THE LARGE HADRON COLLIDER

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The Large Hadron Collider (LHC) project was approved by the CERN Council in December 1994. The machine will provide proton-proton collisions with a centre of mass energy of 14 TeV and an unprecedented luminosity of 10^{34} cm^{-2} s^{-1}. In order to achieve the design energy within the constraint of the 27 km circumference LEP tunnel, the magnet system must operate in superfluid helium below 2 K, with a dipole field of 8.4 Tesla. In addition, space limitations in the tunnel as well as cost considerations dictate a two-in-one magnet design, where the two rings are incorporated into the same cryostat. The machine will also provide heavy (Pb) ion collisions with a luminosity of 10^{27} cm^{-2} s^{-1} using the existing CERN ion facility. Space will be kept above the LHC for the eventual reinstallation of components of the LEP machine to provide future e-p collisions if the physics case justifies it.

I. 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]. The main parameters of the machine for proton-proton operation are given in Table 1.

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 fit the two rings into the tunnel cross section whilst leaving enough space for an eventual lepton ring. The LHC will be installed on the tunnel floor after removal of the LEP ring. However, space will be kept free above the LHC for the future installation of a lepton machine using LEP components for e-p collisions (Figure 1).

The basic layout of the LHC mirrors that of LEP, with eight long straight sections each approximately 500 meters in length available for experimental insertions or utilities (Figure 2). Two high luminosity proton-proton experiments are located at diametrically opposite straight sections, Point 1 (ATLAS) and Point 5 (CMS). Two more low-beta insertions are located at Point 2 (ALICE, Pb ions) and Point 8 (B-physics), which also contain the two injection systems. The beams cross from one ring to the other at these four locations.

The remaining four long straight sections do not have beam crossings. Points 3 and 7 are used for beam "cleaning" and collimation. The beam abort system is located at Point 6 and Point 4 remains spare.

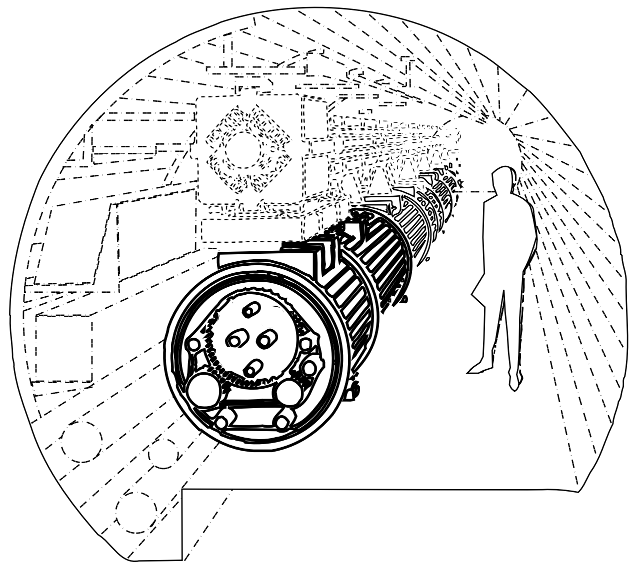


Figure 1: LHC with space for a future lepton machine

Table 1

Energy	*(TeV)*	7.0
Dipole field	*(T)*	8.4
Coil aperture	*(mm)*	56
Distance between apertures	*(mm)*	180
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		$1\text{x}10^{11}$
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)*	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

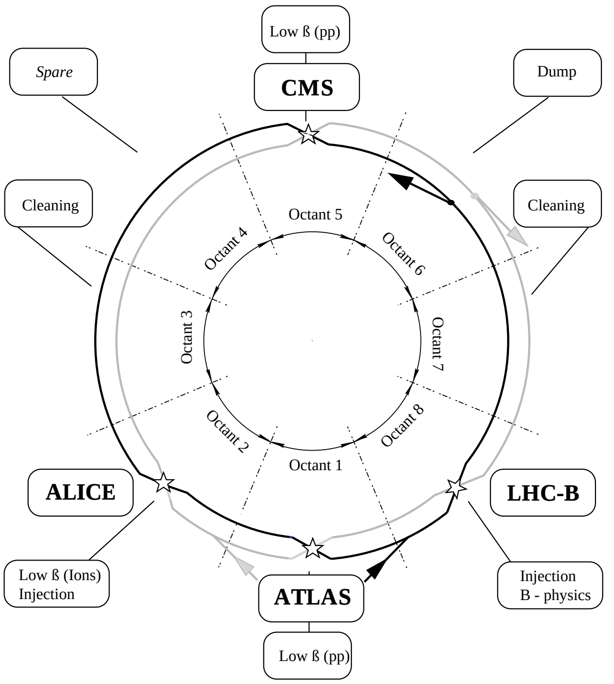


Figure 2: Schematic layout of LHC

II. INJECTORS AND INJECTION PROCESS

The existing accelerator chain (Linac/Booster/PS/ SPS) will be used for LHC proton 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 beams with the correct time structure for the LHC. In the SPS, the main additions are an 80 MHz (700 kV) RF system for capturing the injected beam and a 400 MHz superconducting RF system (6 MV peak) in order to match the bunches to the LHC buckets.

Two new extraction systems at Points 4 and 6 of the SPS are needed together with two new transfer lines at 450 GeV/c to Point 8 of the LHC (counter clockwise beam) and Point 2 (clockwise beam). Injection into the LHC is made horizontally with copper septum/kicker systems. Both injections are made into the outside ring.

The filling sequence starts with the injection of three bunch trains with the right spacing between bunches (25 nsec) into the SPS on three successive PS cycles each separated by 3.6 seconds, filling one third of the SPS circumference. The SPS then ramps to 450 GeV/c and transfers each batch (each containing 4×10^{13} protons) to one or the other of the LHC rings. This is repeated 12 times per ring with a cycle time of 16.8 seconds.

During the injection process the low-beta insertions are detuned in order to reduce the beta values to a tolerable level in the insertion quadrupoles. Once both rings are filled, the beams are accelerated to the nominal collision energy in about 20 minutes.

III. MACHINE LAYOUT

A. The regular arcs

The arcs contain 23 regular lattice periods per octant. Each lattice period, 106.9 meters in length, is made up of six two-in-one dipoles, each with a magnetic length of 14.2 meters [3]. Each dipole contains short sextupole and decapole correctors in order to compensate for unwanted field harmonics. The lattice quadrupoles are 3 meters long with a maximum gradient of 250 T/m and are powered separately from the dipoles. The coil aperture is the same as that of the dipoles (56 mm). The quadrupoles are integrated into "short straight sections" which also contain a closed orbit correction dipole, chromaticity correction sextupoles and some free space for either an octupole or a skew quadrupole. The short straight section also contains a beam pick-up monitor and a cryogenic service unit for the production of the primary superfluid helium needed to cool each half-cell.

The nominal phase advance per cell is 90 degrees although it will be possible to split the horizontal and vertical tunes by a few units in order to make the machine less sensitive to systematic coupling.

B. The dispersion suppressors

The transitions from each of the arcs to the long straight sections are made through "dispersion suppressors". Each dispersion suppressor consists of two perturbed lattice periods with four dipoles per period instead of six and four independently powered quadrupole units. In order to reduce the number of high current feedthroughs, each quadrupole unit consists of a main quadrupole powered in series with the lattice together with a low current trim quadrupole 1.5 meters long, independently powered to allow for optics variations during squeezing of the insertions to their final configurations.

C. The low-beta insertions

The layout of a low beta insertion is shown in Figure 3 together with the optical functions during collision (β^*= 0.5 m). The insertion is antisymmetric and consists of a matching section (the outer triplet) for detuning the optics, and an inner triplet focusing the beams to the interaction point. Between the two, a pair of recombination dipoles bring the beams into a common channel with a small crossing angle (± 100 μrad) at the interaction point. The outer triplet quadrupoles are two-in-one magnets with the

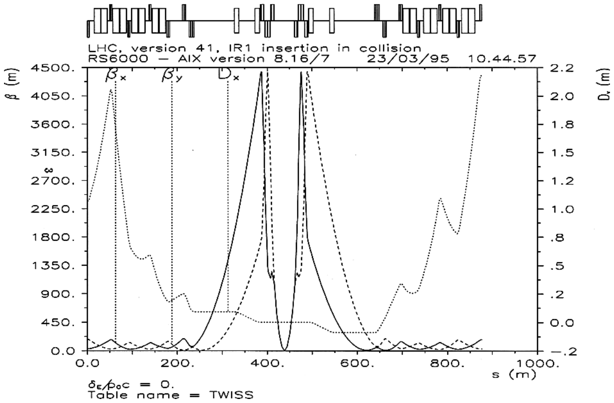


Figure 3: Low-beta insertion

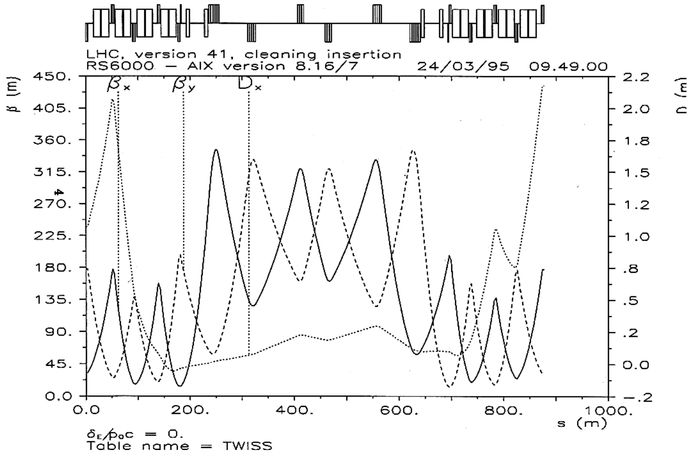


Figure 4: Cleaning insertion

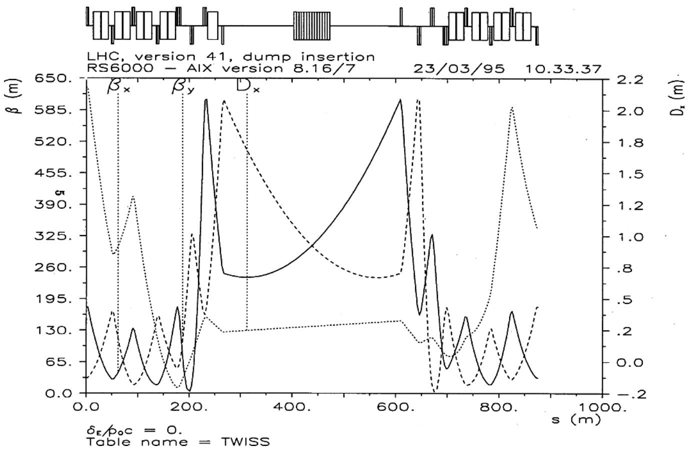


Figure 5: Dump insertion

same cross section as the regular lattice quadrupoles whereas the inner triplet quadrupoles are single bore with the aperture increased from 56 mm to 70 mm (gradient 250 T/m). In the two high luminosity insertions, a free space of ± 23 meters between the two inner triplets is available for the experiments, whereas for the other two insertions this space is reduced to ± 21 meters to allow more room for injection.

During injection and acceleration, the insertion is "detuned", bringing the maximum beta value down from its collision value of about 4500 m to below 400 m.

D. The cleaning insertions

The rôle of the cleaning insertion is to allow for collimation and cleaning of the beam halo in order to minimize the background in the experimental detectors as well as the beam losses in the cryogenic parts of the machine. Two such insertions are foreseen at Points 3 and 7.

The insertion consists of a "pseudo FODO" structure containing only classical magnets (Figure 4). At each end of the insertion there is a double dogleg consisting of a pair of dipoles of opposite polarity which increases the beam separation from 180 mm to 210 mm. This ensures that the spray of neutral secondaries from collimators between the dipoles is directed away from the downstream arc and also makes the design of the two-in one warm quadrupoles easier.

E. The beam abort insertion

The purpose of the abort insertion is to dump the beams in a clean and safe way at the end of physics runs or to protect the machine in case of hardware failure or beam instability. The optics of the insertion is shown in Figure 5.

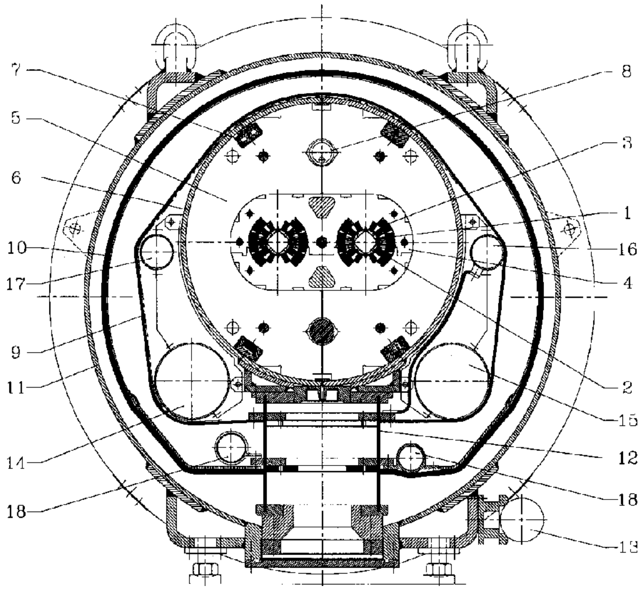
The optics is designed to provide a very long (340 m) drift region at the centre of which is placed a vertically deflecting double Lambertson septum. The beam dump kickers located at the beginning of the straight section deflect the beams horizontally across the septum in which they are vertically extracted from the machine.

IV. MAGNETS

A. Overall design

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 6) and operating in superfluid helium to achieve the very high guide field required. In order to retain the 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.

The main characteristics of the dipole magnet are given in Table 2. The regular lattice and dispersion suppressors will require 1232 dipoles and 368 normal quadrupoles as well as special quadrupoles in the matching and insertion regions.



1. Beam screen, 2. Beam pipe, 3. Superconducting coils, 4. Non-magnetic collars, 5. Iron yoke, 6. Shrinking cylinder/ HeII vessel, 7. Sc. bus-bars, 8. Heat exchanger pipe, 9. Radiative insulation, 10. Thermal shield (55 to 75 K), 11. Vacuum vessel, 12. Support post, 13. Alignment target, 14. 1.8 K GHe pipe, 15. 20 K GHe pipe, 16. 4.5 K GHe pipe, 17. 2.2 K GHe pipe, 18. 50÷75 K GHe pipe.

Figure 6: Cross section of the dipole magnet.

Table 2

Dipole Parameters

Operational field	*(T)*	8.4
Coil aperture	*(mm)*	56
Magnetic length	*(m)*	14.2
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)*	15140
Outer diameter of cryostat	*(mm)*	980
Overall mass of cryomagnet	*(t)*	31
Stored energy for both channels	*(MJ)*	7.2
Self-inductance for both channels	*(mH)*	110

In order to achieve the unprecedented value for an accelerator magnet of 8.4 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 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.

B. Hardware status

A considerable amount of development work on the dipoles and quadrupoles has already been done. More than a dozen short models have been constructed and tested. All of these models have exceeded 9 T with the best reaching 10.5 T.

Four 10 meter long industrially built prototypes have been tested. All magnets have exceeded 9 T with some training. Detailed results are given elsewhere in these proceedings [5]. In addition, two full size quadrupoles have been designed and constructed under a CERN-CEA/Saclay collaboration agreement. Both magnets have reached their design gradient with very few training quenches.

Two long dipoles and a short straight section containing one of the quadrupoles have been assembled into a "string", simulating the basic half-cell, cryogenically cooled, powered and protected in an identical way to the real machine. This unit became operational at the end of 1994 and has run at the LHC nominal design field for an extended period. More details can be found elsewhere in these proceedings [6].

V. CRYOGENICS

Cooling the 30'000 tons of material in the LHC magnets poses a particular challenge. The elementary LHC cooling loop matches the periodicity of the machine lattice and corresponds to the half-cell of 53 m length (Figure 7). 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 (2.2 K) 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 in Grenoble a comprehensive development programme on the design, construction and testing of a prototype LHC multistage cold compressor box.

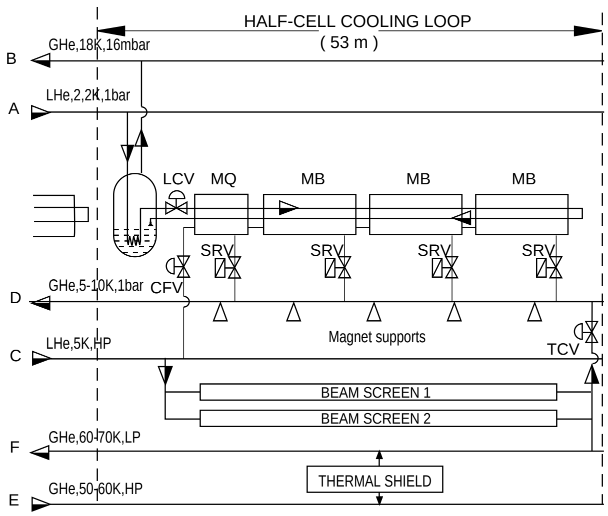


Figure 7: The elementary cooling loop

The four existing LEP cryoplants, each of 12 kW capacity at 4.5 K 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 kms in length must be supplied with liquid helium from the even points.

VI. THE RF SYSTEM

The radiofrequency system will be installed at Point 8. In order to ensure sufficiently short bunches in collision and avoid RF noise diffusion, a voltage of 16 MV per beam at the second harmonic (400.8 MHz) of the SPS frequency is needed. This will be provided by a set of eight superconducting cavities. A prototype cavity has been built and installed in the SPS for tests, where three such cavities will also be needed to match the longitudinal phase space between the two machines. During acceleration, it is necessary to increase the bunch area from the SPS value of 1 eV.s. to 2.5 eV.s. in order to obtain a good intrabeam scattering lifetime at collision energy.

VII. VACUUM

The LHC beam vacuum poses particular problems [7]. 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 2 K 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.

VIII. CONCLUSIONS

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

The main lattice parameters and the allocation of long straight sections have now been fixed. The detailed design of the specialised insertions is making good progress.

IX. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the outstanding contribution of Giorgio Brianti to this project.

X. REFERENCES

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