injection systems. After twin-aperture dipoles completing the dog-leg paths, the beams pass through four independently powered superconducting quadrupoles, matching the insertion. Dispersion suppressors, composed of lattice-like dipoles and quadrupoles, connect the insertion to the regular arcs.

INJECTOR COMPLEX

In the CERN tradition and for the sake of economy, the LHC reuses the chain of existing, older accelerators as injectors. Meeting the challenge of short-bunched, high-brilliance beams demanded by the LHC, however requires significant improvements and modifications to the PS Booster, PS and SPS, a number of which have already been implemented [3, 4], with the help of TRIUMF Vancouver (Canada). The preservation of emittance along the injector chain has in fact been demonstrated, and beams with nominal LHC parameters will be available in 1999. The two injection lines for the 0.45 TeV beams from the SPS, each about 2.6 km in length, will be constructed from conventional magnets, to be supplied by Russia. The first two prototypes of these magnets, made at BINP Novosibirsk (Russia) have been delivered to CERN.

SUPERCONDUCTING MAGNETS

The LHC will require more than 8000 superconducting magnets of different types. The most challenging are the 1232 twin-aperture main dipoles (Figure 2), the development of which has been the object of significant effort over the past years, in order to achieve the required performance reproducibly and economically in industry. The aim is to design magnets with a nominal field of 8.3 T, an ultimate field of 9 T in the twin, 56 mm apertures, which also preserve good field quality at injection (0.58 T) and show stability with respect to thermal cycles and quenches.

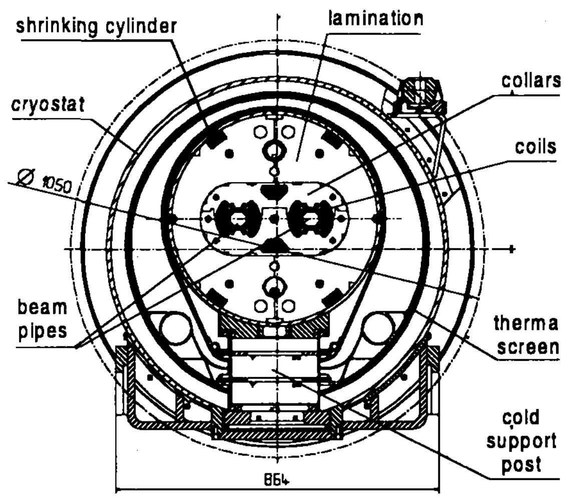

Figure 2: Transverse cross-section of dipole cryomagnet

With the evolution of field quality requirements resulting from progress in dynamic aperture studies, the 5-block, two-layer graded coil geometry which equips the first-generation magnets [5] has now become too constrained, and unable to respond to small adaptations that may be required in the course of series production. A more suitable, 6-block geometry was designed and optimised using genetic algorithms, and implemented in several model magnets, which performed very well, with first quenches well above 9 T, and fast training to the conductor limit at about 10 T [6]. Among other advantages, this new geometry yields higher quench margin, one less turn, better tunability and lower sensitivity of field quality to conductor placement errors. Another important outcome of the experimental R&D programme, is that the level of compressive pre-stress applied to the coils can be significantly lowered,

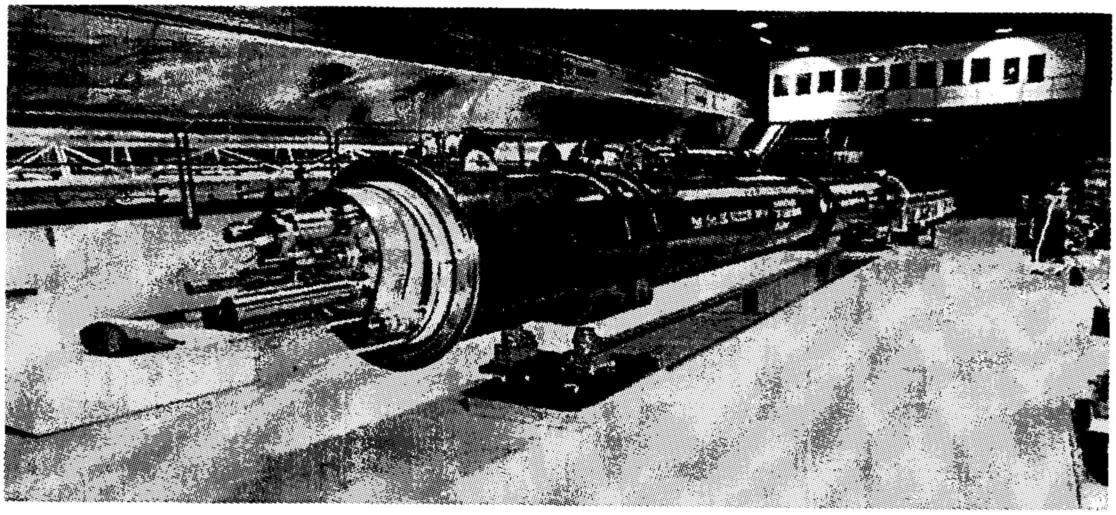

Figure 3: The first 15-m long dipole prototype

without loss of performance. This has led to adapt the design of the collars, and opened the way to the use of austenitic steel, which makes the whole collaring operation less critical on manufacturing and assembly tolerances. Full-length prototypes, presently under construction, will permit to validate this design before adjudicating the contracts for series production in mid 1999. Figure 3 shows the first full-length prototype dipole, produced by industry in collaboration with INFN (Italy).

The procurement of the some 1200 tonnes superconducting cable is a critical path item for the dipole production. It will be procured by CERN and supplied to the dipole cold mass manufacturers. With the available production capacity, more than six years are needed to produce the full quantity. Contracts with several qualified industrial firms in Europe, Japan and the U.S.A. have been adjudicated for this purpose.

The lattice quadrupoles are designed by CEA Saclay (France) in collaboration with CERN. To produce the 223 T/m gradient in the 56 mm apertures, the two sets of separately-collared coils make use of the dipole outer cable, wound in a two-layer geometry. Two such prototypes are under construction, and the first will be tested before the end of 1998. The short straight sections housing the quadrupoles are designed in collaboration with CNRS Orsay (France).

The long straight sections and insertion regions contain many specialised magnets, the most demanding of which are the high-gradient (220 T/m), large-aperture (70 mm) quadrupoles of the inner triplets. Two versions of this quadrupole have been designed, and prototypes built at KEK Tsukuba (Japan) and Fermilab Batavia (U.S.A.). The final integration of both Japanese and U.S.-built magnets into the inner triplets will be made at Fermilab.

CRYOGENICS

The LHC superconducting magnets will operate in static baths of pressurised superfluid helium at 1.9 K, quasi-isothermally cooled by heat exchange with flowing saturated superfluid helium [7]. This cooling scheme, which implies stable, stratified two-phase flow in quasi-horizontal channels, has been studied in a dedicated test set-up at CEA Grenoble (France), and finally validated at CERN on the accelerator test string, as reported below.

In view of the high thermodynamic cost of refrigeration at low temperature, most of the system heat loads, static and dynamic, will be intercepted at higher temperature, by appropriate thermal shielding. As a result, the LHC requires a mix of refrigeration duties at several levels of temperature, to be implemented in the refrigeration plants, distribution lines and magnet cryostats. Refrigeration will be produced by eight cryogenic helium plants, each cooling an adjacent sector of the ring with an equivalent capacity of 18 kW at 4.5 K. Four of these will be the existing LEP refrigerators at Points 2, 4, 6 and 8, adapted for LHC duty after suitable upgrade in capacity from 12 to 18 kW. The other four are new units, featuring each a single cold box, to be installed in surface buildings at Points 1.8, 4, 6 and 8. In the absence of return of high-density helium vapour at 4.5 K in the LHC system, the hydrostatic heads in the machine shafts remain limited, thus allowing surface installation of the main refrigerators, and corresponding savings in underground space occupancy. Moreover, installing a new large-capacity refrigerator at Point 1.8 (instead of Point 2), i.e. in the proximity of the magnet test hall, brings considerable advantage for series component tests. It also saves on civil engineering work and allows more efficient cooling of sector 1-2, in view of the tunnel slope. The four new helium refrigerators have been ordered from industry and will be installed in stages from 2000 onwards. Contracts for upgrading of the existing helium refrigerators have also been adjudicated, in order to benefit from their increased capacity for the high-energy runs of LEP in 1999 and 2000.

The low saturation pressure of helium at 1.8 K, and the large capacity requirements, impose the use of cold hydrodynamic compressors in the eight superfluid helium refrigeration units which will be attached to the 4.5 K cryogenic plants. As the heat of compression is released at low temperature, the efficiency of these machines strongly impacts on the technology and economics of the whole process. CERN has therefore conducted a R&D program with three industrial partners, with the aim of investigating technology alternatives and validating efficient, reliable solutions for such machines. This was done through the procurement and successful testing of three scale 1:5 prototypes [8]. In parallel with this work, cycle studies, matched to LHC boundary conditions and performance expectancy of the compressors, were conducted in collaboration with CEA Grenoble (France) and industry. As a result of this effort, a technical specification and call for tenders has been issued in July 1998 for the procurement of the final units.

A major procurement for the cryogenic system is the compound cryogenic distribution line running parallel to the magnet cryostat, and feeding the local 107-m long cooling loops with cryogenic helium at several levels of temperature (Figure 4). Following an in-house design study, a technical specification and call for tenders has been issued to industry, and prototype modules for qualification will be ordered in September 1998.

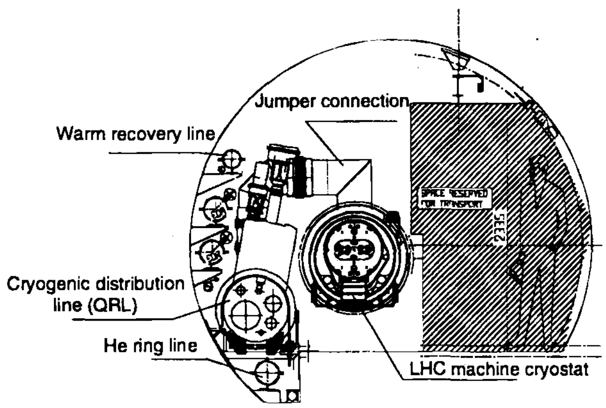

Figure 4: LHC in tunnel showing cryomagnet and cryogenic distribution line

Among the other cryogenic components being developed , it is worth mentioning the high-temperature superconductor (HTS) based current leads for 13 kA and 0.6 kA. In view of the large number and high-current rating of magnet powering circuits in the LHC, this technology will significantly alleviate the cryogenic refrigeration requirements. Prototype pairs of such current leads have been ordered from industry. The first of these has been successfully tested up to the 13 kA design current.

VACUUM

The high-intensity beams induce heat loads in the LHC vacuum system, through different processes: synchrotron radiation, beam image currents in the wall, photo- and secondary emission electrons accelerated by the electric field of the passing bunches, and nuclear inelastic scattering by the residual gas molecules [9]. The comparatively large heat loads produced by the first three processes cannot be taken at 1.9 K, and will mostly be removed by beam screens fitted inside the magnet cold bores, and cooled by circulation of supercritical helium between 5 and 20 K. Nuclear scattering, however, can only be limited by maintaining the low residual pressure required by beam lifetime in the 20 h range. As the cryopumping capacity of the 5-to-20 K surface is much smaller than that of the 1.9 K cold bore, gas molecules desorbed from the beam screen by synchrotron radiation would gradually deteriorate the vacuum. The beam screens are therefore punched with holes over 2% of their surface, so that the desorbed molecules may be cryopumped by the cold bore at 1.9 K, which remains sheltered from impinging synchrotron radiation. This effect has been demonstrated experimentally on a test section operated in VLEPP at BINP Novosibirsk (Russia).

The possible resonant build-up of a cloud of photo-emitted and secondary electrons by the successive proton bunches, could provoke beam instability. This can be avoided by using low-reflectivity surfaces coated with a material providing low photoelectric and secondary-emission yield. While R&D work is still in progress towards detailed investigation of these effects and of their cures, the main components of the beam vacuum system have been designed, and full-scale prototypes, manufactured in industry, will be tested in the accelerator test string.

ACCELERATOR TEST STRING

The accelerator test string, assembled from prototype dipole and quadrupole cryomagnets, is a 35-m long working model of a half-cell of the LHC. Since its commissioning in December 1994, it has proved invaluable to investigate system aspects beyond the reach of single-magnet tests, such as cryogenic transients and control dynamics, electrical and thermohydraulic quench propagation effects, beam and insulation vacuum performance, as well as installation and quality assurance procedures. The test string has operated for more than 11'500 hours at 1.9 K, undergone almost 50 provoked quenches at nominal current or higher, and been subjected to accelerated lifetime tests, in the form of 2200 powering cycles to 12.4 kA, as well as thermal cycles, simulating more than 10 years of integrated operation.

CIVIL ENGINEERING

The LHC makes use of the existing infrastructure of LEP, including the four experimental halls at the even-numbered Points, to house experimental detectors or machine utilities. However, a considerable amount of new civil construction is needed for housing the two large experimental detectors ATLAS and CMS, for the two long transfer tunnels from the SPS, as well as for surface technical buildings and assembly halls. The corresponding civil work has been split into four lots, for which contracts have been adjudicated to industry. Following formal acceptance by authorities in the Host States, ground breaking has started at all locations around the LHC in the summer of 1998.

OUTLOOK

After a decade of R&D on the critical technologies of high-field superconducting magnets and superfluid helium cryogenics, the LHC construction is now in full swing. Special contributions have been secured through bilateral agreements with non-member states in many regions of the world. Procurement contracts have been adjudicated, and firm offers obtained from industry, at budget prices, for more than 45% of the total value of the project. The momentum gathered so far gives confidence in meeting the aggressive construction schedule [10] which foresees an injection test in a full sector by 2003, and first circulating beams in 2005.

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