The Large Hadron Collider - Present Status and Prospects

Lyndon R. Evans
European Organization for Nuclear Research (CERN), Geneva, Switzerland

***Abstract*—The Large Hadron Collider (LHC), due to be commissioned in 2005, will provide particle physics with the first laboratory tool to access the energy frontier above 1 TeV. In order to achieve this, protons must be accelerated and stored at 7 TeV, colliding with an unprecedented luminosity of 10^{34} cm^{-2} s^{-1}. The 8.3 Tesla guide field is obtained using conventional NbTi technology cooled to below the lambda point of helium. Considerable modification of the infrastructure around the existing Large Electron Positron collider (LEP) tunnel is needed to house the LHC machine and detectors. The project is advancing according to schedule with most of the major hardware systems including cryogenics and magnets under construction. A brief status report is given and future prospects are discussed.**

I. Introduction

The Large Hadron Collider, now under construction at CERN will provide proton-proton collisions with a centre-of-mass energy of 14 TeV and an unprecedented luminosity of 10^{34} cm^{-1} s^{-2}. In order to achieve this it must operate with more than 2800 bunches per beam and a very high intensity. The machine will also operate for heavy (Pb) ion physics at a luminosity of 10^{27} cm^{-1} s^{-2}.

Many accelerator physics issues must be taken into consideration in the machine design. The first is sound and flexible optics, robust against inevitable lattice perturbations and able to cater for changes in layout demanded by hardware builders and particle physicists. The interaction of the beam with its immediate environment and with the other beam can produce many undesirable effects. Incoherent single particle effects include the beam-beam interaction due to the influence of the electromagnetic field of one beam on the particles in the other, and intrabeam scattering, multiple Coulomb scattering between the particles in the same beam. Collective effects include single bunch instabilities driven by short range wakefields and coupled bunch effects due to the large number of bunches and small separation. Since the unavoidable imperfections in superconducting magnets produce non-linear field errors, the issue of dynamic aperture, the maximum useful betatron amplitude of particles over a long time duration, is also of fundamental importance.

The attainment of 7 TeV in the existing LEP tunnel also presents some considerable technological challenges. The small tunnel cross section as well as the need for cost reduction imposes a two-in-one magnet design for the main dipoles and quadrupoles. The 8.3 T operating field can only be obtained at an acceptable cost by cooling the magnets to 1.9 K, below the lambda point of helium. This presents serious challenges to both the magnet designers and cryogenic engineers.

After a brief description of the machine layout, some of these issues are discussed.

II. Machine Layout

The basic layout mirrors that of LEP, with eight symmetrically placed long straight sections (Points 1-8), each approximately 500 m in length available for experimental insertions or utilities. Two high luminosity insertions are located at diametrically opposite straight sections, Point 1 (ATLAS) and Point 5 (CMS). A third experiment, optimised for heavy ion collisions (ALICE) will be located at Point 2. A fourth experiment (LHCb) has now been approved and will be located at Point 8. The two detectors at Points 1 and 5 require a substantial amount of new civil engineering infrastructure, whilst the other two will be integrated into existing LEP caverns. The beams cross from one ring to the other only at these four locations. Points 2 and 8 also contain the injection systems for the 450 GeV/c beams provided by the SPS.

The other four long straight sections do not have beam crossings. Points 3 and 7 are practically identical and are used for collimation of the beam halo in order to minimise the background in the experiments as well as the beam loss in the cryogenic parts of the machine. Consequently they only contain classical warm magnets robust against the inevitable beam loss and secondary shower from the collimators. Point 4 contains the RF systems which are independent for the two beams, where the beam separation must be increased from 194 mm in the regular arcs to 420 mm in order to provide the transverse space needed. Finally, Point 6 contains the beam abort system, where the two beams are extracted using a combination of fast pulsed magnets and steel septa and transported to the external beam dumps.

III. Magnets

The LHC will require more than 8000 superconducting magnets of different types. The most challenging are the 1232 superconducting dipoles which must operate reliably at the nominal field of 8.3 Tesla, corresponding to the centre-of-mass energy of 14 TeV, with the possibility of being pushed to an ultimate field of 9 Tesla.

In the early days of magnet development, two technologies for the attainment of fields above 9 Tesla were investigated.

1051-8223/00$10.00

The first of these was using Nb_3Sn at 4.2 K. Indeed a dipole model with a first quench at 11 Tesla was built using this technology. However, the coils are very difficult and expensive to manufacture and are not suitable for economic mass production. Nevertheless this technology is still being pursued on a small scale for possible use in selected areas, for example for second generation low-beta quadrupoles.

The other, more economical alternative is to use conventional NbTi technology at reduced temperature. This suffers from the drawback that the specific heat of the superconducting material and its associated copper matrix falls rapidly as the temperature is reduced. For example, the specific heat of copper falls by about a factor of 5, to 0.03 J/kg.K between 4.2 K and 1.9 K. This makes the coil much more prone to premature quenches due to small frictional movements of conductor strands since the adiabatic temperature rise for a given amount of frictional energy is much higher at 1.9 K than at 4.2 K. One can therefore expect more training of these magnets at the highest field levels than at 4.2 K. The important thing is that there is no retraining below the operational field.

The special properties of superfluid helium can be used in part to compensate for this disadvantage. The most well known property of this material is the absence of viscosity but for the purpose of superconducting magnet design, the most important properties are the very large specific heat (about 4000 J/kg.K) and the enormous thermal conductivity at low heat flux. The cable insulation is therefore designed to be as porous as possible to allow penetration of helium whilst maintaining good electrical insulation properties. In this way the helium can contribute to absorbing energy and transporting heat away from the coils.

The development of two-in-one superconducting dipoles and quadrupoles has proved to be a considerable challenge. For the dipoles, this work has been done both at CERN and in industry where a number of long dipoles have been constructed. Recently the coil geometry has been modified from the original 5-block design to improve the field quality and to allow more flexibility for small changes during series production. A number of models using this modified six-block geometry have performed very well [1], with first quenches well above 9 Tesla and fast training to the conductor limit of 10 Tesla (Fig. 1).

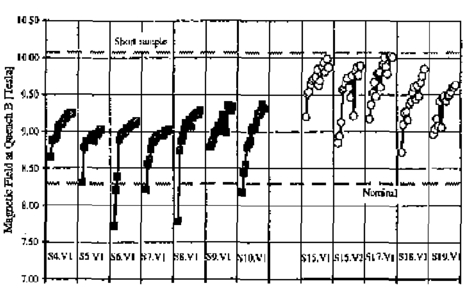

Fig. 1. Training performance of 5-block versus 6-block (open circles) dipole models.

Another important outcome of the R&D programme is that the level of compressive prestress applied to the coils can be considerably lowered without loss of performance. This has opened up the possibility of changing from aluminium to stainless steel collars, reducing tolerances and simplifying magnet assembly during series production.

The first full-length dipole with the 6-block geometry is at present being tested (Fig. 2). Initial results have shown excellent field quality. The training performance is not yet as good as in the short magnets although the nominal field is achieved within a few quenches and there is no retraining below nominal field after a thermal cycle. All quenches are located in the transition regions in the ends of the coils. Strain gauge measurements of the axial loading have revealed much higher forces than expected and have been traced to a bending of the end plate during welding of the domed end covers, a phenomenon first revealed in the SSC magnets. Remedial action is now being taken to reduce these forces. Results of further measurements on this magnet are presented elsewhere in these proceedings [2]. Five more dipoles are under construction, with the collared coils made in industry and the magnet assembly at CERN. The six dipoles together with two quadrupoles will be assembled into a simulation cell of the machine to provide a full system test before the end of 2001.

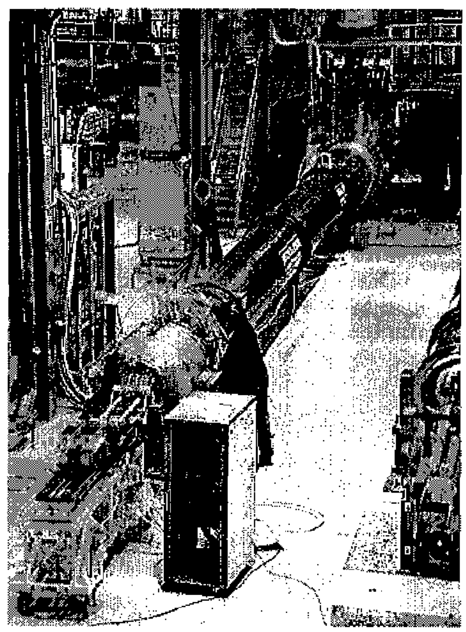

Fig. 2. A full-length dipole on its test bench.

In parallel with this activity, series production of dipoles is in preparation in industry, with an initial order for 30 dipoles in each of the three firms participating in the R&D work on long dipoles.

The lattice quadrupoles [3] are designed by CEA/Saclay in collaboration with CERN. To produce the required gradient of 223 T/m the same cable as for the outer layer of the dipole is used in a two-layer geometry. Two early prototypes have achieved the design gradient. Three more prototypes with some modifications are under construction and the first will be tested before the end of the year (Fig. 3).

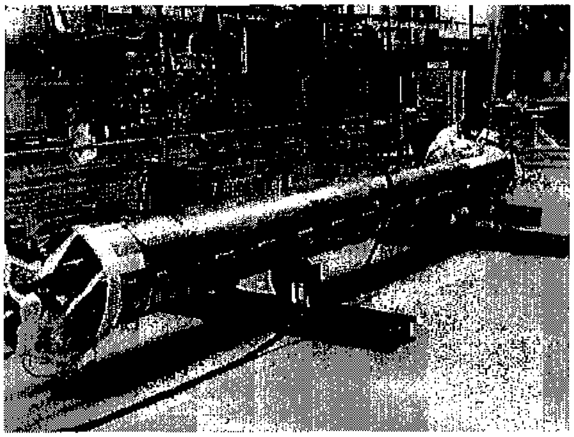

Fig. 3. The cold mass of the first final design lattice quadrupole.

The procurement of some 1200 tons of superconducting cable is a critical path item for the dipole fabrication. The cable will be procured by CERN and supplied to the magnet manufacturers. Contracts for the full supply have been placed with firms in Europe, Japan and the USA. As part of the U.S. contribution to the LHC construction a test facility has been set up at BNL for cable measurement and quality control.

The long straight sections and insertion regions contain many specialised magnets, the most demanding of which are the high gradient (220 T/m), large (70 mm) aperture quadrupoles for the inner triplets of the low-beta insertions. Two versions of this quadrupole have been designed, and prototype models built at KEK and FNAL. The main parameters of the two designs are shown in Table 1.

TABLE 1
MAIN CHARACTERISTICS OF FNAL AND KEK INNER TRIPLET QUADRUPOLES

		FNAL (Q2a, Q2b)	KEK (Q_1, Q_3)
Nominal gradient	(T/m)	205	205
Nominal current	(A)	10630	6050
Magnetic length	(m)	5.5	6.3
Overall length	(m)	5.77	6.68
Coil inner diameter	(mm)	70	70
Stored energy	(MJ)	1.1	1.9
Working point	(%)	80	80

The FNAL quadrupole [4] is a relatively high-current two-layer design. Initial models showed an excellent field quality but relatively poor training. This has been cured by changing the material of the end spacers. The Japanese quadrupole [5] is a 4-layer design with somewhat lower current. Initial prototypes of this magnet showed good training performance but with some of the higher harmonics, particularly b_{10}, at the limit. A small redesign of the coil geometry has reduced this multipole to a tolerable value.

Each insertion triplet will contain a mixture of U.S. and Japanese magnets, the outer elements (Q_1 and Q_3) from Japan and the inner elements (Q2a and Q2b) from the U.S. The final integration into the cryostats will be done at Fermilab in collaboration with LBNL.

In addition to the main dipoles and quadrupoles, a large number of correctors is required. Each dipole is equipped with a small sextupole to correct field imperfections due to persistent currents and every other dipole contains a combined octupole/decapole corrector. Each short straight section contains a sextupole for chromaticity correction and a closed orbit dipole. There is also a free slot for other correctors, all of which have the same dimensions. These include an octupole for Landau damping, trim quadrupoles and skew quadrupoles for coupling correction.

All of these correctors are made using the same novel technique of "scissors" laminations. Their design and performance is described in a number of contributions to this conference [6] - [8].

Not all magnets in the LHC are superconducting. The two transfer lines from the SPS to the LHC contain classical dipoles (360 units) and quadrupoles (180 units) manufactured at BINP Novosibirsk. Series production of these magnets is well under way. The steel septum magnets for injection and beam abort systems are also classical and are under construction at IHP Protvino. Finally, the special two-in-one quadrupoles (52 units) for the collimation insertions are being manufactured in Canada under the responsibility of TRIUMF.

IV. CRYOGENICS

Cooling more than 31000 tons of material spread over 26.7 kms to below 2 K presents a considerable technological challenge [9]. The most convenient way to cool helium to below its critical temperature is to reduce the vapour pressure above the liquid bath. At 50 mbar the liquid crosses the lambda point at 2.17 K and it is necessary to reduce the pressure to below 20 mbar to reach the 1.9 K operating temperature. In practice, the LHC will operate in a static bath of pressurised superfluid helium at 1.9 K cooled with flowing saturated superfluid helium at 15 mbar through a linear heat exchanger extending over each full 107 m long cell of the machine. In view of the high thermodynamic cost of refrigeration at such a low temperature, most of the system heat loads are intercepted at higher temperature. As a result, the LHC requires a mix of refrigeration duties at several temperature levels. The machine will be cooled by eight cryoplants, each with an equivalent capacity of 18 kW at 4.5 K. Four of these will be the existing LEP refrigerators upgraded in capacity from 12 to 18 kW and adapted for LHC duty. The other four new plants, unlike those of LEP, will be entirely installed on the surface, reducing the need for additional underground infrastructure.

In order to create the superfluid helium at 1.9 K, it is necessary to compress cold helium gas from 15 mbar up to atmospheric pressure by the use of cold hydrodynamic compressors attached to the 4.5 K cryogenic plants. CERN has conducted a vigorous R&D effort with three industrial partners with the aim of investigating technological alternatives and validating efficient reliable solutions for these machines. In order to achieve this, three scale 1:5 prototype compressors for the first stage of compression from 10 to 30 mbar have been built and successfully tested (Fig. 4). Orders have now been placed for the eight full-size cold compressors, each handling 125 g/s of helium.

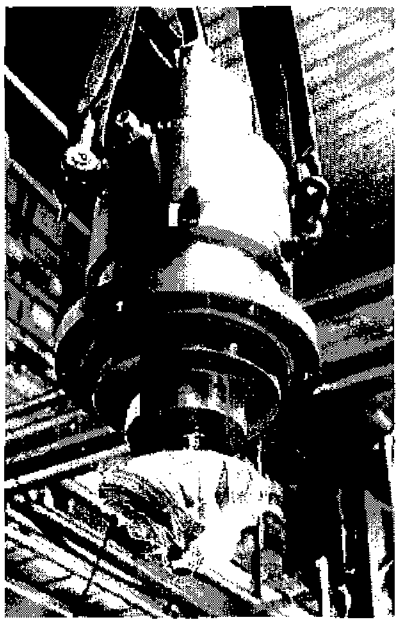

Fig. 4. The impeller of a prototype cold compressor stage.

Among the other cryogenic components under development, it is worth mentioning the high-temperature (HTS) current leads. The superconducting magnets have to be fed with a total current of more than 3.5 MA with current ratings from 13 kA (main dipoles and quadrupoles) to 100 A (orbit correctors). The leads for the higher currents, 0.6 kA to 13 kA, will be made using HTS technology in order to reduce the refrigeration requirements for lead cooling. Prototype pairs of such current leads (Fig. 5) have been ordered from industry and leads from three manufac-turers have already been successfully tested up to the design current of 13 kA.

V. Vacuum

The high intensity beams in the LHC will deposit heat into the cryogenic surface surrounding the beam through a number of effects. The most important of these are image currents (up to about 0.8 W/m) and synchrotron radiation (0.6 W/m).

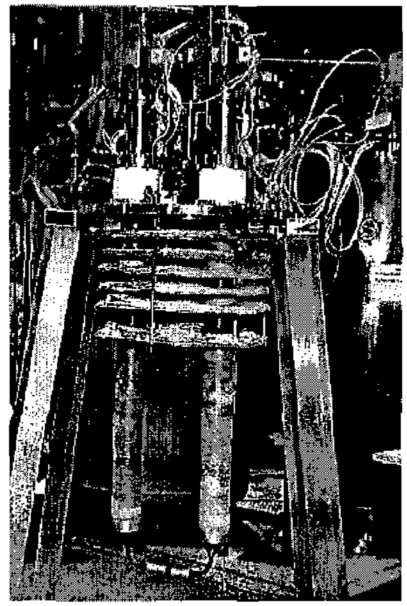

Fig. 5. 13 kA HTS current leads.

These heat loads cannot be taken at 1.9 K and will be intercepted by a beam screen fitted inside the magnet cold bore and cooled by circulation of supercritical helium between 5 K and 20 K. Gas desorbed by the synchrotron radiation cannot be efficiently cryo-pumped by the screen at this high temperature. In order to avoid a catastrophic pressure rise, the screen is punched with small holes over about 2% of its surface so that the cold bore can pump away the gas while being protected from the heat source.

Another effect producing heat is inelastic scattering of protons with the residual gas molecules. This cannot be intercepted by the screen and must be transported away by the superfluid. Recently an additional heat source has been identified, secondary and photoelectrons accelerated across the beam pipe due to the bunched nature of the beam. Under unfavourable conditions, this could result in a resonant build-up of the electron cloud (multipactor), heavily loading the cryogenic system and causing beam instability. In order to avoid this, great care must be taken to produce a screen surface with a low secondary emission coefficient.

VI. Accelerating System

The RF frequency, 400.8 MHz, is the highest multiple of the SPS RF frequency (200.4 MHz) compatible with the length of the SPS bunches at transfer. Each beam has a separate system necessitating an increase of the beam separation from 194 to 410 mm. Eight single-cell cavities per beam are needed. The maximum operating voltage per cavity (2 MV) corresponds to a very conservative average accelerating gradient of 5 MV/m. The cavities are made from copper with a thin film of niobium sputtered on the inside surface, identical to those of LEP. In order not to lose the technology transferred to firms during the LEP project, these cavities are now being manufactured and the first complete two-cavity unit has been assembled and tested up to twice the nominal gradient [10]. The RF coupler is the most critical cavity component with a forward power of 180 kW. It will be an upgraded version of the LEP coupler with a d.c. bias on the inner conductor to suppress multipactoring in the coaxial part.

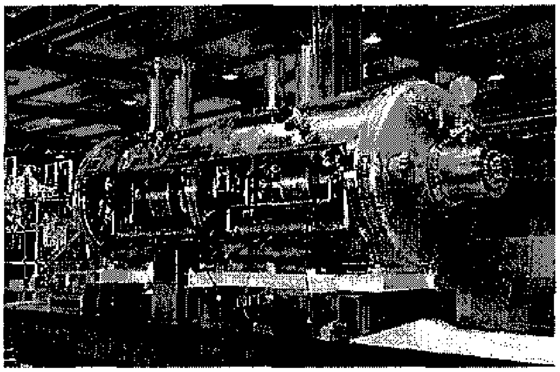

Fig. 6. Two LHC 400 MHz superconducting cavities.

VII. Civil construction

The LHC makes use of the existing infrastructure of LEP, including the four existing experimental halls to house detectors or machine utilities. Nevertheless, a considerable amount of new investment is needed to house the two large detectors ATLAS and CMS, for the long transfer tunnels between the SPS and LHC, and for the surface infrastructure, mainly for cryogenic equipment.

At Point 1, the ATLAS detector requires an underground cavern of more than 50000 m^3 and an associated service cavern of nearly 20000 m^3 together with considerable surface hall space. The site opened in April 1998 and work is proceeding according to schedule. The experimental caverns will be delivered to ATLAS in September 2002 so that they can start in situ assembly of the detector.

At Point 5, the CMS detector requires an experimental cavern of about 30000 m^3 and a service cavern of 17000 m^3 as well as the surface infrastructure for the assembly and testing of the 14000 ton detector. In contrast to ATLAS, CMS will be assembled on the surface and lowered in pieces of about 2000 tons into the cavern. The site was opened in August 1998 and the experimental cavern will be delivered in July 2003. The sinking of the shafts at Point 5 poses a particular challenge since they have to pass through water bearing moraine. A special technique of ground freezing has to be employed. Up to the present time, the work is proceeding according to schedule

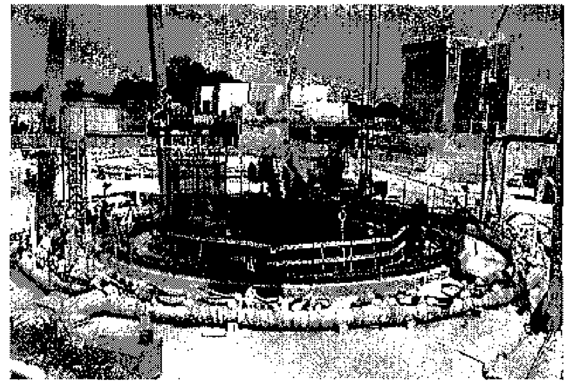

Fig. 7. Ground freezing before shaft excavation at the CMS experimental area.

VIII. Conclusions

The LHC represents a technological step forward, stimulated by the need to achieve the best possible performance within the constraints of the existing infrastructure and at the lowest possible cost. The project is proceeding according to the foreseen schedule.

Acknowledgment

On behalf of the CERN LHC design team, I would like to acknowledge the enthusiastic collaboration of our colleagues from laboratories in Canada, India, Japan, Russia and the USA as well as from laboratories in the CERN Member States in the realisation of this project.

References

[1] K. Artoos et al., "Status of the short dipole model program for the LHC", *these proceedings*.

[2] K. Artoos et al., "Design, manufacturing status, first results of the LHC main dipole final prototypes and steps towards series manufacture", *these proceedings*.

[3] M. Peyrot et al., "Construction of the new prototype cold masses for the arc short straight sections of the LHC", *these proceedings*.

[4] J. Kerby et al., "Recent results from the development program for the LHC inner triplet quadrupoles at Fermilab", *these proceedings*.

[5] T. Nakamoto et al., "Training characteristics for the 1-m model magnets for the LHC low-β quadrupoles", *these proceedings*.

[6] M. Allitt et al., "Further development of the sextupole and decapole spool correctors for the LHC", *these proceedings*.

[7] A. Hobl et al., "Development of tuning quadrupole (MQT) prototype magnets for LHC", *these proceedings*.

[8] Z. Ang et al., "Further development of the sextupole dipole corrector (MSCB) for LHC", *these proceedings*.

[9] Ph. Lebrun, "Cryogenics for the Large Hadron Collider", *these proceedings*.

[10] D. Boussard, T. Linnecar, "The LHC superconducting RF system", *CEC-ICM'99 conference*, Canada, 12-16 July, 1999.