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THE SUPERCONDUCTING MAGNET SYSTEM FOR THE LHC

R. Perin

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R. Perin
CERN, European Organization for Nuclear Research
1211 Geneva 23, Switzerland

Abstract

CERN is preparing for the construction of a new high energy accelerator/collider, the Large Hadron Collider (LHC). This new facility will mainly consist of a 27 km long double ring of high field superconducting magnets installed in the LEP tunnel, above the LEP machine components. The magnet system comprises nearly 2000 twin-aperture, 8 to 10 T, 10 m long, dipole bending magnets, more than 500, 250 T/m, twin-aperture quadrupoles and a very large number of other superconducting magnetic components.

A general description of the system is given together with the main features of the design of the regular lattice magnets. The paper describes also the present state of the magnet R&D programme, which, after the successful phase of short model magnets, is now aimed at the construction of a full prototype 100 m long cell of the LHC machine.

1. Introduction

After the very successful start-up of the Large Electron-Positron Collider (LEP) in 1989, and its first spectacular physics results, CERN is considering the construction of a new accelerator/collider which will enable exploration of matter at energy levels at least ten times higher. This new machine, the Large Hadron Collider (LHC)¹, will mainly consist of a double ring of advanced technology superconducting magnets which will be installed in the 27 km long LEP tunnel, above the LEP collider components (Fig. 1). It will guide, accelerate and collide intense beams of protons of up to about 8 TeV energy and about $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity. Heavier ions can, of course, also be accelerated and made to collide at extremely high centre-of-mass energy. In addition, there will be a unique possibility of colliding high energy protons with the electrons of LEP up to about 1.8 TeV centre-of-mass energy.

Figure 1. Model of the tunnel showing the LHC on top of LEP.

A general simplified scheme of the LHC is shown in Fig. 2. The axes of the two counter-rotating particle beams are separated by 180 mm in the regular arcs of the machine and cross each other in 8 points regularly spaced around the circumference. The two bunched beams circulating in separate beam channels alternate from the inner arcs to the outer arcs passing, between two successive crossing points, through a straight section (~ 250 m long), a short circular arc containing the so-called dispersion suppressor section (~ 170 m long), a long arc made up of standard repetitive cells (2500 m long) and again a short circular arc followed by a straight

section as above. In seven crossing points, the proton bunches can be made to collide and 3 or 4 are at present considered for physics experiments, one crossing region is reserved for the beam dumping system.

Figure 2. Schematic layout of the LHC.

The performance parameters of the LHC are presented in Tables 1 and 2. The luminosity for proton-proton collisions can be pushed to about $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in a single experiment.

Table 1. LHC proton-proton performance

Maximum proton beam energy (TeV)	7.7
Maximum collision energy (TeV)	15.4
Number of bunches	4725
Particles per bunch	10^{11}
Stored beam energy (MJ)	580
Luminosity ($\text{cm}^{-2} \text{ s}^{-1}$)	1.7×10^{34}

Table 2. LHC ion-ion performance

Type of ions	Pb
Maximum collision energy (TeV)	1262
Number of bunches	800
Ions per bunch	6.2×10^7
Luminosity ($\text{cm}^{-2} \text{ s}^{-1}$)	1.8×10^{27}

The high-field superconducting magnets are the most important and technologically the most critical components of the projected machine. For this reason, some years ago CERN has launched a R&D programme for their development in collaboration with National Institutes and Universities and with a vast and intense participation of industrial firms. The programme is focused on the standard cell components and includes study and construction of several magnets and other items:

- high aspect ratio and high current density cables,
- single-aperture 1 m-long dipole models following both technologies, NbTi at 2 K and Nb₃Sn at 4.3 K (8 TM1, 8 TM2, 9 TM1 magnets),
- twin-aperture 1 m-long dipole models (MTA1 magnets),
- a twin-aperture 10 m-long prototype using HERA coils for a field of 7.5 T with its cryostat working at 2 K (TAP magnet),

- (e) 10 m-long, high magnetic field prototypes and their cryostats,
- (f) main quadrupoles,
- (g) prototype auxiliary magnets, such as tuning quadrupole, sextupole, dipole corrector,
- (h) high-current diodes for protection,
- (i) and finally a complete cell of the LHC machine.

To achieve this ambitious R&D program, a collaboration has been set up between CERN and several European Laboratories and Institutions as Wien Tech. University (A), CEA (F), PSI (CH), DESY and KfK (D), INFN (I), ECN-FOM-UT-NIKHEF (NL), RAL (UK), etc. A special effort in R&D has been done by a number of industrial firms by designing and building magnets as joint ventures with CERN: ACICA (E), Ansaldo (I), Elin-Union (A), Tesla Eng. (UK). Many others participate in different ways or by supplying to CERN magnets, cryostats and other components, as ABB (CH, D), Alsthom (F), FBM (I), Holec (NL), IMI (UK), Jeumont-Schneider (F), LMI (I), Marconi (UK), Siemens (D), Vacuumschmelze (D), Zanon (I), etc.

2. The magnet system

About 24 km of the LHC ring will be occupied by superconducting magnets of various types. The long arcs, covering approximately 20 km of the circumference, are composed of "standard cells" a bending/focusing configuration which is periodically repeated 196 times around the ring. One half of a standard cell (Fig. 3) consists of four, ~ 10 m long, dipole magnets (D), one half focusing quadrupole magnet (QF), a tuning quadrupole (QT+0) which includes octupole correction windings, a combined dipole/sextupole/decapole corrector magnet (S+DE+COD), a beam observation station (BOM) and one half defocusing quadrupole (QD), and a central sextupole/octupole/decapole corrector (S+O+DE) (which is placed between the two central dipoles of the half cell).

Figure 3. Standard half-cell.

The quadrupoles, the S+DE+COD corrector and the beam observation station are all mounted on a common girder in a single cryostat, which covers the whole short straight section. Dipoles and main quadrupoles of the two rings are combined into "two-in-one" units, each pair having a common yoke and cryostat. Focusing quadrupoles of one ring are paired with defocusing quadrupoles in the other ring. Multipole correctors are assembled concentrically on a common beam pipe. All correctors, and the tuning quadrupoles of one ring are magnetically decoupled from the magnets of the other ring.

In each ring, dipoles and main quadrupoles are powered in series. The dipole correctors are excited independently and have low current. Cryogenic leads in each short straight section. The multipole correctors are grouped into families; each family is connected in series by superconducting lines.

In addition to the regular arcs, there are other magnets in the dispersion suppressor sections and on either side of each crossing point. These are "standard cell type" superconducting dipoles and quadrupoles, special beam separation/recombination dipoles and special high gradient, large aperture quadrupoles for the focusing (low-beta) insertions. Most of the magnets will use the technology of NbTi superconductors working at superfluid helium temperature in order to reach the demanded high field. The Nb₃Sn route to high field may be applied in some special parts of the machine, as for

example in a number of very powerful quadrupoles in the long straight sections on either side of the collision regions.

Table 3. Type and number of superconducting magnets

Type	Nominal strength	Magnetic length (m)	Number
Regular lattice			
Main dipoles	$B_0 = 10\text{ T}$	9.0	2 x 1792
Main quadrupoles	$G = 250\text{ T/m}$	3.05	2 x 392
Tuning quadrupoles + octupoles	$G = 120\text{ T/m}$ $B^{\text{III}} = 1 \times 10^5\text{ T/m}^3$	0.72	800
Combined correctors			
Dipole	$B = 1.5\text{ T}$		
6-pole	$B^{\text{II}} = 4500\text{ T/m}^2$	1.0	800
10-pole	$B^{\text{IV}} = 3.2 \times 10^7\text{ T/m}^4$		
Central correctors			
6-pole	$B^{\text{II}} = 1540\text{ T/m}^2$		
8-pole	$B^{\text{III}} = 1.8 \times 10^5\text{ T/m}^3$	0.5	800
10-pole	$B^{\text{IV}} = 1.4 \times 10^8\text{ T/m}^4$		
Interaction regions			
Twin-aperture quadrupoles	$G = 250\text{ T/m}$	5.0 4.0 3.05	2 x 18 2 x 72 2 x 136
Single bore quadrupoles	$G = 250\text{ T/m}$	6.8 6.1	12 12
Skew quadrupoles	to be defined		64
Separation dipoles	$B = 5.4\text{ T}$	9.0	6
Dipole correctors	to be defined	0.5	286

3. Conductors

The conductors of the main dipoles and quadrupoles are Rutherford type trapezoidal cables made of NbTi/Cu composite strands. Their main characteristics are reported in Tables 4 and 5.

Table 4. Design characteristics of the two superconducting cables for the 10 T dipoles

	Cable for the inner layer	Cable for the outer layer
Critical current (A)	≥ 14800 at 11 T, 2 K	≥ 17100 at 9 T, 2 K
Cross-section (mm ²)	2.02/2.48 x 17	1.30/1.65 x 17
Number of strands	26	40
Transposition pitch (mm)	≤ 120	≤ 120
Strand diameter (mm)	1.29	0.84
Cu/Sc ratio	1.6:1	1.8:1
Filament diameter (μm)	5	5
Filament twist pitch (mm)	25	25
J_c (non-Cu) (A/mm ²)	≥ 1190 at 11 T, 2 K	≥ 2280 at 9 T, 2 K

The development of these high-current, large aspect ratio (width/thickness), cables was encouraged by several pilot orders to European companies and has been successful to a large extent. Only some relatively small improvements are still needed to fully meet all requirements.

In the outer layer cable, the required critical current is now obtained. In the 1.29 mm diameter strands of the inner layer cable, a 1000 A/mm² current density is now reached in 10 μm Ø filaments at 11 T, 2 K. Work is continuing to obtain this current density in 5 μm Ø filament wires. Strands containing 28000, 5 μm Ø, NbTi filaments and capable of 1150 A/mm² at 8 T, 4.2 K have already been produced (Fig. 4), but more work has to be done to optimize the current density at high field. From measurements of wires before and after cabling, it was found that the degradation of current density due to the cabling operation remains less or equal to 5%. Concerning the mechanical stability of the cables during winding, it

appears that the inner layer cable is sufficiently stable, and fortunately does not require to be filled with solder. This would have been forbidden because of the unacceptably high a.c. losses, which could have induced magnet quenches at each fast discharge of the LHC magnet ring. On the contrary, the outer layer cables (40 strands) that have been produced so far are intrinsically not sufficiently stable and had to be, at least partially, soldered. Experimental production are being tried with the aim of achieving a better locking of the strands in this cable.

Figure 4. Strand of a cable for the inner layer of the LHC dipole coils: wire diameter 1.29 mm, 28314, $\varnothing$ 5 μ m, NbTi filaments in copper matrix (Courtesy of ALSTHOM-Intermagetics).

Table 5. Design characteristics of the cable for the main quadrupoles

Critical current at 9 T, 2 K (A)	≥ 15600
Cross-section (mm ²)	1.70/2.16 x 17
Number of strands	24
Transposition pitch (mm)	< 100
Strand diameter (mm)	1.09
Cu/Sc ratio	≥ 1.8
Filament diameter (μ m)	5
Filament twist pitch (mm)	25
Jc (non-Cu) at 9 T, 2 K (A/mm ²)	≥ 2280

An important activity is also proceeding on Nb₃Sn superconductors. A significant length (~ 150 m) of cable having approximately the cross-section of the outer layer cable of Table 4, and reaching 1600 A/mm² at 11 T, 4.2 K in the non-copper part of the cross-section with 15 μ m diameter filaments, was produced and is being used to wind a short dipole model.

4. Dipoles

The main parameters of the twin-aperture dipoles are presented in Table 6 and Fig. 5 shows its cross-section. The design, already described in ref. 2 is based on:

- Field range: 8 to 10 T
- Twin apertures in a common force retaining structure/flux return yoke and cryostat.
- Coil aperture I.D. = 50 mm.
- Distance between the axes of the apertures: 180 mm.
- Use of NbTi superconductor operating in superfluid helium at 2 K.
- Two-shells coils with graded current density, supported by high strength aluminium alloy collars and vertically split iron yoke,

with an open gap at room temperature³, surrounded and compressed by a shrinking cylinder.

Table 6. Dipole parameters

Nominal field B ₀ (2 K)	10	T
Operation current	15060	A
Turns per beam channel	1st layer	2 x 13
	2nd layer	2 x 24
Overall current density in compressed and insulated cable (A mm ⁻²)	1st layer	357.5
	2nd layer	532.9
Coil inner diameter	50	mm
Coil outer diameter	120.2	mm
Distance between aperture axes	180	mm
Collars outer dimensions	201 x 381	mm
Iron outer diameter	540	mm
Stored energy for both channels combined	684	kJ m ⁻¹
Resultant of magnetic forces in the first coil quadrant		
ΣF_x	2.27	MN m ⁻¹
ΣF_y 1st layer	-0.23	MN m ⁻¹
ΣF_y 2nd layer	-0.98	MN m ⁻¹
Longitudinal magnetic force	0.70	MN

Figure 5. Cross-section of LHC dipole

1. Vacuum chamber, 2. Coils, 3. Al collars, 4. Yoke, 5. Shrinking cylinder, 6. Bus-bars, 7. Bore for helium pipe, 8. 4.5 K shield, 9. 77 K screen, 10. Superinsulation, 11. Vacuum vessel, 12. Support foot, 13. 4.5 K GHe pipe, 14. 1.8 K GHe pipe, 15. LN₂ pipe.

The shrinking cylinder is at the same time the outer wall of the helium II tank, the inner wall being the beam vacuum chamber. Between these two cylindrical walls, the cold mass is kept at 1.8 to 2 K. In order to reduce the heat load on the cryogenic system at this very low temperature, the heat generated by the proton beams is intercepted by shields that are inserted in the vacuum chambers and cooled by circulation of helium at 4.5 to 8 K. In the last two years, the design has evolved from an oval outer configuration of the cold mass cross-section which would be the most efficient shape from the magnetic and mechanical viewpoints, to a circular contour which is easier to manufacture, especially for models and prototypes. The support of the cold mass in the cryostat has been changed from a suspension system using tension elements to feet working mainly in compression.

Major problems still to be solved in these dipoles are related to the combined effects of high field and compactness, and stem from the extremely high electromagnetic forces on the windings (Fig. 6)

and stored energy density. At 11.2 T, the field level assumed for the design of the mechanical support structure, the resultant of the outward horizontal electromagnetic forces is ~ 600 t/m. This has to be transferred through small surfaces and taken entirely by a very compact and efficient external structure, with a minimum of deformation. The vertical forces (~ 160 t/m per aperture quadrant) are contained within the coil, but have to be transferred through cabled strands and interturn insulation which are then submitted to very high specific pressure, which is further enhanced by the initial prestress that must be applied to avoid tensile stress over the whole coil cross-section.

Figure 6. Electromagnetic forces in the coils of an LHC dipole at $B_0 = 11.2$ T.

This has required a very careful study of the mechanical structure⁴ and it is believed that an adequate solution has been found, as demonstrated by tests on 1 m long model magnets. Further improvements are, however, still needed on the collaring procedures and on the cable insulation which is still not entirely satisfactory for an efficient industrial production of about 8000, 10 m long, coils and for their reliable operation during at least 20 years. The problem is made even more difficult by the need to maintain some porosity in order that the superfluid helium may permeate the conductors and carry away, thanks to its high heat conductivity, the heat deposited by possible beam losses.

The high stored energy requires an absolutely reliable system (heaters) of artificial fast quench propagation to the whole mass of the windings and sure means (cold diodes or safety leads) of bypassing any quenching magnet. Contrary to lower field superconducting magnets, the LHC dipoles will not survive a quench if the quench propagation heaters would not work correctly. The protection system which has been carefully studied on paper and tested so far only in 1 m long model magnets need to be thoroughly experimentally proved as soon as full length prototype magnets will become available.

The expected field quality is given in Table 7, under the form of multipole field errors according to the standard formula:

$$B_y + iB_x = B_0 \sum_n (b_n + i a_n) (Z/R_r)^{n-1}$$

where B_0 = magnitude of dipole field in the y (vertical) direction
 b_n = normal multipole coefficient
 a_n = skew multipole coefficient.

$b_1 = 1$; a_1 = dipole x-component; $Z = x + iy$;
 a_2, b_2 = quadrupole components; R_r = reference radius;
 a_3, b_3 = sextupole components; etc..

Table 7. Relative field errors at $R_r = 1$ cm in 10^{-4} units

Multipole	Normal systematic	Skew systematic	Normal random	Skew random
a ₂		± 0.8		1.7
b ₂	-1.4 ± 1.6		1.2	
a ₃		± 0.1		0.5
b ₃	- 3.0		1.7	
a ₄		± 0.03		0.2
b ₄	± 0.05		0.15	
a ₅		± 0.03		0.07
b ₅	0.40		0.22	
a ₇		± 0.02		0.04
b ₇	0.13		0.02	
a ₉		± 0.001		0.002
b ₉	0.024		0.005	

As it can be seen, the introduction of the individual dipoles in the "two in one" geometry produces additional multipole components, especially a quadrupole. Iron inserts between the two individual dipoles reduce the quadrupolar component and the saturation effects⁵. The residual error can be eliminated by introducing a left-right asymmetry in the coils, e.g., a wedge of 2×0.8 mrad. placed in the mid-plane of the central coil layers. The main contribution to the normal 6-pole, 10-pole and 14-pole components comes from persistent currents in the superconductor.

5. Quadrupoles

The design of the lattice quadrupoles is conditioned by the following points:

- Coil aperture I.D. = 56 mm.
- Two-in-one geometry with magnet centre spacing of 180 mm.
- Quadrupoles excited in series with the main dipoles.
- Operation at 2 K as for the dipoles.

From the beginning it was understood that only the F-D combination could be realized in the two-in-one geometry without excessive magnetic saturation effects. As for the dipoles a common yoke is shared by the two quadrupole coil assemblies. However, the coil dimensions and the forces allow to use separate sets of collars around each coil assembly. The 56 mm coil aperture provides the space to insert a twelve-pole correction coil, if this should turn out to be indispensable. The same conductor is used for the inner and outer shells of the windings.

The overall cross-section is shown in Fig. 7 and the main parameters are presented in Table 8.

Table 8. Main parameters of the LHC lattice quadrupoles

Nominal current	15060	A
Gradient at nominal current	250	T/m
Effective length	3.05	m
Maximum induction in coils	7.8	T
Current density in NbTi at nom. curr.	1883	A/mm ²
Inner coil bore diameter	56.0	mm
Outer diameter of coil	110.6	mm
Outer diameter of collar	166.0	mm
Inner diameter of iron yoke	172.0	mm
Outer diameter of iron yoke	444.0	mm
Overall length of yoke	3.22	m
Stored energy (both apertures)	445	kJ
Self inductance (both apertures)	3.9	mH

The conductor, whose main characteristics are listed in Table 5, is insulated by two half overlapped layers of polyimide tapes, the first 25 μ m thick, and the second 12.5 μ m. A third layer consists of a 120 μ m thick glass-fibre tape impregnated with B-stage epoxy resin and spaced by 2.5 mm between successive turns.

Figure 7. Overall cross-section of a LHC lattice quadrupole.
1. Coils, 2. Non-magnetic collars, 3. Yoke, 4. Inertia tube, 5. Bore for helium duct, 6. Passage for bus-bars.

The winding technique is similar to that of the dipoles, but there is no cable joint between the two shells, as the same conductor is used.

The conductors are grouped in 2 blocks (2+6 conductors) in the inner layer and in 1 block (12 conductors) in the outer layer of the coil. The coils are insulated against the collars by six layers of 125 μm thick polyimide film. Quench protection heater strips made of 30 μm thick stainless steel are placed between these layers and the coil.

The collars are made of aluminium alloy punched out of 3 mm thick sheets. As for the dipoles, their function is to provide the required prestress before and after cool-down and to withstand the electromagnetic forces during excitation. Contrary to the dipole design, the collars are not assisted by the yoke structure in their task of force containment. The quadrupole geometry implies that the collar laminations have to be mounted transposed by 90 degrees with collar separation lines along the 45 degree pole axes. Alternative means of coil prestressing and locking of the collars have been studied: locking the collars by means of rods inserted into tightly fitting holes or by means of wedged bars keyed on the collar outer circumference. Presently, the latter technique is favoured for the quadrupoles as it entails a moderate coil compression at assembly. The prestress is built-up by progressively inserting wedge shaped keys, made of stainless steel, into grooves placed on each side of the horizontal and vertical planes (Fig. 7). This technique gives a minimum local elastic deformation of the collars and avoids over-stressing the coils at room temperature by limiting the stress to 4 daN/mm².

The yoke is assembled of 5 mm thick iron laminations. In contrast with the vertically split dipole yoke, the laminations cover the full cross-section of the two-in-one quadrupole. The locking of the laminations is realized by four rods. Four tie-bars, together with the end-plates, provide the longitudinal prestress of the yoke stack. The yoke is inserted into a stainless steel tube which provides the overall stiffness of the magnet assembly. The straightness and position of the magnet is ensured by locating dowels, positioning keys and fixation screws, which are placed in precise dowel-holes in the tube and grooves in the yoke. In order to avoid a separate outer helium vessel, all openings are sealed by welding half tubes along the lines of the holes (Fig. 7).

The design of the prototype quadrupole⁶ is being carried out by a joint CEA, Saclay/CERN team. The assembly of the first prototype will be made in Saclay by the same team who developed the quadrupoles for HERA.

6. Correction magnets

The correction magnets for the LHC are not all defined yet, but for some of them, namely for the tuning quadrupoles and the combined sextupole/dipole correctors, the work has advanced to the point that prototype magnets are presently being built in industry.

6.1 Tuning quadrupole and octupole correction windings

The working point of the machine will be adjusted by special quadrupoles installed in pairs in each regular cell next to the main quadrupoles. They allow a variation of the tune by ± 2 units and compensate the tracking differences between main dipoles and quadrupoles and also the quadrupole error caused by iron saturation at high field in the dipoles. Since this latter error changes sign between the inner and outer beam channels, the two families of tuning quadrupoles of each machine are separately powered per octant to obtain equal phase advances in the regular lattice of each octant.

A prototype⁷ is the subject of a common development with the consortium ACICA (E). The nominal strength is 86.4 T with a gradient of 120 T m⁻¹. The design is based on individually built, magnetically decoupled quadrupoles. The aperture of the winding is 56 mm which allows to install an octupolar correction winding inside the quadrupole. The coils are made from insulated monolithic multifilamentary conductors 1.35 x 2.30 mm² and vacuum impregnated with epoxy resin. The design of the coils and their supporting structure follows the well proved technology of the CERN ISR quadrupoles⁸. The coils, 15.1 mm thick, are surrounded by glass epoxy bandages and an antifriction sheet. They are placed in a 30 mm thick Al alloy shrinking cylinder which gives the required prestress and supports the electromagnetic forces of 0.12 MN m⁻¹ per octant. The overall diameter of an individual tuning quadrupole is 170 mm and the length 800 mm. The stored energy is 12.85 kJ and the current 1600 A. The peak field in the winding amounts to 3.8 T. The completion of a first prototype is foreseen for mid-1991.

A preliminary design study foresees an octupole correcting winding inside the tuning quadrupole. The nominal strength of the octupole is 55000 T m⁻³ and the peak field in the winding reaches 3 T. This octupole which could be wound with an insulated wire of 0.6 mm ϕ has a self-inductance of 0.4 mH.

Figure 8. Cross-section of a tuning quadrupole

6.2 Combined correctors (dipole, 6-pole, 10-pole)

An inevitable consequence of "two-in-one" magnets is the restricted freedom to correct the closed orbits by moving the lattice quadrupoles. However, since these are horizontally focusing for one orbit and defocusing for the other, it could theoretically be envisaged to make compromise adjustments, but in reality this solution turns out to be unpractical and anyway the remaining correction must be provided by orbit correction dipoles. These will be adjacent, magnetically independent, units providing vertical field on one beam and horizontal field on the other. Clearly, since there is a large number of independently excited units, the current must be as low as possible, compatibly with sufficient mechanical strength of the conductor and packing factor in the windings, in order to minimize the cost of power supplies and cables and the heat load introduced by the current leads.

Figure 9. Cross-section of prototype sextupole-dipole corrector
1. Sextupole coil, 2. Dipole coil, 3. Al rings, 4. Yoke.

Sextupoles operating in the range $\pm 4500 \text{ Tm}^{-1}$ are necessary for the correction of chromaticity and to compensate for sextupolar errors in the main dipole magnets. Decapoles operating in the range $\pm 3.2 \times 10^7 \text{ Tm}^{-3}$ are needed to compensate decapolar errors.

These three correctors are combined together in the form of coaxial coils surrounded by a common iron yoke and located next to the main quadrupoles in the lattice short straight sections.

A prototype sextupole-dipole corrector magnet⁹ is built in the frame of a cooperation agreement with the firm Tesla Engineering with the collaboration of Rutherford Appleton Laboratory. The main parameters of this magnet are listed in Table 9 and its cross-section is shown in Fig. 9.

Table 9. Parameters of prototype sextupole-dipole corrector

	Sextupole coil		Dipole coil	
BII, B	4000	T/m ²	1.5	T
Peak field in coil	4.2	T	3.5	T
Current	458	A	47	A
Number of turns/coil	104		1200	
Inductance	0.059	H	4.6	H
Length	1	m	1	m
	Sextupole conductor		Dipole conductor	
Overall section	0.7x1.2	mm ²	Ø 0.35	mm
Metal section	0.5x1.0	mm ²	Ø 0.3	mm
Copper/NbTi ratio	1.6		4.4	
Current density	915	A/mm ²	666	A/mm ²
Current density (NbTi)	2379	A/mm ²	3596	A/mm ²

The coils are vacuum impregnated and placed in aluminium alloy shrinking rings, giving the required precompression after cooldown. The yoke for the combined sextupole-dipole corrector is a thick low carbon steel pipe. The mechanical structure has been designed to cope with the various distribution of forces and bending moments due to the different possible modes of operation of sextupole and dipole. The construction of the prototype is progressing actively and the magnet should be tested at RAL and at CERN within 1990.

6.3 Central correctors

These combined 6-pole, 8-pole, 10-pole magnets are being developed by a joint CERN-RAL team. The design, still in the initial stage, features three coils nested around a 56 mm diameter bore and surrounded by a common force retaining structure and yoke.

Studies are going on to compare such a design with another where each of the coils form an individual magnet which is then assembled one next to the other. The latter solution has the disadvantage of being about 15 % longer, mainly due to the spaces that have to be introduced between successive coils, but the advantage to result in completely decoupled magnets, eliminating the operational complications occurring if the strength of one correction changes when one of the others is put in operation or varied in excitation.

7. Development programme and industrialization

The high-field compact magnets for the LHC present several technical challenges which require advances in technology beyond the so far reached limits. Examples are the required high current density, high aspect ratio, superconducting cables, the extremely large electromagnetic forces concentrated in such a compact coil/structure configuration, the high accuracy and stability of the positioning of the conductors, and the very high energy density, a consequence of the high-current high-field capacity of the superconductors at 2 K, entailing very critical conditions for the protection of the magnets at quench.

Right from the start, CERN has sought the collaboration of the European Institutions who were experienced in the application of superconductivity, and of industrial firms likely to participate in the manufacture of the final LHC components. Some of these Institutions and Companies have already given important contributions to the R&D programme and are listed in the Introduction. Their field of activity may be found in ref. 10. Industry is in fact taking part not only by development and supply of components, such as conductors, insulation systems, high-current diodes, cryogenic current leads, etc., but also in the design and construction of magnets and cryostats. The joint ventures with industry operate in general in the following way:

- CERN proposes a well identified goal, e.g. the design and manufacture of a prototype magnet. The proposal is discussed thoroughly with the firm and, if accepted, a cooperation agreement is prepared and signed and the work starts.

- The repartition of tasks between CERN and the industrial firm is typically the following:

CERN contributes with:

- scientific and technical know-how;
- a preliminary design;
- the needed superconductor;
- scientific and technical assistance during design and manufacturing;
- the tests of the finished object.

The firm contributes with:

- participation in the final design by sending to CERN some of their staff (in general 2 to 3 persons) to work with the LHC Magnet Team during several months;
- procurement of all materials (except superconductor) and tooling;
- fabrication of the complete object;
- assistance during the tests at CERN.

In this way, a smooth exchange of information and mutual understanding of the different requirements are achieved and

manufacturing methods are taken into account at every step of the design process. Moreover, industry becomes aware of what is really important in the construction and is prepared for an efficient mass production of the large number of cryo-magnets required for the LHC.

7.1 Single-aperture model dipoles

Several very successful single-aperture, 1 m long, model magnets have been built on common development programmes with industry. Their results have been reported elsewhere^{10,11,12}. Two magnets of 8 T nominal field have been built at Ansaldo with a 12.6 mm wide cable of NbTi/Cu strands. They had their first quench above 8.5 T and reached 9.3 T at 1.6 K after 4 quenches. This field was subsequently attained at 1.9 K. After extensive tests and measurements at CERN and Saclay, the first magnet was given back to the manufacturer, who uses it for various tests, including ship propulsion experiments. The second magnet is now part of a test facility at CERN. Long storage of these magnets at room temperature and repeated thermal cycling do not appear to affect their behaviour: in a recent test, after more than one year at room temperature, the CERN magnet reached a field of 9.5 T at 1.8 K.

A Nb₃Sn model magnet has been built in Elin (A) using a 17 mm wide cable. This magnet reached 9.5 T at 4.3 K. During a second test campaign, 8 months later, the maximum bore field of 9.5 T was obtained again after two quenches. The work carried out by the CERN-Elin collaboration has demonstrated that the "wind and react" route for building high-field superconducting Nb₃Sn magnet is feasible.

The single-aperture model programme has assessed the validity of the mechanical design of the high-field superconducting magnets suitable for LHC.

7.2 Twin-aperture model dipoles

To demonstrate the validity of the two-in-one configuration, four one-meter long twin-aperture dipoles are under construction in industries: Ansaldo, Elin, Holec, Jeumont-Schneider. The four models which feature various technical solutions for the coils, the collars, and the shrinking cylinder, are at present in the final assembly stage and three of them will be delivered to CERN within 1990, the fourth one is expected for February 1991.

One preliminary important result is the feasibility of the winding with 17 mm wide cables. The present electrical insulation, though acceptable for models and prototypes, has still to be improved for mass production.

Another twin-aperture model magnet is being built by KEK in Japan in close cooperation with Japanese industry¹³. Its design is based on a high keystone angle cable which permits to wind the coils around the circular aperture without wedged spacers. It should result in a very compact magnet.

To explore further the Nb₃Sn route, a 10 T twin-aperture model magnet is being built in the Netherlands by a CERN-FOM-UT-NIKHEF Collaboration¹⁴.

7.3 Twin-aperture prototype TAP

A twin-aperture, 10 m long, prototype magnet¹⁵ was designed by CERN and built by industry (ABB) in order to gain experience in the construction of full scale, twin-aperture, high-field magnets and with the superfluid helium operation of a long horizontal cryostat. In order to reduce the cost of development and tooling, HERA coils, operated at 2 K, have been used. Apart from the coils, the external dimensions and the yoke are the same as for the 10 T dipoles. The manufacture of the magnet active part has unfortunately suffered from long delays, some of them independent from technical reasons. The completed magnet is now being inserted in its cryostat at FBM (I) before being tested at CEN, Saclay (F). Figs 10 and 11 show the active part before the welding of the shrinking cylinder, and the cryostat vacuum vessel respectively.

Figure 10. Active part of TAP magnet (Courtesy of ABB).

Table 10. Main parameters of TAP magnet

Magnet parameters	
Expected central field at 1.8 K	7.5 T
Excitation current at 7.5 T	8625 A
Stored energy at 7.5 T	4.06 MJ
Maximum field in winding at 7.5 T central field	8.05 T
Coil inner diameter	75 mm
Distance between aperture axes	180 mm
Overall length of magnet	9.15 m
Outer diameter of magnet	580 mm

Figure 11. Vacuum vessel of the TAP cryostat (Courtesy of FBM-Hudson Italiana).

Table 11. Main parameters of TAP cryostat

Cryostat parameters	
Overall length	10.1 m
Cold mass (magnet and helium vessel)	15000 kg
Mass of vacuum vessel	5000 kg
Number of support posts	3
Outer diameter	1.0 m
Nominal temperature levels	80 K, 5 K, 2 K

7.4 High-current bypass diodes

High-current diodes are foreseen across the superconducting dipoles and quadrupoles to by-pass a quenching magnet while the machine is discharged. These diodes work at low temperature and have to sustain a peak current of 15 kA and an integrated $I^2 dt$ of about $10^{10} A^2 s$ when the whole magnet ring is deenergized with a time constant of 100 s. The energy absorbed by the diode arrangement amounts to 1.5 MJ. A development programme is pursued with companies as ABB (CH), Marconi (UK) and Siemens (D) to produce single diodes meeting the specification. On the other hand, tests have been carried out with two commercially available diodes (ABB) arranged in parallel connection. At 77 K, the diode

pair can carry a current up to 16.5 kA during 60 sec. with a current sharing between the two diodes of 40 % and 60 %. At 1.8 K, the current distribution is unfortunately worse and a diode may burn out due to overheating. A new mechanical/thermal arrangement of the diodes and a current balancing circuit are now under construction to improve the current sharing between the two diodes. Irradiation tests are made at 77 K with diodes placed in an external beam of the CERN SPS. After a dose of 93 Gy, it has been observed that the electrical capacitance of the diode is decreased by 1.7 %, the voltage drop increased by 2.2 % at 500 A, and 4.8 % at 5 kA. The increase of the reverse blocking voltage, about 0.15 %, is almost negligible. It seems that the variation of the diode characteristics is linear with the irradiated dose. An experimental programme is now set-up to test rejuvenation of irradiated diodes by carrier injection. The first result obtained by passing ~ 15 kA, 2 μ s current pulses are encouraging¹⁶.

8. Prototype lattice cell of the LHC and prospects

The R&D programme is now centred on the construction and installation in a hall of a complete prototype cell of the LHC regular lattice in 1992. This includes eight twin-aperture dipoles, two twin-aperture quadrupoles, all correcting elements and the necessary cryostats, cryogenics, vacuum chambers, power supplies, protection systems, etc.. The aim is to test under realistic conditions about 100 m of the LHC magnetic structure.

Offers from European industry for the manufacture of full-size (10 m long) dipole magnets, of the design which is now considered for the LHC, and of the necessary tooling have been received. CERN intends to order eight such magnets in October 1990. The specifications foresee delivery of the first magnets in December 1991.

In the meantime, INFN (I) has placed an order for the manufacture of two such prototypes according to the same technical specifications.

If the final decision to proceed with the LHC project is taken in 1992, series production of magnets should start in 1993.

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