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PROGRESS ON THE SUPERCONDUCTING MAGNETS FOR THE LARGE HADRON COLLIDER

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PROGRESS ON THE SUPERCONDUCTING MAGNETS FOR THE LARGE HADRON COLLIDER

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Abstract

After a review of the proposed CERN Large Hadron Collider (LHC) project, the present design of the high field superconducting magnets is described. The paper then presents the main aspects and the first results of the R&D programme that has been undertaken in close collaboration with European Industries and Laboratories. This programme includes the development of suitable NbTi and Nb₃Sn wires and cables and the construction of magnet models (1 m long) and of a 9 meter long twin-aperture prototype dipole.

1. Introduction

A powerful proton-proton collider providing collisions with 16 TeV centre-of-mass energy and a luminosity exceeding $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ is being proposed at CERN as one of the next possible steps towards higher energy for particle physics. This Large Hadron Collider (LHC)[1] will be installed in the ~ 27 km long tunnel of the Large Electron Positron colliding beam accelerator (LEP)[2] above the LEP machine components (fig. 1). As in a given tunnel the attainable beam energy is directly proportional to the bending magnetic field, it is important to push the technology of superconducting magnets towards the highest possible fields. The envisaged field level is in the range 8 to 10 T, the latter corresponding to 8 TeV beam energy. The proton beams cross in 8 points where they can be made to collide. The projected facility will, in addition, provide a unique possibility of colliding high energy protons with the electrons of LEP up to about 1.8 TeV centre-of-mass energy.

The LHC will be a particularly cost-efficient machine since it will make use of the existing tunnel with its associated infrastructure, the proton (and anti-proton) injectors and the general services of the CERN Laboratory.

Figure 1 - Schematic view of the LHC in the LEP tunnel.

2. The Large Hadron Collider (LHC)

General Layout and performance

A detailed description of the Large Hadron Collider may be found in ref. 1. The LHC will be a particle accelerator/storage ring, in which two

counter-rotating beams of hadrons (protons) will circulate in quasi-circular paths in separate beam channels and cross each other in eight points regularly spaced around the circumference. A schematic layout of the machine with some principal dimensions is shown in Fig. 2.

Figure 2 : Principle layout of the Large Hadron Collider (LHC).

There are eight arcs and eight long straight sections. The two bunched beams, separated by 180 mm in the arcs, alternate from the outside arc to the inside arc (and vice-versa) eight times around the circumference. An octant of each ring between two successive crossing points consists of a straight section (~ 250 m long), a short circular arc with reduced bend containing the dispersion suppressor section (~ 170 m long), a long arc made up of standard cells (2500 m long) and again a short circular arc followed by a straight section as above.

One long straight section in which the beams do not interact, is reserved for the beam dumping system. In the other seven crossing regions the counter-rotating proton bunches will pass through a single channel and could in principle be made to collide for physics experiments. The present design considers 4 interaction points for experiments, each with a $\pm 10 \text{ m}$ or $\pm 20 \text{ m}$ long drift space.

The possibility of colliding protons of the LHC with electrons of LEP has also been incorporated in the LHC design.

Main parameters and performance of the LHC are presented in Tables I and II.

Table I - LHC pp performance

Maximum proton beam energy (TeV)	8
Maximum collision energy (TeV)	16
Number of bunches	3564
Particles per bunch	2.6×10^{10}
Number of interaction points	4
Stored beam energy (MJ)	117
Luminosity ($\text{cm}^{-2} \text{ s}^{-1}$)	1.4×10^{33}

Table II - LHC-LEP ep performance

Maximum proton beam energy (TeV)	8
Number of proton bunches	540
Protons per bunch	3×10^{11}
Electron energy (GeV)	50
Number of electron bunches	540
Electrons per bunch	8.2×10^{10}
Luminosity ($\text{cm}^{-2} \text{s}^{-1}$)	
with ± 3.5 m free in interaction region	2.7×10^{32}
with ± 10 m free in interaction region	2.1×10^{32}
Maximum collision energy (TeV)	
with 100 GeV e^-	1.8
Luminosity with 100 GeV e^- ($\text{cm}^{-2} \text{s}^{-1}$)	1×10^{31}

Magnet System

The long arc standard cells are periodically repeated 196 times around the ring, covering approximately 20 kilometers of the circumference. Including the short arcs, about 24 kilometers of the LHC ring will be occupied by superconducting magnets of various types. One half of a standard cell (Fig. 3) consists of four, ~ 10 m long, dipole magnets (D), a focusing quadrupole magnet (Q), a tuning quadrupole (TQ), a combined sextupole/dipole corrector magnet (S+DC) and a beam observation station.

Figure 3 : Standard half-cell.

The quadrupoles, the correcting elements and the beam observation stations are all mounted in one cryostat, which, in the superfluid helium version, includes a local refrigeration station (Fig. 4). The dipoles as well as the quadrupoles of the two rings are combined into "two in one" units, each pair having a common yoke and cryostat. Each focusing quadrupole in one ring is paired with a defocusing quadrupole in the other ring. Sextupoles and dipole correctors, which are $\cos n\theta$ type superconducting magnets, are assembled concentrically on a common beam pipe. Tuning quadrupoles, sextupoles and dipole correctors of one ring are magnetically decoupled from the magnets of the other ring.

The horizontal beam spacing between the two rings is 180 mm and the inner diameter of the magnet coils 50 mm.

In each ring the dipoles and regular lattice quadrupoles are powered in series by means of superconducting bus-bars. The dipole correctors are excited independently and have low current cryogenic leads in each short straight section. The sextupoles and the tuning quadrupoles are subdivided into two families: each family is connected in series by superconducting bus-bars. There are 49 standard half cells in each octant of the LHC collider. Taking into account the rest of the machine i.e. dispersion suppressor regions and long straight sections, the total number of dipoles is approximately 1760 and the number of quadrupoles 568. General characteristics and number of magnets are reported in Table III.

Table III - General characteristics and number of magnets (For 8 TeV beam energy)

		Magn. Length (m)	Number of magnets
Dipoles	$B_0 = 10$ T	9.54	2×1760
Quadrupoles	$G = 250$ T/m	3.08	2×568
Tun. quadrupoles	$G = 120$ T/m	0.72	796
Sextupoles	$B'' = 3640$ T/m ²	1.1	796
H corr. dipoles	$B_0 = 1.36$ T	1.1	398
V corr. dipoles	$B_0 = 1.36$ T	1.1	398

To give an idea of the size of the project in terms of superconducting magnets and cryostats, the approximate needed material quantities are given in table IV.

Table IV - Approximate quantities of material for the LHC magnets and cryostats

Material	Quantity (t)
Superconductor (s. compound + copper)	1'400
Insulation	180
Copper spacers	260
Aluminium alloy collars	3'000
Laminated low-carbon steel	22'000
Other steel components	3'700
Stainless steel for magnets and cryostats	4'500
Radiation shields (if s.s. or copper)	1'000
Overall mass	36'000
Cold mass (4.5 or 2 K)	30'000

Figure 4 : Layout of the components in a short straight section of the standard cell.

Figure 5 - Cross-section of a dipole magnet in its cryostat.

The maximum stored beam energy in each ring of the LHC is about 120 MJ (200 MJ in case of electron-proton experiments because of the increased intensity of the proton beam). A safe and efficient beam dumping system has been designed to quickly remove the beams from the machine in the event of equipment malfunction or at the slightest indication of abnormal behaviour of the beam or to end normal operation cycles [1].

3. Design of the magnets

Main features of present design

Details of the design of the magnets may be found in ref. 1 and 3. Only the main features of the dipoles are reported here.

The design of the dipole magnets is based on the following :

- Field range : 8 to 10 T.
- Twin apertures in a common magnetic circuit and cryostat according to the so-called "two-in-one" concept.
- Inner coil diameter : 50 mm.
- Distance between the centres of the apertures : 180 mm.
- Use of NbTi conductor at 2 K, or of Nb₃Sn at 4.5 K.
- Design critical current density in the superconductor $j_c = 1300 \text{ A/mm}^2$ at 11 T.
- Two-shell coils with graded current density, surrounded by aluminium alloy (or stainless steel) collars and vertically split cold iron to form the so-called "mechanically hybrid" structure [4, 5].

The above mentioned design critical current density has been confirmed for NbTi at 2 K and also for Nb₃Sn at 4.5 K, at least for one, still experimental, production method [6]. From recent optimization work on the coil geometry, it appears that for a 10 Tesla nominal induction (B_0) the peak field in the windings can be kept below 10.5 T. This allows the percentage of stabilizing copper in the wire cross-section to be ~ 61 % in the first layer and ~ 64 % in the second layer.

Although Nb₃Sn (or similar materials) may have a greater potential for future developments, most of the magnet studies have been concentrated on the NbTi, 2 K version, because it is the most demanding in space and cryogenics and more straightforward in magnet fabrication technology. Most of the information reported here refers, therefore, to this version. The Nb₃Sn line is, however, being pushed forward in parallel, with the development of conductor and the construction of model magnets in collaboration with industry.

Among a number of possible options for the LHC magnets (e.g. separate beam channels horizontally or vertically spaced) the preferred solution is the twin apertures configuration. The superconducting coils, providing equal but opposite field in the two beam channels, are mounted inside a common iron yoke and force retaining structure, the whole being housed in one cryostat (fig. 5). This solution, the most compact and economical one for two beam channels, is the only way to reach a field as high as 10 T in two dipole apertures within the space available in the existing LEP tunnel. The horizontal spacing between the two beam channel axes is mainly determined by the size of the corrector magnets for each beam, which must be magnetically uncoupled.

As shown in Fig. 5, the coil support structure is formed by :

- A twin collar made from a non-magnetic alloy (Aluminium alloy or stainless steel), in which the coils are assembled and moderately prestressed at room temperature.

- An iron yoke split in two parts at the vertical symmetry plane of the twin aperture magnet. The two iron inserts between collars and yoke, serve to reduce the quadrupole component due to saturation.
- A stainless steel or aluminium alloy shrinking cylinder around the yoke.

During the cooling process the shrinkage of the collars (if they are made of an aluminium alloy) increases the pre-compression in the coils, while the two main parts of the yoke, which are actuated by the outer shrinking cylinder, move horizontally inwards applying additional compressive forces to the collar-coil assembly in the direction just opposite to the main action of the e.m. forces. If the gap between the two parts of the yoke is properly adjusted at room temperature, it will close at a predetermined lower temperature and when cool-down is completed a compressive force will be produced at the mating face between the two yoke parts. If this force is equal or larger than the horizontal resultant of the e.m. forces, the gap remains closed in all operating conditions and the split iron behaves as a single solid body, so that the structure results very rigid and allows only negligible displacements of the collar-coil assembly. In the present design the horizontal radial outward elastic displacement of the coil inner edge at the median plane at 10 T is only about 0.05 mm with respect to the centre of the aperture.

The main parameters of the dipole and of its superconducting cables are reported in Table V and VI.

Table V - Dipole parameters at 2 K

Nominal field B_0	10 T
Operation current	15650 A
Turns per beam channel	1st layer 2 x 13
	2nd layer 2 x 24
Peak field in winding (T)	1st layer 10.2
	2nd layer 8.5
Stor. energy for both channels combined	684 kJ/m
Overall current density in compressed and insulated cable (A/mm^2)	1st layer 373
	2nd layer 556
Coil inner diameter	50 mm
Coil outer diameter	122 mm
Distance between aperture axes	180 mm
Length	10 m
Weight	18 t

Table VI - Characteristics of the two cables for the 10 T dipole

	Cable 1	Cable 2
	inner layer	outer layer
Strand diameter (mm)	1.29	0.84
Cu/Sc ratio	1.6	1.8
Number of strands	26	40
Cable dimensions (mm^2)	2.06/2.50x17.0	1.3/1.67x17.0

Field quality

Details of the expected field quality are discussed in ref. 1. The most worrying error is the sextupole component at injection field produced by persistent currents in the superconductor. Table VII gives sextupole and decapole errors for two diameters of the superconducting filaments.

Table VII - Relative field errors due to persistent currents

At $B_0 = 0.5$ T (injection field)
Normalized to $R = 1$ cm, in 10^{-4} units

	fil. $\phi = 10$ μ m	fil. $\phi = 5$ μ m
b_3 (6-pole)	- 7.2	- 3.6
b_5 (10-pole)	0.84	0.42

Obviously the best way of reducing these errors is to minimize the strength of their source by using a conductor with small "effective" filament diameter and this is part of the development programme in industry. There are, however, technical difficulties (anti-diffusion barriers, rupture of filaments) in the industrial production of conductors with ≤ 5 μ m diameter filaments in copper matrix and limitations arising from proximity effects between closely packed fine filaments in high current density wires. In addition, the economical optimum for production is probably for strands with $10 + 15$ μ m filament diameter and the cost increment for producing the very small filament conductors might be larger than the cost of providing distributed correction windings. The present design is based on 5 μ m diameter filaments, but the possibility of using ~ 10 μ m filament conductor and installing correction windings remains open and will be further studied. It is clear that for equal costs, the correction windings solution would offer the additional advantage of a better flexibility in the operation of the machine.

4. Development Programme

The technology of the LHC high field compact magnets is difficult and requires a sustained effort of research and development. For this to be successful, it is essential to make use of all existing expertise and facilities. A European Collaboration, open to other interested parties, has been started among CEA (France), CEN-MOL (Belgium), CERN, DESY (Germany), ECN (Netherlands), ENEA (Italy), INFN (Italy), KFK (Germany), NIKHEF (Netherlands), RAL (United Kingdom), SIN (Switzerland), Techn. Universität Wien (Austria). Fruitful exchange of information and, whenever possible, mutual help is also going on with the American Laboratories who are working on the magnets for the SSC. CERN intends to order from industries all magnets and ancillary components for the LHC and is willing to entrust to them all the needed developments that they can effi-

ciently carry out. Industry is, therefore, taking part from the beginning in the R.&D. effort, not only in the development of components, such as conductors, insulation systems etc., but also in the design and construction of magnet models. In this way CERN will prepare the way to industrial manufacture of the required large number of high field magnets, while at the same time fulfilling one of its indirect tasks, i.e. know-how transfer to the industrial world and promotion of technology.

The main components under development are conductors for both NbTi and Nb₃Sn lines, insulation systems especially for the Nb₃Sn line, dipole magnets, quadrupoles, correction magnets, high current diode assemblies for magnet by-pass at quench, ultra low-resistance junctions ($< 5 \times 10^{-10}$ Ω) of superconducting cables, low-loss current leads for 15 to 20 kA, electronics, hardware and software for diagnostics and controls.

Conductors

NbTi fine filament wires

Pilot orders have been placed with European industry for the development of suitable wires with 2 to 5 μ m diameter filaments in a copper matrix. One firm has succeeded the production of a suitable ϕ 0.83 mm strand with 4.5 μ m filaments of very regular shape and without any rupture. The obtained critical current meets the specified value of 2500 A/mm² at 5 T, 4.2 K. Work is continuing on the industrialization of the process.

High aspect ratio cables

To make the LHC dipole magnet coils in only two layers requires high-current large-aspect ratio (width/thickness) cables never previously tried. Experimental production of such cables in European industry has been successful and small scale winding tests have shown that they can be bent around a radius of curvature corresponding to the first turn of the inner coil shell. The choice is still open between a single stage or a two-stage cable for the inner layer and will be determined by the experience on the model magnets. Fabrication and winding tests with the outer cable, which has the highest aspect ratio, have shown that the mechanical stability can be obtained for the NbTi cables by soldering the

Table VIII - Cables for model magnets

Model magnet	SC	Dimensions [mm ²]	Number of strands	Strand diameter (mm)	Filament diameter (μ m)	Stab. copper (vol.%)	Specified critical current (A)
8 T	NbTi	1.67/1.30x12.6	30	0.84	10	64	13000 at 8.0 T, 2 K
"Two-in-one" 10 T	NbTi	2.50/2.06x17	26	1.29	14	61	17500 at 11.0 T, 2 K
		1.67/1.30x17	40	0.84	14	64	17500 at 8.5 T, 2 K
10 T Nb ₃ Sn	Nb ₃ Sn "1"	2.69/2.19x16.8	24	1.38	2.6	33	17000 at 11 T, 4.2K
		1.79/1.47x16.8	36	0.92	2.6	33	18200 at 8.5 T, 4.2K
	Nb ₃ Sn "2"	2.67/2.18x16.4	24	1.35	7	50	17000 at 11 T, 4.2K
		1.77/1.45x16.4	36	0.90	5	50	18200 at 8.5 T, 4.2K
	Nb ₃ Sn "3"	2.67/2.18x16.4	24	1.35*	10	55	17000 at 11 T, 4.2K
		1.77/1.45x16.4	36	0.90	10	55	18200 at 8.5 T, 4.2K

"1" Bronze route ; "2" Internal diffusion ; "3" ECN powder method ; * Subcable made of 5 ϕ 0.55 mm strands around a central copper wire.

cables and that soldered cables do not open in the ends during winding. The present design is therefore based on the use of soldered cables having some void space to allow the penetration of superfluid helium and thus an improvement in enthalpy reserve. Cables for the magnet models have been ordered as listed in table VIII, where the specified critical currents are for field perpendicular to the broad face. Some of these cables have already been delivered and meet the specifications.

For the Nb_3Sn model two experimental conductors, produced by the internal diffusion method and by the ECN powder method respectively, have been ordered in addition to the better known, but less performing, bronze route conductor. The non-copper critical current density measured on experimental $\varnothing 0.85$ mm wires recently produced by ECN and having filaments of about 10 μm diameter is 1650 A/mm² at 11 T, 4.2 K [6].

High Tc superconductors

The advent of the recently discovered superconductors might simplify the cryogenics and perhaps could open the way to easier and safer high field magnets that would be less sensitive to energy deposition, thanks to the larger specific heats and higher operating temperature margin, if conductors of suitable characteristics would become available in a not too distant future. CERN is, therefore, closely following the progress in this field.

The first applications of which we are thinking are in the cryogenic current leads, to reduce cross-sections and heat intake, and in the long straight superconducting busbars. The latter would be a massive and important application as it could permit a large reduction of the busbar cross-section and a safer machine discharge in case of magnet quench, while at the same time reducing the heat load to the cryogenic system. Brittleness of the material would not be an obstacle as the main parts of the busbar system will be straight and rigid.

Model magnets

Three one meter long model magnets are under fabrication or designed at present.

8 Tesla model

This single aperture, 8 T nominal field, magnet is a joint project of ANSALDO Componenti, Italy, and CERN [7]. Its main purposes are to test the vertically split yoke "mechanically hybrid" structure and the magnet behaviour under different operating conditions in superfluid helium. In order to simplify and speed-up the procurement of the conductor, the same cable is used in the two shells of the coils, but the second layer has been "overloaded" with turns in order to simulate a graded current density construction from a mechanical point of view. All components and tooling (Fig. 6) for this model are ready and the coils are presently being wound at ANSALDO.

Nb_3Sn , 10 T, model

In order to test the Nb_3Sn , 4.2 K route to 10 T LHC magnets, it has been decided to build a 1 m long, single bore model magnet. The coils of 50 mm inner diameter will be made in two layers with the cables of table VIII following the wind-and-react process. After reaction the coils will be impregnated with epoxy resin and mounted inside aluminium alloy collars. The force retaining structure will consist of the collars and of the other components of the "mechanical hybrid" structure, i.e. the vertically split iron yoke surrounded by an aluminium alloy

Figure 6 - Curing mould and collaring press for the 8 T model.

(Courtesy of ANSALDO Componenti, Italy).

shrinking cylinder. Design and construction of this model is a joint project of the firm ELIN-UNION, Austria and CERN with an important contribution of the firm AUSTRIA-METALL AG for the aluminium alloy parts of the magnet. The necessary preliminary work is almost completed. Small winding tests, made with a thick dummy superconducting cable of a geometry suitable to the coil inner shell, have shown that only small and acceptable harm is done to the Nb_3Sn filaments by bending the conductor around a 5.5 mm radius before reaction. This was confirmed by some hairpin samples bent with 5.5 mm and 25 mm radii which were prepared at CERN and measured in Fermilab at 10.3 T and 4.2 K. The selected conductor insulation, a commercial glass-mica tape, has been thoroughly tested under all conditions met in coil manufacturing. It has shown acceptable electrical and mechanical properties and it will be used in the first model magnet, but more work still needs to be done in this field. In order to check the mechanical behaviour of the structure a 15 cm long slice of the magnet (called 15 cm model) has been built by ELIN-UNION (Fig. 7), using a coil assembly made at CERN with Nb_3Sn cable and the selected insulation.

Figure 7 - Coil-collar assembly for the 15 cm model. (Courtesy of ELIN-UNION, Austria).

It is presently undergoing thermal cycles and simulated e.m. force loading tests, which so far confirm the design calculations. The design of the magnet has now been completed and the various components as well as the necessary tooling are being procured, so that the winding of the superconducting coils can start in January 1988.

Two-in-one, 10 T. model

To test the high field "two-in-one" concept, a 1 m long model having the cross-section of the present design LHC dipoles (fig. 5) will be built using NbTi conductor. The design of the magnet as well as of all the tools for its manufacture has been completed at CERN, and the necessary cables (see table VIII) ordered. It is intended to launch fabrication by end 1987 [3].

Twin-aperture 9 m long prototype

In parallel with the effort on the 1 m long models, it has been decided to design and order from industry a twin aperture, 9 m long, prototype magnet. Its main purpose is to gain experience in the construction of long two-in-one "mechanically hybrid" structures and in operation with superfluid helium. The magnet cross-section is shown in Fig. 8. In order to gain in time and cost, use is made of superconducting coils of the same type and geometry as those of the DESY HERA proton ring dipoles. The expected nominal field is 7.5 T in the 75 mm diameter coil apertures. The design of the active part of the magnet has been done and the conductor ordered, while the design of the 1.8 K cryostat has just started. The order for the active part will be placed within 1987.

Figure 8 - Cross-section of the twin aperture prototype

Other items

A test station for the 1 m long model magnets has been assembled at CERN mostly from re-adapted existing components and is now operational. It consists of : a vertical cryostat with a superfluid helium bath at 1.8 K and atmospheric pressure, 18 kA cryogenic current leads which were supplied by a European firm, a 100 l/h helium liquifier, a stabilized d.c. 20 kA power supply completed with a thyristor switch of novel design, diagnostic, control and protection equipment.

A more sophisticated and powerful test station is being prepared by CEA at Saclay, France, for more refined tests and magnetic measurements on model and prototype magnets.

A development program on high current cold diode assemblies is starting in collaboration with a specialized firm.

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