Advanced Technology Issues in the LHC Project

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Abstract

The LHC (Large Hadron Collider) project is based on a pair of superconducting storage rings to be installed in the LEP tunnel. The primary objective of the machine is to provide proton-proton collisions with a centre of mass energy of 14 TeV and an unprecedented luminosity of 10^{34} cm^{-2} s^{-1}. It will also provide colliding beams of Pb ions and a number of proposals are under study for B-physics experiments, either with colliding beams or in fixed-target mode. In a second phase, e-p collisions could be provided if desired by colliding the proton beam in one of the rings with LEP. The most critical elements of the LHC are the superconducting magnet system operating at a bending field of 8.65 Tesla and its associated cryogenic system. In order to reach this high field, the magnets must be cooled to below 2 degrees Kelvin over more than 24 km of its circumference. In addition, space limitations in the tunnel as well as cost considerations dictate a novel two-in-one magnet design where the two rings are incorporated into the same cryostat. An overview of the project status is given and the main technological issues are discussed.

1. INTRODUCTION

The CERN Large Hadron Collider will provide proton-proton collisions with a centre of mass energy up to 14 TeV with a nominal luminosity of 10^{34} cm^{-2} s^{-1} and heavy ion (Pb-Pb) collisions with a luminosity of up to 10^{27} cm^{-2} s^{-1}. The reference design of the LHC has been presented at several conferences and two design reports exist [1, 2, 3]. The main parameters of the machine for proton-proton operation are given in Table 1.

Table 1

Energy	(TeV)	7.0
Dipole field	(T)	8.65
Luminosity	(cm^{-2} s^{-1})	10^{34}
Beam-beam parameter		0.0032
Injection energy	(GeV)	450
Circulating current/beam	(A)	0.53
Bunch spacing	(ns)	25
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
Crossing angle	(μrad)	200
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

The basic layout of the LHC mirrors that of LEP, with eight long straight sections available for experimental detectors or utilities (Figure 1). The present experimental programme envisages two high luminosity proton-proton experiments (ATLAS and CMS), one heavy ion experiment (ALICE) and a possible B-physics initiative to be chosen from a number of proposals. Two major utilities, the beam cleaning and dump insertions also require long straight sections. The existing LEP experimental caverns at the even numbered points will be modified and reused as much as possible but the size and shape of the major proton-proton detectors, in particular ATLAS makes it economically sensible to open up a new experimental area at Point 1 of the machine.

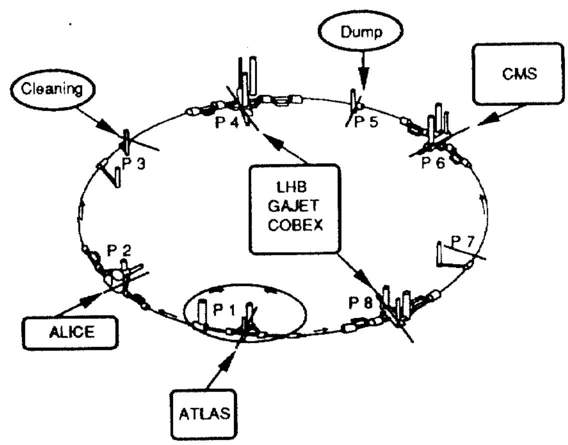

Figure 1 Layout of experimental areas.

In view of the fact that the machine will be installed in the existing 27 km circumference LEP tunnel, considerable technological innovation is needed to achieve the high magnetic field required to fit the two rings into the existing tunnel cross section whilst leaving enough space for an eventual lepton ring based on existing LEP components for possible future ep operation. In this report, design features of the major systems are reviewed with particular emphasis on the technological developments required to achieve the performance goals.

2. INJECTORS

The existing accelerator chain (Linac/ Booster/ PS/ SPS) will be used for LHC injection. The achievement of the small transverse emittance, high bunch intensity and bunch spacing shown in Table 1 requires substantial modifications in the PS and Booster. In the Booster a new harmonic h=1 system will be needed for acceleration with a superimposed h=2 system for bunch shaping in order to minimize the space charge effects. In addition, in order to reduce the Laslett detuning in the PS at injection, the booster energy must be upgraded from 1 GeV to 1.4 GeV (kinetic).

In the PS the main hardware addition will be a harmonic 84 (40 MHz) RF system for rebunching the protons to give the time structure finally required for the LHC.

Recently, machine experiments where one of the Booster rings was modified to give the necessary beam parameters have succeeded in producing bunches at PS extraction (26 GeV) of the nominal emittance and intensity for the LHC.

3. MAGNETS

The magnet system [4] contains many innovative features in order to reduce cost and to fit the two rings into the constrained geometry of the LEP tunnel. The basic structure of both dipoles and quadrupoles are the two-in one design, where the two beam channels are incorporated into a single iron yoke and cryostat (Figure 2) and operating in superfluid helium to achieve the very high guide field required. In order to retain the very large bursting force of more than 500 tons per meter the coils must be very firmly clamped in a rigid mechanical structure. Combined aluminium collars have been chosen instead of the alternative separate stainless steel collars in order to minimise the pre-stress required at room temperature and to ensure the best possible parallelism between the dipole fields in the two channels.

Each fifty one meter long lattice half-period contains three dipoles with a nominal field of 8.65 Tesla each 13.14 meters in magnetic length and a short straight section containing a 3.05 meter long quadrupole with a gradient of 220 T/m together with correction elements, quench protection diodes, beam instrumentation and a cryogenic service unit in which the primary superfluid helium is fabricated. The dipole, octupole and sextupole correction elements adjacent to each quadrupole are not of the 2-in-1 construction in order to completely decouple the two rings as far as the correction packages are concerned.

The main characteristics of the dipole magnet are given in Table 2. The regular lattice will require 1280 dipoles and 384 quadrupoles as well as the specialised elements in the dispersion suppressors and insertions.

In order to achieve the unprecedented value for an accelerator magnet of 8.65 Tesla in the dipoles, the magnets must be cooled to 1.9 K below the lambda point of helium. The magnet cryostat must therefore be of an advanced design in order to limit the heat influx to the 1.9 K cold mass. This requires two layers of thermal insulation (Figure 2) to intercept the radiated heat at temperature levels of 50 K and 4.5 K as well as a careful design of the cold mass support structure. The cryostat also serves to carry the considerable amount of cryogenic piping, thus obviating the need for a separate line.

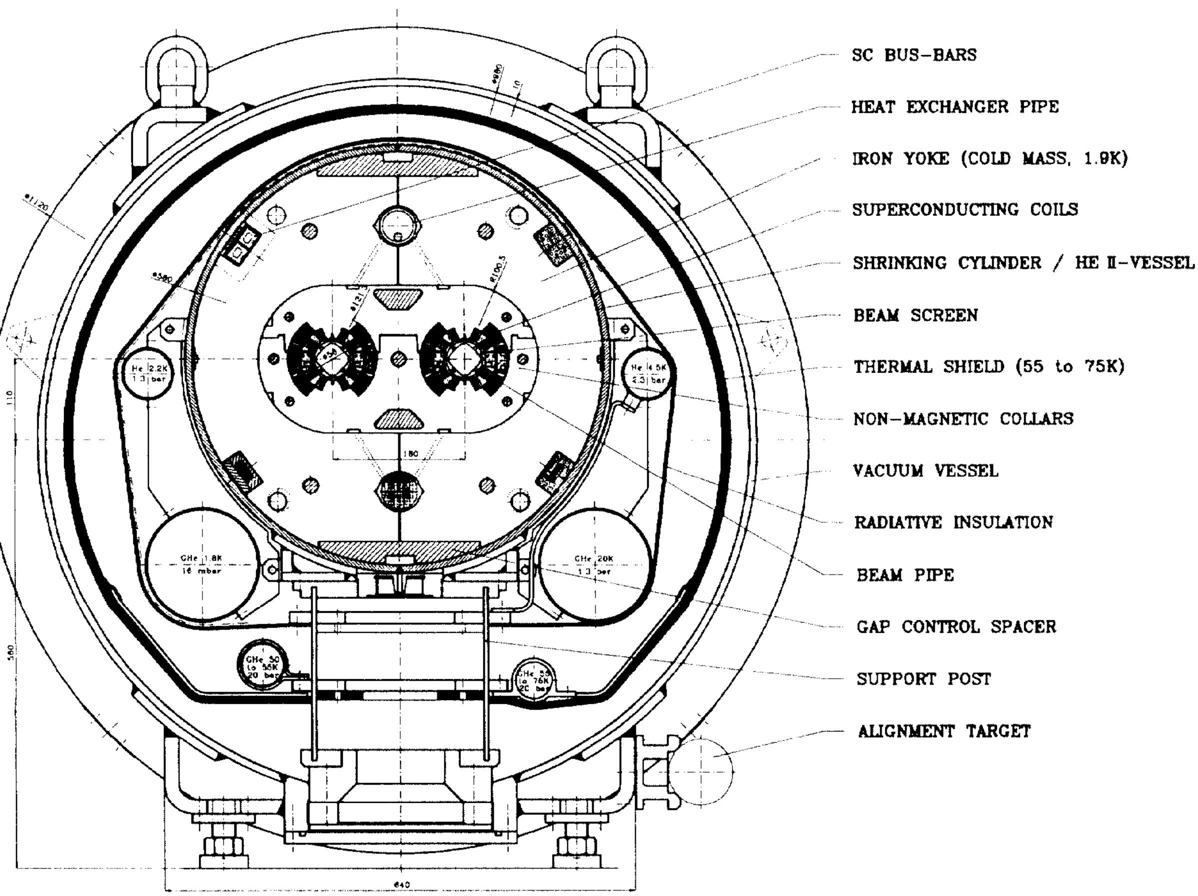

Figure 2 Cross section of the dipole magnet.

Table 2
Dipole Parameters

Operational field	(T)	8.65
Coil aperture	(mm)	56
Magnetic length	(m)	13.145
Operating current	(A)	12000
Operating temperature	(K)	1.9
Coil turns per beam channel:		
inner shell		30
outer shell		52
Distance between aperture axes	(mm)	180
Outer diameter of cold mass	(mm)	560
Overall length of cold mass	(mm)	14085
Outer diameter of cryostat	(mm)	980
Overall mass of cryomagnet	(t)	29
Stored energy for both channels	(MJ)	7.2
Self-inductance for both channels	(mH)	110

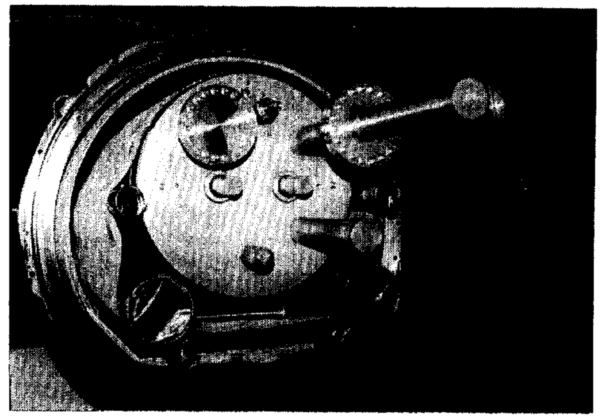

Figure 3 The first long dipole prototype.

The quench protection [5] system is based on the so-called "cold diode" concept. The diodes will be installed in the He-II cryostat of the short straight section of a half cell where they could be exposed to a radiation dose of up to 50 kGy and a total neutron flux of 10^{15} n/cm^2 over 10 years. Test results obtained by irradiating diodes at liquid nitrogen temperature in an SPS beam line have shown that only the thin base epitaxial diodes are really radiation resistant and that annealing by carrier injection and occasional warm-up to room temperature can extend the service life of irradiated diodes considerably.

The large stored energy (500 kJ/m) of the magnets make it necessary to detect quickly a developing quench and fire strip heaters which spread the quench over the full volume of the magnet. Since the quench protection diodes operate at the level of the half cell, these heaters must be fired not only in the quenching magnet but also in its neighbours

A considerable amount of development work on the main dipole and quadrupole design has already been done.Ten 1.3 m long dipole models have been constructed and tested. Detailed results of these tests have been reported elsewhere [6]. Generally these models have behaved in a very similar way, achieving short sample field with little or no training at 4.2 K and showing some training behaviour at 1.8 K. All models have exceeded 9 T, with the best reaching 10.5 T. The great majority of quenches are observed to occur in the magnet ends.

Seven 10-meter long prototypes have been ordered in industry and the first two have arrived at CERN (Figure 3). The first of these has been fully tested. It reached 8.67 T on the first quench and 9 T after two more quenches. Measurements of field quality have shown that the multipole coefficients are close to the values expected. The other five prototypes will arrive at CERN before the end of the year. Three of these, together with a short straight section will be mounted in a "string" test facility simulating the basic half-cell, cryogenically cooled, powered and protected in an identical way to the real machine. The string will be mounted on a slope of 1.4%, the maximum slope of the LEP tunnel in order to simulate the cooling of the magnets under the least favourable conditions.

Two full-size quadrupoles of 56 mm aperture and 3 meters length have been designed and constructed under a CERN-CEN/Saclay collaboration agreement [7]. Both magnets have been tested and have reached their design field with very few training quenches. The quadrupoles will be mounted into short straight sections (Figure 4) which also contain the beam pick-up monitor, dipole, sextupole and octupole correction elements and the quench protection diodes. The precise alignment of this ensemble is very important. The straight section also contains a vacuum barrier of advanced composite material to segment the insulation vacuum and the cryogenic service unit from which the primary superfluid is derived.

Models of the main correction elements have also been successfully built [8]. Prototypes of the tuning quadrupole (120 T/m, 0.8m length) and octupole corrector (10^5 T/m^3) have been built in industry. A prototype combined dipole/ sextupole corrector (1.5 T, 8000 T/m^2) has been built and tested at 4.5 K at RAL and at 1.8 K at CERN. A single aperture enlarged quadrupole for the low-beta insertions is being built in collaboration with industry (250 T/m, 70 mm bore) [9]. An important feature of this quadrupole is the very large heat flux (up to 40 W) it must absorb due to irradiation by particles from the interaction point.

The LHC magnet system will involve one of the most massive applications of superconductivity ever undertaken. About 1200 tons of conductor will be needed of which more than 400 tons will be Nb/Ti alloy. A large amount of research and development on the superconducting cable has been required to achieve the required performance. More than 70 km of cable satisfying all the main requirements have been produced by five European manufacturers to date.

The two-layer coil uses graded cable with different conductors in the inner and outer layer. The main characteristics of the wire and cable are given in Table 3.

To reduce persistent and eddy current effects during ramping of the magnets the filaments must be very fine, 6/7 microns diameter. The finished cable must also have very tight dimensional tolerances (6 microns in the 1.47 mm mid-plane thickness) in order to achieve the required field quality in the finished magnets.

One particular problem to be overcome is that of current sharing in the conductors distorting the magnetic field during ramping. In order to minimise this effect an inter strand resistance of at least 10 mΩ is needed. A number of coating materials for the cable strands are under investigation. These include Ni, AgSn and "poisoned" Sn coatings.

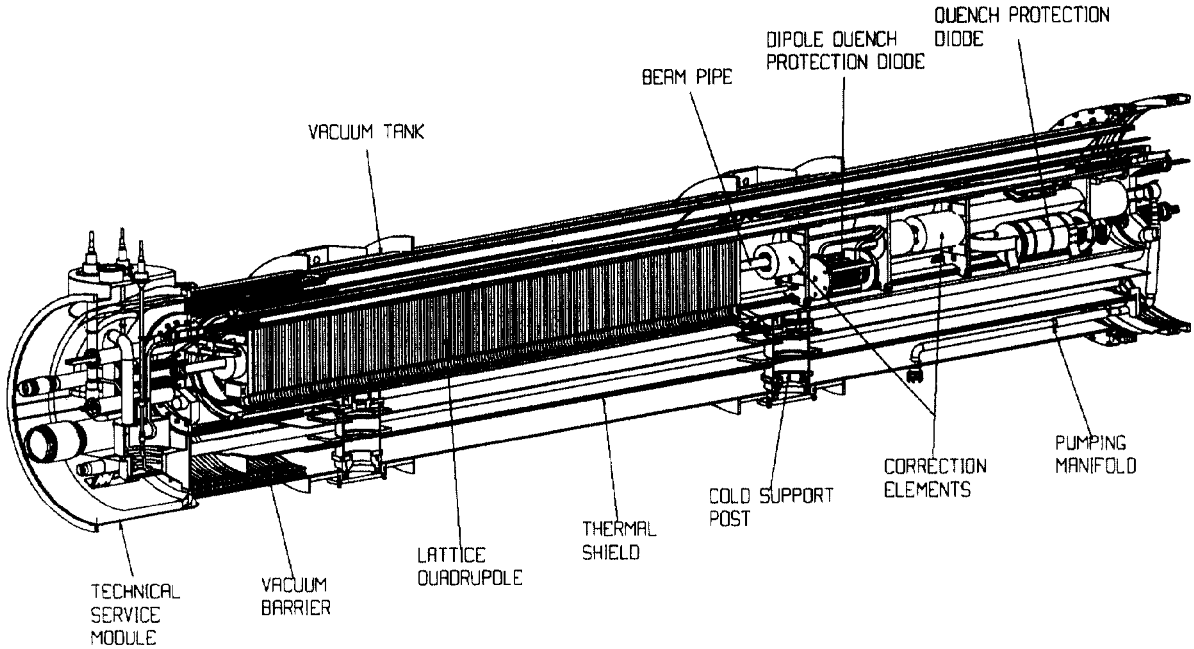

Figure 4 Short straight section.

Table 3
Cable parameters

		Inner layer	Outer layer
Strand			
Diameter	(mm)	1.065	0.825
Cu/Sc ratio		1.6	1.9
Filament size	(mm)	7	6
Number of filaments		8900	6520
Twist pitch	(mm)	25	25
Critical current	(A)		
10 T, 1.9 K / 9T, 1.9 K		≥ 510	≥ 370
Cable			
Number of strands		28	36
Cable dimension:			
thin edge	(mm)	1.72	1.34
thick edge	(mm)	2.06	1.60
Transposition pitch	(mm)	110	100
Critical current	(A)		
10 T,1.9 K/9 T,1.9 K		≥ 13750	≥ 12960

4. CRYOGENICS

Cooling the 30000 tons of material in the LHC magnets poses a particular challenge [10]. The elementary LHC cooling loop matches the periodicity of the machine lattice and corresponds to the half-cell of 51m length (Figure 5). Static superfluid helium pressurised at 1 bar permeating the magnet laminations is cooled by heat exchange with saturated superfluid helium flowing through a tube running through the magnet chain over the whole length of the half-cell. Sub-cooled helium (2.2K) is tapped from line A, expanded to saturation through a Joule-Thomson valve and sent to the end of the loop from where it returns, gradually vapourising as it gathers heat in the heat exchanger tube. The whole loop including heat exchanger tube and phase separator is maintained at saturation pressure by line B, through which cold helium vapour is pumped back to the cryoplant.

An important advantage of using the latent heat of vapourisation is that the temperature of each magnet is independent of its distance from the cryoplant. A key technology for the attainment of large capacity refrigeration in this temperature range is the development of cold sub-atmospheric helium compressors. The design of these units builds on previous experience at the Tore Supra tokamak and at CEBAF. In view of the importance of this technology, CERN has launched in collaboration with CEA (Grenoble) a comprehensive development programme on the design, construction and testing of a prototype LHC multistage cold compressor box.

The four existing LEP cryoplants, each of 12 kW capacity at 4.5K will be boosted to 18 kW and supplemented by a further four units of the same capacity. The eight cryogenic units will be concentrated at the four even LEP pits where adequate infrastructure including compressor buildings and cooling towers already exist. Consequently, the whole octant, 3.4 km in length must be supplied with liquid helium from the even points.

The cryogenic infrastructure for LEP already uses a two stage cold box in order to avoid large hydrostatic pressure. The upper cold box on the surface cools helium gas to 20 K whereas the lower cold box at tunnel level performs the final liquefaction. The lower cold box will be supplemented by a cold compressor box responsible for further cooling of the liquid to just above the lambda point and for the production ofthe 16 mb pressure in the low pressure line. In order to avoid a too large pipe diameter the lower cold compressor box is split into two, one at each end of the octant.

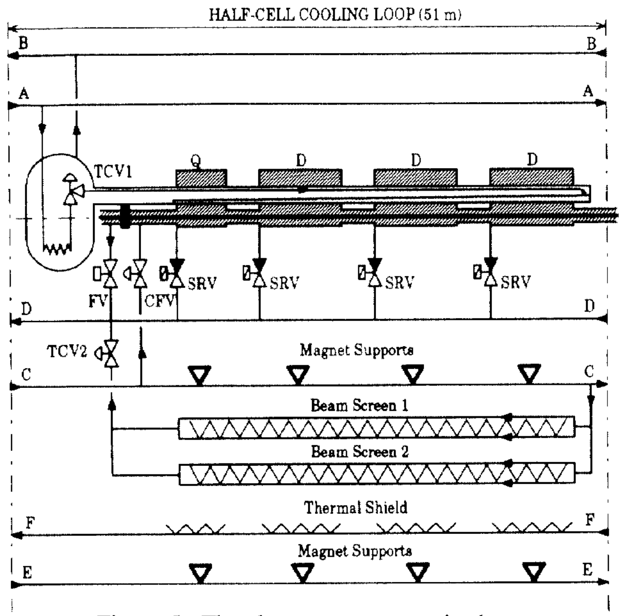

Figure 5 The elementary cryogenics loop.

5. VACUUM

The LHC beam vacuum poses particular problems [11]. Due to the synchrotron radiation emitted by the protons (4 kW per ring at 7 TeV) and the heating due to the image currents in the wall of the vacuum chamber, the magnet cold bore at 1.8 K must be shielded from the beam, otherwise the required cryogenic power would become excessive. (1 Watt at 2K needs approximately 1 kW at room temperature.) An inner liner cooled to around 20 K through tubes carrying high pressure gas will therefore be installed inside the cold bore.

Synchrotron radiation impinging on this liner will cause gas to be desorbed from the bulk material which will in turn be cryopumped to the surface of the liner. This is particularly undesirable especially for hydrogen. Once a surface layer of this gas builds up the pressure will rise to that of the vapour pressure of hydrogen at the temperature of the liner, more than two orders of magnitude higher than required for an adequate beam lifetime. In order to avoid this, slots must be cut in the liner so that hydrogen can be cryopumped by the cold bore surface at much lower temperature.

The inner wall of the liner must be copper plated in order to reduce the growth rate of the transverse resistive wall instability to a tolerable value but at the same time it must be able to withstand the strong forced due to eddy currents during a quench.

6. BEAM DUMP

In order to remove the beams from the machine in a safe and efficient manner at the end of a physics run or in case of equipment malfunction, two beam dumps are required. Each beam dump must be able to absorb the stored energy of more than 300 MJ per beam and will be built from a graphite core surrounded by aluminium and iron, with a total weight of close to 1000 tons.

The kickers needed to extract the beam must have a rise time of 3 µs with a flat top length of 89 µs and must operate at a very high field of up to 0.85 T. Such field levels are beyond the capability of ferrite magnets. Instead, a construction based on tape-wound cores made from 0.05 mm thick silicon steel is envisaged. A prototype kicker based on this design has been built and first results are encouraging.

The kicker pulse generators require fast high power switches (35 kV, 30 kA, 6 µs) of very low repetition rate and high reliability. Alternative solutions based on both pseudo-spark switches employing ferro-electric triggers [12] and alternative solid state devices [13] are being developed in collaboration with industry.

7. CONCLUSIONS

The considerable amount of R&D accomplished over the past few years has validated the main technical choices for the construction of the LHC. In particular, the two-in-one magnetic structure operating at high field in helium II has proved to be a cost effective and viable solution for obtaining the required performance.

8. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the outstanding contribution of Giorgio Brianti, who has guided this project from its conception.

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