SUPERCONDUCTING MAGNETS AND RF CAVITIES FOR THE LHC

Th. Taylor

Abstract

The Large Hadron Collider (LHC) presently under construction at CERN relies on superconducting technology both for the complex magnet system and the radio frequency accelerating structure. The technologies adopted for these systems are described.
1 Introduction

The Large Hadron Collider (LHC) is a new facility under construction at CERN which will provide interactions between beams of protons at hitherto unattainable centre of mass energy of $7 + 7$ TeV. The accelerator will be installed in the circular tunnel of 27 km in circumference, presently occupied by the LEP electron-positron collider, and which will cease operation in October 2000. The collider was first discussed in the early 1980s, and the first design study appeared in 1987 [1]. Approval of the project was obtained in 1996, and the LHC is scheduled to come into operation in 2005. It is expected that the design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ will be achieved within 2 to 3 years.

The counter-rotating beams will be accelerated by means of radio-frequency (RF) cavities and guided and focused using magnets. This equipment is mainly superconducting, which calls for a comprehensive cryogenic system. Moreover, the beam channel needs to be free of gas, which requires an ultra-high vacuum system. Of these four main systems the magnet system is the most complex and the most expensive, accounting for about 60% of the total budget for the project.

2 Magnets

Dipole magnets are required to deflect the beams, and quadrupole magnets are required to focus them. Many smaller magnets are needed for correction of the field in the main magnets, for correction of the orbit and for adjustment of the characteristics of the beam. For the LHC in the LEP tunnel, the ultimate energy is given by the integrated dipole field which can be accommodated there. This motivated the drive to get the highest possible field and to pack this as tightly as possible over the longest possible length – within the obvious constraints of full reliability and reasonable cost. The R&D on the dipole magnet was started in the early 1980s. The small transverse dimensions of the LEP tunnel (3.8 m diameter) led to the early adoption of a twin-aperture design. In this concept, which had been first proposed at the Brookhaven National Laboratory in the 1970s, the magnetic flux in one aperture is returned, via the iron yoke, in the opposite direction through the adjacent aperture. The guiding fields for both counter-rotating beams of particles carrying the same charge are contained in the same cryogenic enclosure, leading to a compact design. The drawbacks are the more complicated magnet units and interconnects, and having to use the same energy in each beam - but with an estimated cost saving of up to 30% and the above-mentioned problems of space the decision was easy to take.

Another decision taken early in the R&D programme was to base the design on the use of niobium titanium (NbTi) superconductor rather than the potentially higher performance niobium tin (Nb$_3$Sn) material. Although a successful model was built using Nb$_3$Sn, the lower cost and the comparative facility of producing and working with NbTi multi-filamentary conductor were strong arguments in favour of using this material. Instrumental in this was the maturity of the technology, thanks to development for the SSC and the boom in MRI. In order to reach the highest possible field it was also decided to cool the conductor to 1.9 K using superfluid helium, rather than the usual 4.5 K cooling with forced flow of supercritical helium. The critical field is increased by 3 T, bringing the current density to that which can obtained using Nb3Sn at 4.5 K and 10 T. The technology required for superfluid helium had been developed for Tore Supra [2]), and while not without difficulties, the use of superfluid helium is advantageous for the LHC. It does require, however, that the magnets be particularly well made because of the lower specific heat of the conductor - implying a smaller tolerance level for micromovements.

2.1 The main dipole

The heart of the 8.3 T main dipole magnet is a coil of 15.3 mm wide “Rutherford” conductor wound on a circular mandrel of diameter 56 mm, in 2 layers approximating the cos$\theta$ distribution required to produce a pure dipole field. The cable of the inner layer consists of 28 strands of 1.065 mm diameter and that of the outer layer has 36 strands of 0.825 mm diameter. The Cu:SC ratio is 1.65 for the strands of the inner layer and 1.95 for the outer layer; and the diameter of the NbTi filaments is 7 and 6 $\mu$m respectively. After extensive optimization of the coil geometry to maximize the field while minimizing its harmonic content [3], the keystone angles have been chosen to be respectively 1.25 and 0.9 degrees, and the conductors distributed in 6 blocks. The cables are insulated with wrapped polyimide film. At the short sample limit of the cables the field is about 9.7 T, and in order to contain the Lorentz forces, which attain the level of 300 tonnes/m when the dipole is excited to this level, the coils are supported in an interlocking structure of stainless (austenitic) steel collars. Two 15 m long coil sets are assembled in the collars and compressed to provide sufficient azimuthal pre-stress to ensure that the coils remain in compression when the magnet is cold and excited to 9 T (for 7 TeV operation the dipole needs to be at 8.3 T, but components are being designed to allow achievement of an ultimate maximum energy of 7.5 TeV). The
collars are locked together by inserting calibrated rods. The collared coils are surrounded by a laminated 4-piece iron yoke, for flux return and magnetic shielding, and the whole assembly is contained in a tight fitting stainless steel shell which serves as a longitudinal support and a helium containment vessel [4]. A cross-section of the dipole, which has a magnetic length of 14.3 m, is shown in Figure 1.

**Figure 1. Cross-section of the main LHC dipole magnet**

The R&D programme for the main dipole magnets started in 1984, with a parallel development of cables and model magnets for the testing of concepts at the level of the coil, and the assembly and testing of HERA coils in a twin-aperture configuration to verify that aspect of the design. In the initial years (until about 1990) the construction of both short and full-length models was done in collaboration with industry. CERN was busy constructing LEP at the time, and it was felt to be both politically desirable (for getting the project approved) and technically useful to familiarize prospective vendors with the product they would eventually be asked to tender for. This approach however proved to be slow, the companies executing the work with small teams, and being understandably reluctant to invest in an operation without seeing the certainty of a big following order. Subsequently the work was therefore supplemented with an aggressive parallel campaign of model building and full-length magnet assembly at CERN. The model programme included the establishment of a Coil Test Facility in which single-aperture 1 m long coils can be tested, modified, and re-tested quickly. In this way it has been possible to optimize the coil support structure and the coil end geometry, and to determine the best pre-stress to apply, both from the point of view of quench performance and field quality. To date over 30 models have been built and tested, and recent models work well, achieving more than 9 T with few training quenches. Coil winding and collaring for the full-size prototype magnets continued in industry. These magnets take much longer to build, and not featuring all the latest science from the model programme they just meet the required performance. It is however confidently expected that the series magnets will exceed the requirements.

Orders have now been placed for 30 pre-series magnets from each of the three vendors which have been participating in the development programme. The first of these magnets is scheduled to be delivered in autumn 2000, and each of the 3 vendors should have produced 10 magnets by summer 2001 when the call for tenders for the remaining 1142 units of the full series will be issued.

The dipoles will be powered in eight circuits (one circuit per arc). At nominal field each circuit carries just under 12 kA, and has a stored energy of 1.3 GJ, so special measures must be taken to avoid damage in case one of the magnets should quench, due for example to loss of some particles from the beam. All magnets are equipped with cold diodes which by-pass the current while the circuit is discharged into a large dump resistor. The energy in the quenching magnet is spread though the coil by firing heaters in close thermal contact with the coils.

### 2.2 Quadrupoles

Quadrupole magnets are used to focus the beams. In the arcs each regular cell of the FODO lattice consists of 6 dipoles and 2 quadrupoles; these lattice, or main, quadrupoles are 3.1 m long twin-aperture magnets whose 2-
layer coils are wound using the same conductor as that of the outer layer of the dipole. They feature the same aperture as the dipoles, and the nominal gradient is 223 T/m. The design of these magnets was entrusted to CEA, Saclay, and follows closely that successfully developed for HERA. The coils are assembled and pre-stressed in separate stainless steel collars, around which the single piece, twin-aperture, iron yoke laminations are stacked in a vertical fixture [5]. Coil centering in the yoke is achieved by means of keys; all the Lorentz force is taken by the collars. The cold mass is completed by lowering on the helium vessel, which also serves as an inertia tube to keep the magnet straight via more keys. A cross-section of the magnet is shown in Figure 2. The main quadrupoles are excited in two series, focusing and de-focusing, per arc, and, like the main dipoles, are protected by cold by-pass diodes and quench heaters. The nominal current, corresponding to 7 TeV operation is 11'780 A. Successful full-length prototypes have been produced, and the call for tenders has been launched for the series of about 400 units.

![Figure 2. Cross-section of the main quadrupole magnet](image)

In the dispersion suppressors and matching sections between the dispersion suppressors and final focusing inner triplet, it is necessary to tune the quadrupoles independently, calling for individual powering. It has therefore been decided to introduce another type of quadrupole, based on a smaller cable (8 mm wide) operating at up to 5.8 kA. These magnets come in three lengths, 2.8 m, 3.5 m, and 4.8 m, from which combinations are made to satisfy the optics requirements. The design is similar to that of the main quadrupole except that the inertia tube will be replaced by welding half shells around the magnet as is done for the dipole. A 1 m model magnet has been tested with good results and the call for tenders for the series of about 100 units will be issued early next year.

2.3 Large-Aperture Quadrupoles

Near to the four interaction points at which the experiments are situated, the beam trajectories imposed by the geometry of the beam crossing and injection schemes, and the locally large amplitudes of the betatron oscillation function, give rise to the need for quadrupoles having a larger coil diameter than the 56 mm chosen for the arc and dispersion suppressor magnets. This diameter has been chosen to be 70 mm. There is one type of twin-aperture quadrupole having this aperture, a magnet employing 4-layer coils featuring two thicknesses of 8 mm wide cable, and of length 3.5 m. This magnet will be operated at 4.5 K, and provides a gradient of 160 T/m at a current of 3.5 kA. Short models have been built and tested with good results, and the call for tenders for the series of 24 units will be issued next spring.

The other large aperture quadrupoles are the single aperture, high performance magnets which make up the final focusing inner triplets of the low-beta insertions. An inner triplet consists essentially of 4 quadrupole units, Q1, Q2a, Q2b, Q3, which correspond optically to three quadrupoles. The LHC provides 4 interaction points so 8 inner triplet assemblies will be required. Q1 and Q3 are 6.3 m long units and will be supplied by KEK, Japan, and Q2a and Q2b are 5.5 m long units which will be supplied by Fermilab, USA. The integration of the inner triplets into their cryostats will also be assured by Fermilab. The magnets will be called upon to operate in the hostile environment downstream of the beam-beam interactions at the centre of the experiments, which will deposit up to 10 W/m of power in the inner layers of the coils. The magnets must provide up to 215 T/m and be
trained to beyond 230 T/m. Excellent field quality is also required. Both KEK and Fermilab have developed designs and produced short models which satisfy the requirements, and work is now in progress to produce full length prototypes. The KEK magnet features 4-layer graded coils using 12.3 mm wide cable; the coils are assembled in thin stainless steel collars and pre-stressed in the rigid cavity formed by collaring the iron laminations forming the flux return yoke [6]. The Fermilab design features 2-layer graded coils using 15.3 mm wide cable; the coils are pre-stressed by collaring in thick stainless steel collars, designed to withstand all the Lorentz force without the participation of the flux return yoke, which is simply assembled around the collars [7].

2.4 Beam Separation Dipoles

The superconducting dipoles used for separation and combination of the beams are based on the use of standard 9.4 m long RHIC dipole coils, and will be provided by Brookhaven National Laboratory (BNL), USA. These magnets come in 4 types: D1, D2, D3, and D4. D1 and D2 are used in the low-β insertions and D3 and D4 are used to separate the beams from 194 mm to 420 mm to accommodate the RF cavities at point 4. D1 is a standard RHIC dipole except that it is straight, and will be operated at 1.9 K – which impacts on the detailed design of the cryostat. D2 and D4 are twin-aperture dipoles in which, unlike the main dipoles, the magnetic field is oriented in the same direction in both channels. In this configuration all the flux is returned through the yoke on the median plane, calling for a greater cross-section there than that required for the main dipoles. This is achieved by making the magnet wider that it is high, yet still fitting into the standard 36-inch vacuum vessel used elsewhere in the LHC. The magnet differs from the standard RHIC magnet in that the coils are supported in stainless steel collars which withstand all the Lorentz force, and differs from the main dipole in that the yoke is split in the horizontal plane. The soundness of the design had been demonstrated with a 3 m model which has been built and tested at BNL [8]. The beam channel axis separations of 188 mm, 194 mm and 224 mm for D2, D4a and D4b respectively, have been chosen to provide the maximum aperture for the beam.

2.5 Correction magnets

Although the dipoles and quadrupoles which guide and focus the charged particle beams will be built to tight tolerances and installed with great accuracy, it will be nevertheless necessary to install many smaller magnets to correct for imperfections in the magnets and their alignment. Families of other small magnets, namely sextupoles and skew quadrupoles and octupoles, are also required to correct chromatic effects and coupling between betatron oscillations in the horizontal and vertical planes, and to provide Landau damping. It is both practical and cryogenically efficient to operate these magnets, of which there are about 5000 in all, at relatively low currents. For reasons of standardization, these have been chosen to be 60, 120 and 600 A. The magnet technology is also different in that the coils are made using monolithic conductor instead of flat cable, they are vacuum impregnated, and the required pre-compression is applied using so-called “scissor” collars or laminations. It is possible to use impregnated coils because in these magnets the conductor works at not more than 60% of the short sample limit, which means that there is effectively a comfortable temperature margin of several degrees. The scissor laminations are disks with the central hole punched slightly off-centre which are assembled around the coils in such a way that when compressed on the outer diameter with a shrinking cylinder the coil assembly is compressed [9].

The most numerous of the correctors are the small sextupole and decapole magnets which are installed at the ends of the dipoles, commonly referred to as spool pieces. All of the 1232 dipole cold masses will be equipped with a sextupole spool piece mounted on each aperture at the connection end, and half of the dipoles will also have decapole spool pieces mounted at the opposite end. These magnets are excited in 4 circuits (one per aperture, one per type) per arc of the machine, and serve mainly to correct for persistent current effects in the main dipoles at injection. The magnets, which consist of counter-wound 2-layer coils compressed using silicon-steel scissor laminations are supported off the end plate of the dipole via a steel casing which also serves as a magnetic shield. The decapole is special in that it is an assembly of 5 coils, suitably connected, making for a more economical design than the traditional 10 coils.

Every quadrupole assembly is equipped with a dipole orbit corrector magnet on each aperture. Being individually excited, these magnets are wound from enamel-insulated superconducting wires which are glued together to make a flat cable and connected in series. The magnets, which produce up to 3 T, are of length 0.65, 0.9 or 1.25 m long depending on the quadrupole assembly concerned, and are powered at up to 60 A for the shortest version and up to 120 A for the others. The orbit correction magnets for the inner triplets consist of a 0.6 m long combined vertical and horizontal field unit which together provide a field of 3 T, the direction of which can be chosen at will. The clear bore (diameter 90 mm) of the coils provides space between it and the cold bore for the installation of the multipole windings required for local field correction. These magnets are wound from an ribbon assembly of 0.73 mm x 1.53 mm conductors, and will run at up to 600 A. In the arcs 0.6 m dipoles are combined with the chromaticity sextupoles. At the opposite end of some quadrupole assemblies are mounted
tuning quadrupoles, skew quadrupoles or octupoles. The octupoles resemble the spool pieces, but are 0.32 m long; the tuning quadrupoles are also 0.32 m long and provide a gradient of up to 120 T/m, and the skew quadrupoles are tuning quadrupoles rotated through 45 degrees. All of these latter magnets are built using a rectangular conductor of size 0.97 mm x 1.53 mm which is insulated using a PVA enamel coating, and also run at currents of up to 600 A.

Prototypes of all the correctors have been built and successfully tested; the series sextupole spool pieces are ordered and the decapole should be ordered by the end of this year. In the course of next year all of the correctors will be ordered.

3 Superconducting RF cavities for the LHC

The RF for the LHC is based on the work done for LEP [10]. While there were initially some problems, mainly due to couplers, the 352 MHz cavity system for LEP has proved to be very good, exceeding the design goal of 5 MV/m and allowing LEP to operate at up to 102 GeV. At this energy the 288 cavities must work at an average of 7 MV/m. The reliability has also been excellent.

The experience gained in producing the LEP cavities with the new technique of sputtering niobium onto the spun copper has been exploited for the 400 MHz cavities required for the LHC. In some respects the layer of about 2 µm of niobium on copper is better than the more expensive alternative of forming the cavities from solid niobium. The copper, being a better conductor of heat than niobium, is found to reduce the impact of local heating which may occur due to microscopic surface defects. The cavities are also less sensitive to stray magnetic fields.

One of the companies which produced the LEP cavities won the order to produce the 21 new cavities, and these have already been made and tested. A short module consisting of two cavities complete with (variable) power and HOM couplers has also been tested with excellent results, and it is confidently expected that the 4 modules (+ one spare) will be finished and tested by the end of 2001.

The RF for the LHC will be housed at point 4. Unlike LEP, each counter-rotating beam will have its own independently controlled acceleration system. The beam separation of 194 mm in the arcs will be locally increased to 420 mm in the straight section at point 4 to allow the installation of two modules of 4 cavities per beam, together with other equipment which requires more transverse space.

4 Energy Limiting Factors

The energy of the LHC is essentially limited by its installation in the existing LEP tunnel. Even if magnets with a higher field could be built on a large scale, the synchrotron radiation load, which, for a machine of constant radius increases with the fourth power of the energy, would call for a corresponding increase in cryogenic power. For the foreseeable future the energy of the LHC is thus likely to be limited to 7.5 TeV. In fact, all equipment which is being designed to last for the expected duration of operation of the LHC should be capable of working at up to 7.5 TeV, or at 7 TeV with the beam current increased by a factor of two, implying

• the dipole should be trained at up to 9 T,
• the cryogenic system should just handle to load, and
• the customary 10% safety margin of the power converters should only apply to the nominal conditions of operation,

and these are the called the ultimate working conditions. On a more modest scale, it may be possible to increase the luminosity to beyond the design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ by reducing the β-function at the IPs. This will call for new quadrupoles in the low-β insertions, having the same gradient but providing a larger aperture.

The KEK team has a reputation for innovation in the use of materials in superconducting magnets, e.g. high manganese steel – which is strong and has exceptionally low magnetic permeability at low temperatures, and high strength, high RRR aluminium – which finds application in stabilizing the superconductor in large spectrometer magnets. In collaboration with the National Research Institute for Metals (Tsukuba), the team is now investigating the use of multi-filamentary Nb$_3$Al. This material has some attractive features for use in high field accelerator-type magnets, being less sensitive to strain than the more common Nb$_3$Sn A15 compound, and having potentially the high current density required for quadrupoles. INFN-LASA in Italy has also made a design of a quadrupole based on the use of high-performance Nb$_3$Sn conductor developed at Europa Metalli.

The University of Twente (UT) in the Netherlands designed and built for CERN a successful LHC model dipole using a cable of Nb$_3$Sn conductors produced by the powder-in-tube method. UT is now making a 1 m model of a dipole which could replace the separation dipole closest to the interaction point. The challenge is to reduce the filament size of this type of conductor from about 30 to less than 20 µm, while maintaining a high current density, and to make tooling suitable for long magnets.
For the time being we do not envisage the use of HTS for magnets to upgrade the LHC insertions, because the current density is as yet insufficient. We are however committed to the use of HTS for the power leads, and we have already tested prototype leads for the most difficult application – feeding an octant of 13 kA main dipoles, having over one gigajoule of stored energy.

5 Conclusion

The specification and ordering of components for the superconducting magnet and RF systems is progressing according to plan and largely in line with the budgeted cost. While the major design decisions appear to have been sound, a future project could benefit from avoiding some of the pitfalls alluded to in this report, such as expecting too much of industry in the early stages. Regarding human resources, while CERN may suffer presently from the age structure of its staff, on completion of the LHC, CERN will be home to unrivalled teams of trained experts in the field of cryogenics and superconducting magnets. And these teams will surely want nothing better that to undertake a future, even larger, project!

6 References