THE LARGE HADRON COLLIDER PROJECT

Lyndon R. Evans
CERN, Geneva, Switzerland

Abstract
The Large Hadron Collider (LHC), approved by the CERN Council in December 1994, will be the premiere research tool at the energy frontier of particle physics. It 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}. The most critical technologies of the LHC are the superconducting magnet system, with a dipole field above 8 Tesla, and the huge cryogenic system operating at below 2 K needed to achieve such high fields. A brief overview of the project is presented and the main technological challenges are discussed.

1. INTRODUCTION

The LHC will be a unique facility for basic research, providing the world's highest energies to probe the mysteries of matter and the forces that control it. The machine will be located in the existing 27 km circumference tunnel that presently houses the Large Electron Positron collider (LEP). It 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}. It will also be capable of providing heavy ion (Pb–Pb) collisions with a luminosity of 10^{27} cm^{-2} s^{-1} using the existing CERN heavy ion source. The main parameters and performance goals for proton–proton operation are shown in Table 1.

Table 1
LHC parameters

Energy	(TeV)	7.0
Dipole field	(T)	8.4
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)	0.53
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
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

In view of the fact that the machine will be installed in the existing tunnel, a very high bending field (8.4 Tesla) is needed to achieve the nominal energy. In order to achieve this goal at acceptable cost, the design is based on superconductors consisting of well developed mass produced Nb–Ti alloy operating in pressurised superfluid helium below 2 K. Space constraints as well as cost considerations dictate a novel two-in-one design of the main magnetic elements, where the two beam channels are incorporated into a single magnetic structure with the two apertures separated by only 194 mm. The main technical challenge of the project is the exploitation of applied superconductivity and large capacity helium cryogenics on an unprecedented scale, to develop them well behind the present state of the art and to integrate them in a reliable way into an accelerator environment.

2. MACHINE LAYOUT

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

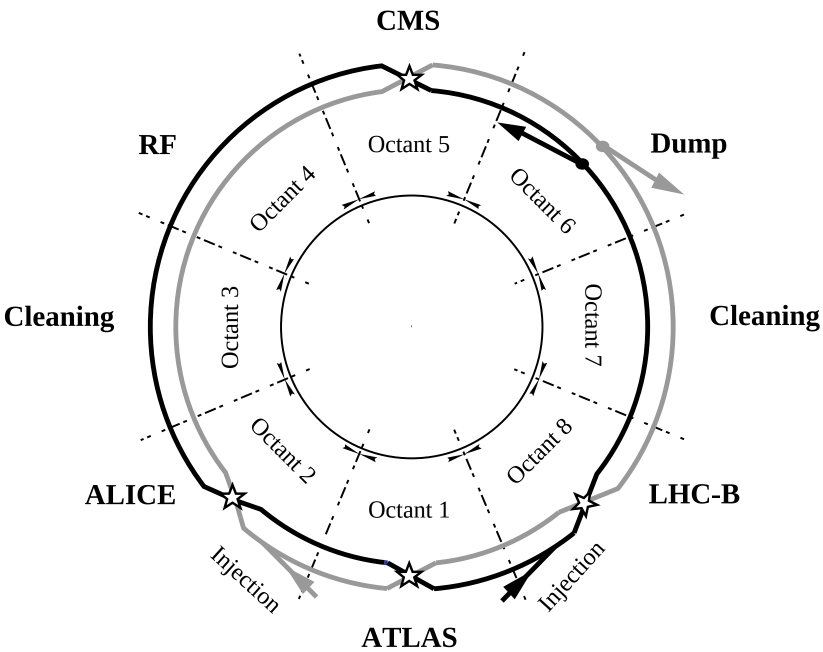

Fig. 1 Global layout of the LHC.

The remaining four long-straight sections do not have beam crossings. Points 3 and 7 are identical and are used for 'beam cleaning'. The role of the cleaning insertions is to allow for the collimation of the beam halo in order to minimise the background in the experimental detectors as well as beam loss in the cryogenic parts of the machine. These insertions contain only classical warm magnets robust against the inevitable beam loss on the primary collimators. The use of warm magnets also permits a low-current design so that their power supplies can be located in surface buildings instead of in specially constructed underground caverns as is the case for high current superconducting magnets.

Point 4 contains the Radio-Frequency acceleration systems. In an earlier version of the machine design the RF system was based on common cavities for the two beams. A more flexible design has now been adopted with separate cavities for each of the two beams, alleviating the problem of transient beam loading and damping of injection oscillations. This requires the beams to be separated from the 194 mm in the arcs to 420 mm in order to provide the transverse space needed.

Finally, Point 6 contains the beam abort insertion. The purpose of this insertion is to dump the beams in a safe and reliable way at the end of physics runs or in case of hardware failure. The principle of the beam dump system is the use of a combination of horizontally deflecting fast-pulsed kicker magnets and vertically deflecting steel septum magnets to extract the beams vertically from the machine. They are then transported along 700 metre long transfer tunnels and dumped into two massive absorbers.

Between long straight sections the arcs contain 23 regular lattice periods with a dispersion suppressor at each end. A lattice half-period, 53.5 m long, contains 3 dipoles and a short straight section incorporating a quadrupole, correction elements, a beam pick-up monitor and a cryogenic connection unit.

3. MAGNETS

The magnet system contains many innovative features in order to reduce cost and to fit the two beams into the constrained geometry of the tunnel. The basic structure of both dipoles and quadrupoles is the two-in-one design, where the two beam channels are incorporated into a single iron yoke and cryostat (Fig. 2), operating in pressurised superfluid helium. In order to retain the large bursting force of more than 500 tonnes per metre the coils must be firmly clamped in a rigid mechanical structure. For the dipoles, combined aluminium collars have been chosen in order to minimize the pre-stress at room temperature and to ensure the best possible parallelism between the dipole fields in the two channels.

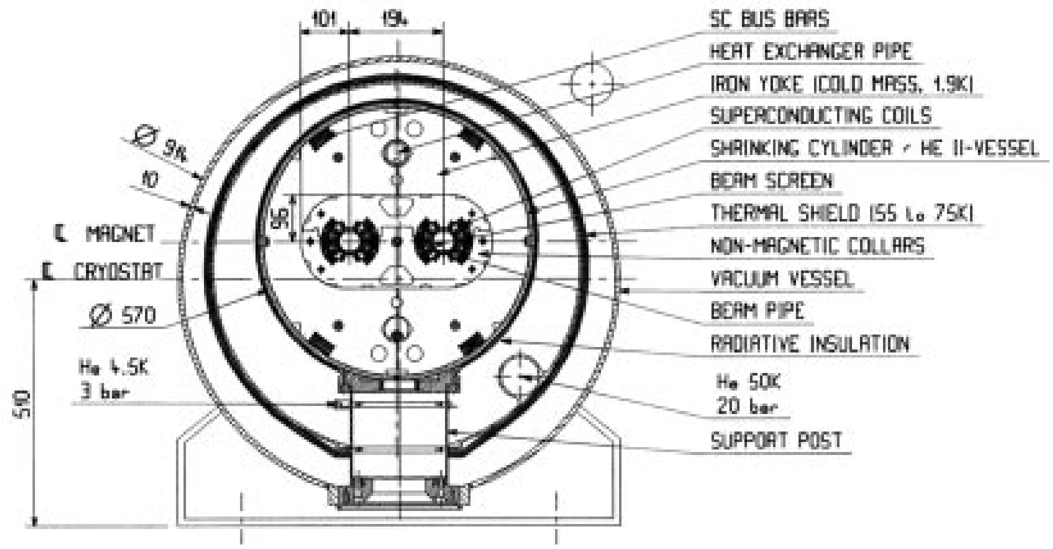

Fig. 2 Dipole magnet cross section.

The main characteristics of the dipole are shown in Table 2. The principle differences compared with the earlier machine design are an increase in coil aperture from 50 to 56 mm, an increase in length from 10 to 14.2 m and increased intra-beam separation from 180 to 194 mm. The machine will contain 1232 main dipoles.

The dipole coil is of a two-layer graded cable design in order to optimize the use of super-conductor. The main parameters of the cable for inner and outer layers are shown in Table 3. The filament size of 7 μm for the inner strand and 6 μm for the outer strand allows fabrication by a single stacking process whilst keeping persistent current sextupole and decapole components small enough to be corrected by small corrector magnets in the dipole ends. More than 25 tons of cable of the required quality has now been made by four European manufacturers.

The cables are insulated by two half-overlapping wraps of 25 micron thick polyimide tape and a third wrap of adhesive-coated polyimide tape wound in 'barber pole' fashion with a 2 mm space between windings in order to leave channels for helium penetration. A perforated glass-epoxy spacer is placed between inner and outer coil shells to provide further channels for superfluid helium. The insulation to ground is composed of superposed polyimide films including quench protection heater strips. Quench protection is assured by cold diodes connected to each dipole cold mass.

Table 2
Main dipole parameters

Operational field	(T)	8.36
Coil aperture	(mm)	56
Magnetic length	(m)	14.2
Operating current	(A)	11500
Operating temperature	(K)	1.9
Coil turns per beam channel:		
	inner shell	30
	outer shell	52
Distance between aperture axes	(mm)	194
Outer diameter of cold mass	(mm)	570
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)	7.4
Self-inductance for both channels	(mH)	119
Quantity		1232

Table 3
Strand and cable parameters

		Inner layer	Outer layer
Strand			
Diameter	(mm)	1.065	0.825
Copper to superconductor ratio		1.6	1.9
Filament size	(μm)	7	6
Number of filaments		8900	6500
RRR		≥ 70	≥ 70
Twist pitch (after cabling)	(mm)	25	25
Critical current	(A)	≥ 115 (10 T, 1.9 K)	≥ 380 (9 T, 1.9 K)
Cable			
Number of strands		28	36
Cable dimension			
thin edge	(mm)	1.72	1.34
thick edge	(mm)	2.06	1.60
width	(mm)	15.0	15.0
Critical current I_c	(A)	≥ 13750 (10 T, 1.9 K)	≥ 12950 (9 T, 1.9 K)

The main lattice quadrupole design uses the same cable as the dipole outer layer. The detailed design, being carried out at CEA-Saclay is similar to that of the dipole but since the electromagnetic forces are considerably smaller, it is possible to contain the forces by the collar structure alone as long as they are made from austenitic steel laminations. The main parameters of the arc quadrupole are given in Table 4.

Table 4

Arc quadrupole parameters

Operational gradient	(T/m)	223
Coil aperture	(mm)	56
Magnetic length	(m)	3.1
Operating current	(A)	11750
Operating temperature	(K)	1.9
Coil turns per aperture		96
Outer yoke diameter	(mm)	456
Stored energy for both channels	(kJ)	784
Self inductance for both channels	(mH)	11
Quantity		376

The magnet cryostats must be of an advanced design in order to minimize the heat in-leak at the 1.9 K level. Two intermediate heat intercept levels at 5–20 K and at 50–75 K limit the steady-state operational heat loads to 6.4 W/m at 50–75 K, 1.5 W/m at 5–20 K and 0.43 W/m at 1.9 K.

4. CRYOGENICS

Although the general principles of the LHC cryogenic system have not changed since the early design, the detailed layout has considerably evolved as more information becomes available through prototype work and model testing.

4.1 General architecture

An important principle of the LHC design is to make the maximum possible use of the technical infrastructure of the LEP machine including the cryogenic system. LEP uses four cryogenic plants, each of 12 kW at 4.5 K capacity, located at the four even points. Consequently the even points are much more developed than the odd points, equipped with cooling towers and heavy electrical infrastructure. For the LHC, the four existing plants will need to be upgraded to 18 kW and supplemented by a further four 18 kW plants. These new plants will also be located at the even points with a consequence that the refrigeration power must be transported over a full octant of 3.3 km length.

The general architecture of the LHC cryogenics scheme is shown in Fig. 3. The large plants are concentrated in pairs at the even points, with two split cold box refrigerators of the LEP type. The upper cold box (UCB) located on the surface cools helium gas to 20 K and the lower cold box (LCB) located some 80 m underground, to 4.5 K. The close proximity of the plants allows some redundancy to be built in by means of the cryoplant interconnection box (CIB). Refrigeration at 1.8 K is provided by two cold compressor boxes (CCB), consisting of multi-stage axial centrifugal compressors, installed underground and fed from the 4.5 K refrigerators through the CIB. No infrastructure or utilities are needed at the odd points apart from 1000 m^3 storage at 2 MPa for recovery of gaseous helium after a full sector quench.

The magnets operate in a static bath of pressurized superfluid helium, cooled through a linear heat exchanger in which the heat is absorbed quasi-isothermally by gradual vapourisation of flowing two-phase saturated superfluid helium (Fig. 4). The linear heat exchanger extends over each half cell, 53.5 m in length, cont ining three dipoles and a short straight section.

Sub-cooled helium from the sector refrigerator distributed through line A (Fig. 4) is expanded to saturation through valve TCV1 and fed to the far end of the heat exchanger tube, gradually vapourizing as it flows back. The low saturation pressure (16 mbar) is maintained on the flowing two-phase helium by pumping the cold gas through line B. Lines C and F provide cooling of the cryostat thermal shields at two temperature levels. In case of a quench the resulting pressure rise is contained below the 2 MPa design level by opening the quench discharge valve SRV and discharging into line D at the level of the short straight section.

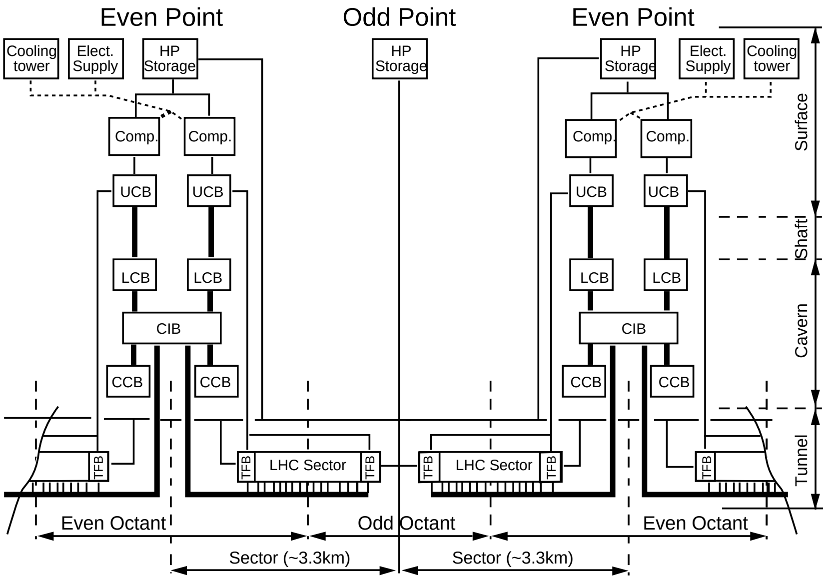

Fig. 3 General architecture of the LHC cryogenic scheme.

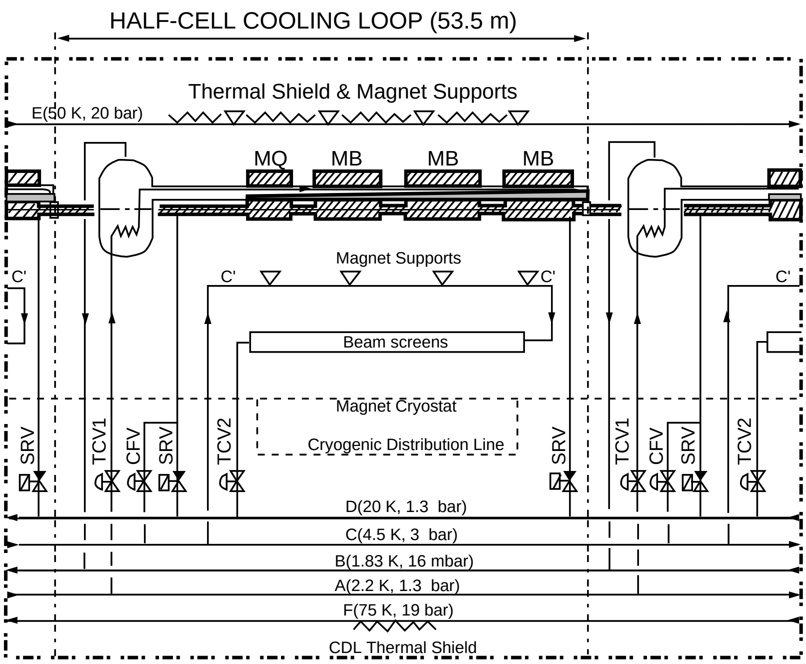

Fig. 4 Cryogenic flow scheme of an LHC half-cell.

The decision to concentrate the refrigerators at the even points has had a profound effect on the design of the cryogenic distribution. In particular, the diameter of the cold pumping line B (267 mm) needed to attain the required pressure over a full sector makes it no longer possible to integrate all piping into the magnet cryostat. Instead, a separate cryogenics distribution line (CDL) carries most of the piping, connecting to the short straight section cryostat every 53.5 m (Figs. 5 and 6). The extra cost of the CDL is offset by the savings in infrastructure cost at the odd points and better decouples the problems of the magnets from those of the cryogenic system.

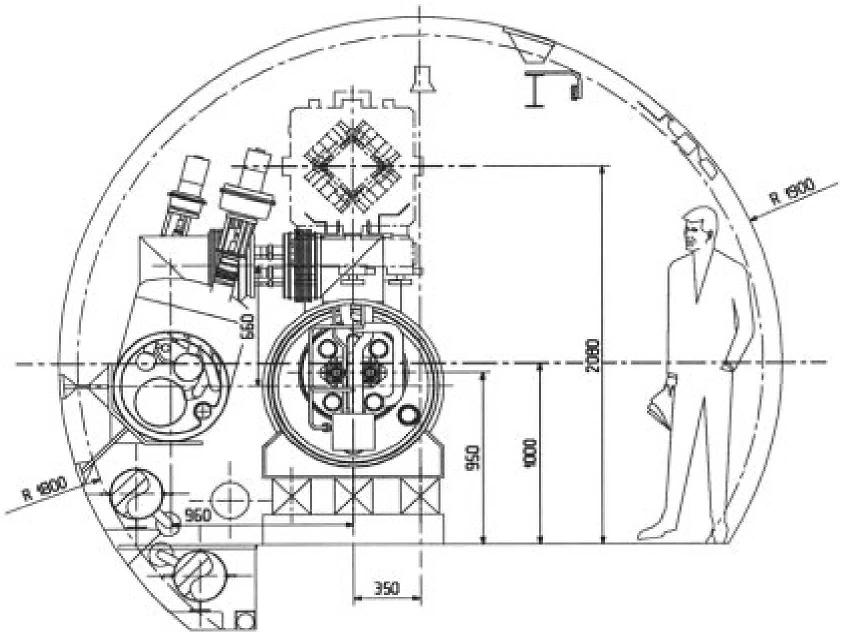

Fig. 5 Transverse cross-section of the LHC at a short-straight section.

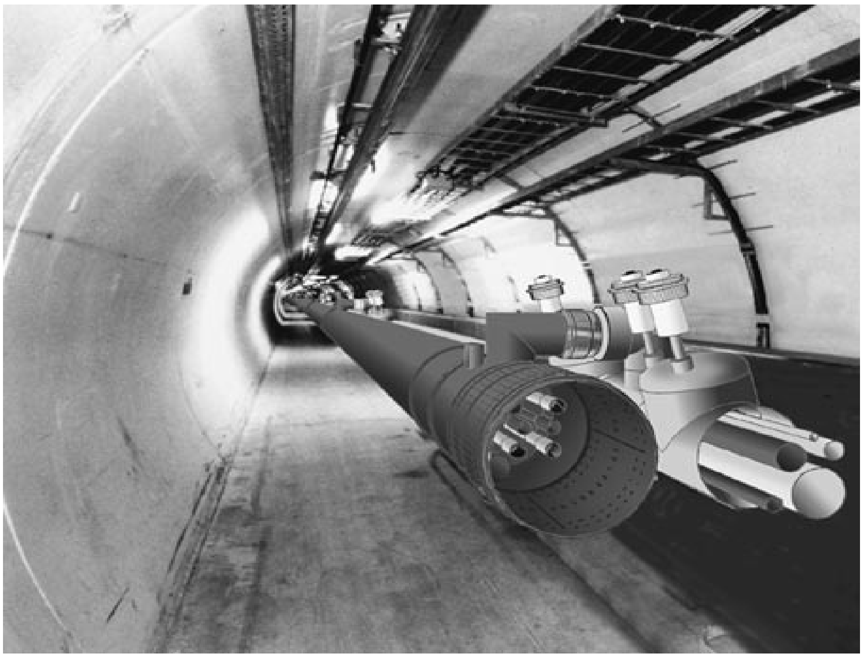

Fig. 6 Perspective view of the LHC with separate cryogenic distribution line.

5. VACUUM

The LHC beam vacuum poses particular problems. 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 1.9 K must be shielded from the beam, otherwise the required cryogenic power would become excessive. 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 would 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 1.9 K.

6. HARDWARE STATUS

A considerable amount of development work on the dipole and quadrupole have already been done. More than a dozen short models have been constructed and tested. All have exceeded 9 Tesla with the best reaching 10.5 Tesla. The main purpose of the short model programme is to optimize the coil end design and the difficult 'layer jump' region, where the two different cables of the inner and outer coils are spliced together.

Seven long dipoles of the first generation (10 m long, 50 mm aperture) have been constructed in industry and five of these have been tested at CERN. All have exceeded 9 Tesla with some training. The measured field harmonics are as expected. In addition, two full size quadrupoles have been constructed under a CERN/CEA collaboration agreement. Both magnets have reached their design gradients with very few training quenches.

A number of other prototypes have been constructed and tested including a combined dipole/sextupole, an octupole and the sextupole-and-decapole spool pieces for the correction of persistent current effects in the main dipole. Recently, a short model of a large aperture insertion quadrupole (70 mm aperture, 235 T/m) of a novel four-layer coil design has been successfully tested.

Six dipoles with the final aperture are under construction, two with the full 14.2 m magnetic length and four of 10 m length, restricted by the length of the heavy presses available at the time. All CERN-owned tooling is now being extended to the final length in preparation for pre-series production.

Three of the 10 m dipoles together with a short straight section containing one of the quadrupoles have been assembled into a 'string test facility', a simulated half-cell of the real machine (Fig. 7). This facility has been operational for more than a year and has yielded extremely valuable information feeding back into the optimization of the machine design. In particular it has validated the superfluid helium cooling scheme as well as the principle of discharging helium gas in case of a quench only at the ends of a half cell and not at each individual dipole as originally foreseen. The string is now being prepared for a long life test, where it will be continuously cycled up to operational field.

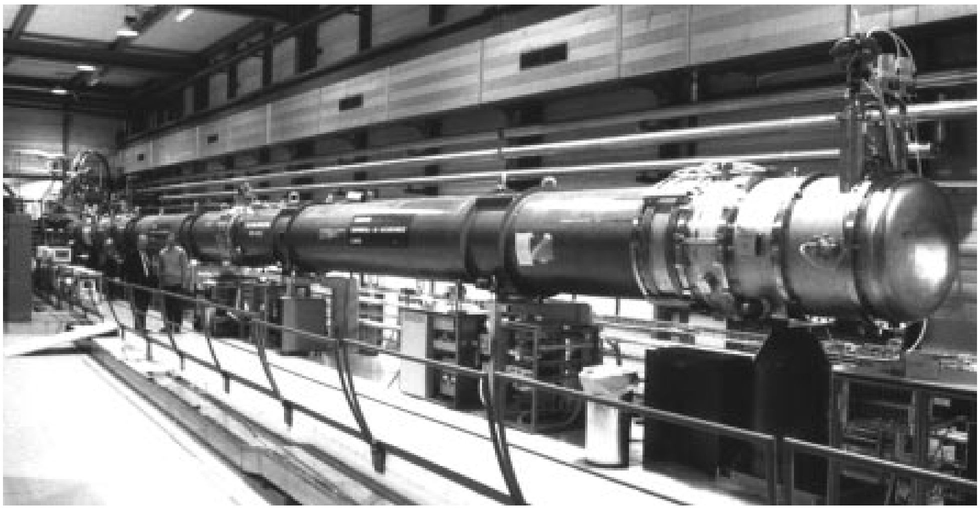

Fig. 7 Overall view of the LHC string test facility.

Considerable progress has been made in the definition and validation of the cryogenic cooling system. One of the key developments has been the successful demonstration of an axial-centrifugal cold compressor operating with a nominal flow rate of 18 g/s at 1 kPa inlet pressure and a compression ratio of 3:1, a prototype of the first stage of the multi-stage cold compressor box (CCB).

7. CONCLUSIONS

The considerable amount of R&D accomplished over the last years has validated the main technical choices for the construction of the LHC. In the key technologies of superconductivity and cryogenics progress has been such that the detailed engineering design and procurement may now commence.

ACKNOWLEDGEMENTS

We thank Lyn Evans for allowing us to use his paper as a model.

REFERENCES

[1] The LHC Study Group, The Large Hadron Collider Conceptual Design, CERN/AC/95–05 (LHC) (1995).