EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN LIBRARIES, GENEVA

CM-P00063434

CERN AT / 92-29 (MA)
LHC Note 207

Status Report on the LHC Magnets

presented for the LHC Team

by R. Perin

Abstract

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Invited paper presented at the 1992 World Congress on Superconductivity,
3rd International Conference and Exhibition,
Munich, 14-18 September 1992.

Geneva, Switzerland
November 1992

STATUS REPORT ON THE LHC MAGNETS

Presented for the LHC Magnet Team

by Romeo Perin

CERN, CH-1211 Geneva 23

1. ABSTRACT

CERN is finalizing the design of a new accelerator collider, the Large Hadron Collider (LHC) to be installed in the existing 27 km long LEP tunnel. To reach the wanted collision energy, dipole magnets with field of 9 to 10 T and quadrupoles of 250 T/m gradient will be used. A twin-aperture configuration of magnets in common yokes and cryostats has been adopted. The magnet system comprises about 1300, 13.5 m long dipole units, 600, 3.2 m long quadrupole units and a large number of other superconducting magnetic elements. Several prototypes of main magnets and correctors have been built. Short dipole models reached fields of 10 T, albeit with substantial training above 9 T. The causes of this behaviour are being investigated in parallel with the construction of new models. A 10 m long prototype making use of HERA type coils reached 8.3 T, the cable short sample limit at 1.8 K, showing no adverse effect of the twin-aperture configuration as compared to single-aperture magnets. The construction of ten 10 m long dipole prototypes and of two quadrupoles is well advanced.

2. INTRODUCTION

CERN is preparing the construction of a new accelerator/collider which will enable exploration of matter at energy levels at least ten times higher than presently attainable with the existing facilities. This new machine, the Large Hadron Collider (LHC)^{1), 2)}, 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. It will accelerate and collide intense beams of protons producing a collision centre of mass energy of about 15 TeV with a luminosity higher than $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Heavier ions can, of course, also be accelerated and made to collide at extremely high centre-of-mass energy. For Pb ions this will be 1262 TeV with a luminosity of $1.8 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$. In addition, there will be a unique possibility of colliding high energy protons with the electrons of LEP up to about 1.4 TeV centre-of-mass energy and a $2.8 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ luminosity.

The LHC will be a natural extension of the present CERN facilities and a particularly cost-efficient machine since it will make use of the existing tunnel with its associated infrastructure and of a whole injection chain of already existing accelerators (Linac, Booster, 26 GeV PS and 450 GeV SPS), and the general services of the laboratory.

A general simplified scheme of the LHC is shown in Fig. 1. The two counter-rotating particle beams circulate in separate channels and cross each other in 8 points regularly spaced around the circumference. The two bunched beams 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; one crossing region is reserved for the beam dumping system.

Figure 1: Schematic layout of the LHC

As the circumference of the LHC is fixed by the LEP tunnel and the available cross-sectional space is limited, there has been from the start the quest for compact magnets, operating at the largest possible field to reach highest collision energy, this being directly proportional to the bending magnetic field. A field of about 8.5 T corresponds to collision energies which already would justify the LHC project from the physics point of view. The nominal LHC energy of 7.7 TeV per beam will be reached with a **9.5 T field** in the dipole magnets. A 10 T field level has, however, been chosen as an arduous, but not impossible goal for the R & D on magnets. The dimensions of single magnets operating in the range of 8 to 10 tesla exclude the possibility to install two separate magnetic rings on top of the LEP machine. This constraint has led to the development of the "two in one" concept, already tested at Brookhaven National Laboratory for fields up to 5 T, in which two magnetic apertures are placed in a common yoke and cryostat assembly, leading to smaller cross-sectional dimensions and to a more economical solution^{3), 4)}.

The LHC machine magnets will use the technology of NbTi superconductors and operate at superfluid helium temperature in order to reach the demanded high field. The Nb₃Sn superconductor route at 4.2 K, along which two model magnets were successfully built, is still being investigated with a short dipole model under construction, but further development of conductor and coil construction techniques would be necessary for such an option to become technically and economically valid for the whole machine. It might, however, be applied in some special components, as e.g. in second generation high field gradient quadrupoles, on either side of the collision regions.

Benefits of using superfluid helium are its very large heat conductivity and its ability to penetrate the coils through insulation porosities, permeating and thus cooling the conductors. This aspect is of special importance, considering that, to reach the desired luminosity, the LHC will have to operate at a beam current of nearly 1 A, distributed around the machine in a large number of bunches. Inevitably, some of the particles leaking out of the beam halo will be lost in the magnet coils.

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 particularly on the dipoles, but includes study and construction of several other magnets and items.

3. THE MAGNET SYSTEM

A description of the magnet system may be found in ref. 5).

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 192 times around the ring. Recent studies aimed at maximizing the global bending power resulted in a reduction of the number of dipoles and an increase of their length from ~ 10 m to ~ 13 m. One half of a standard cell (Fig. 2) consists now of three, ~ 13 m long, dipole magnets (MB), one half focusing quadrupole magnet (MQ), a tuning quadrupole (MOQC) which includes octupole correction windings, a combined dipole/sextupole/decapole corrector magnet (MDSB), a beam observation station (BPM) and one half defocusing quadrupole (MQ).

Figure 2: Standard half-cell

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. The combined correctors are in the present design assembled concentrically on a common beam pipe. Short sextupole and decapole correctors are appended respectively at each end of the main dipoles. All correctors, and the tuning quadrupoles of one ring are magnetically decoupled from the magnets of the other ring.

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.

Table 1: Type and number of superconducting magnets

Type	Nominal strength	Magnetic length (m)	Number
Regular lattice			
Main dipoles	$B_0 = 9.5 \text{ T}$	13.15	$2 \times 1280^*$
Main quadrupoles	$G = 238 \text{ T/m}$	~ 3.10	$2 \times 384^*$
Tuning quadrupoles + octupoles	$G = 120 \text{ T/m}$ $B^{\text{III}} = 1 \times 10^5 \text{ T/m}^3$	0.72	768
Combined correctors			
Dipole	$B = 1.5 \text{ T}$		
6-pole	$B^{\text{II}} = 4500 \text{ T/m}^2$	1.0	768
10-pole	$B^{\text{IV}} = 3.2 \times 10^7 \text{ T/m}^4$		
Sextupole correctors	$B^{\text{II}} = 7000 \text{ T/m}^2$	~ 0.10	1280
Decapole correctors	$B^{\text{IV}} = 7 \times 10^7 \text{ T/m}^4$	~ 0.10	1280
Interaction regions			
Twin-aperture quadrupoles	$G = 238 \text{ T/m}$	5.0 4.0 3.1	$2 \times 18^*$ $2 \times 72^*$ $2 \times 136^*$
Single bore quadrupoles	$G = 250 \text{ T/m}$	6.8 6.1	12 12
Skew quadrupoles	$G = 120 \text{ T/m}$	0.7	60
Separation dipoles	$B = 5.4 \text{ T}$	9.0	6
Dipole correctors	to be defined	0.5	286
* Twin-aperture magnets.			

The LHC magnets will be one of the most massive applications of superconductivity. The quantity of conductor will be about 1400 t of which $\sim 400 \text{ t}$ will be NbTi alloy. The mass to be kept at 1.8 K temperature will be about 30'000 t distributed over a 27 km circumference.

4. THE DIPOLE MAGNETS

4.1 General

The main parameters of the prototype twin-aperture dipoles are presented in Table 2 and Fig. 3 shows their "standard" cross-section. The design, already described elsewhere^{3), 6)} is based on a field range 8 to 10 T, twin apertures in a common force retraining structure/flux return yoke and cryostat, and two-shell coils with graded current density, supported by high strength aluminium alloy or non-magnetic steel collars and vertically split iron yoke, surrounded by a stainless steel shrinking cylinder.

Table 2: Dipole parameters

Nominal field B_0 (2 K)	9.5	T
Operation current	13900	A
Coil inner diameter	50	mm
Coil outer diameter	120.2	mm
Distance between apertures	~ 180	mm
Iron outer diameter	~ 540	mm
Stored energy for both channels combined	618	kJ/m

Figure 3: Cross-section of LHC prototype dipoles

1. Vacuum chamber, 2. Coils, 3. Collars, 4. Iron yoke, 5. Shrinking cylinder, 6. Bus-bars,
7. Bore for HeII heat exchanger, 8. Radiative insulation, 9. Thermal shield,
10. Superinsulation, 11. Vacuum vessel, 12. Support post, 13. 1.8 K GHe pipe,
14. 10 K GHe pipe, 15. 4.5 K He pipe, 16. 2.2 K LHe pipe, 17. 50÷75 K GHe 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.

Major problems 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 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. This has required a careful study of the mechanical structure⁷⁾. 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 by-passing any quenching magnet. The protection system which has been tested so far in 1 m long model magnets and on a 10 m long, but lower field, magnet (TAP) need to be thoroughly experimentally proved as soon as a full length prototype magnet string will become available.

The dipoles being the most important and difficult components of the system, they are naturally the main subject of the R & D effort which comprises

- Conductors.
- Short models (~ 1.3 m long):
Single-aperture models. Two in NbTi and one in Nb₃Sn, made by European industry were completed and successfully tested. One model, in NbTi, developed by KEK and made in Japan was recently tested at CERN.
Twin-aperture models. Four twin-aperture models, so-called MTA1, have been made by European companies and tested at CERN. One twin-aperture model, developed by KEK, is now being manufactured in a Japanese industry. New twin-aperture models are being built and assembled at CERN, using partly components made by industry. In parallel, an important effort in calculation and design work is going on for these new models.
- Long twin-aperture prototypes:
A twin-aperture, 10 m long, prototype (TAP), using HERA type dipole coils was designed at CERN, built in industry, and recently tested at CEN, Saclay. Ten, 10 m long, prototypes are being manufactured by European industry.

A review of the dipole programme has been reported recently in ref. 8). A summary of the most outstanding features and results is given below.

4.2 Superconducting Cables

The dipole windings consist of two layers. The inner layer cable has 26 strands of 1.29 mm diameter and a 2.02/2.50 x 17 mm² cross-section. The cable for the outer layer has 40 strands of 0.84 mm diameter and a 1.30/1.65 x 17 mm² cross-section. The design Cu/Sc ratio is 1.6 in the inner layer and 1.8 in the outer layer strand. About 20 km of the inner layer cable and 35 km of the outer layer cable have been ordered to European firms for short model and long prototype dipoles. Parts of these supplies have been delivered and measured. Some parameters of the commercially produced strands and their measured average critical current density in the non-copper part of the cross-section are presented in Table 3.

Table 3: Present characteristics of LHC dipole strands

Firm	Strand diameter (mm)	Number of filaments	Filament diameter (μm)	J_c A/mm ² at $10^{-14} \Omega\text{m}$	
				6T 4.2K	8T 4.2K
1	1.29	21780	5.4	2104	1087
1	0.84	9438	5.1	2195	1032
2	0.84	9438	5.1	2113	1060
3	1.29	28158	4.7	-	1025
4	1.29	27954	4.8	1885	937
4	0.84	10164	5.0	1970	992
5	1.29		7÷8	-	1005
5	0.84		7÷8	2185	-

4.3 Short Model Magnets

4.3.1 Single-aperture models. Very successful single-aperture models were developed some years ago⁹⁾. The NbTi models (8 TM) were designed for 8 T nominal field and had the distinctive feature of making use of 12.6 mm wide, solder impregnated cables, which were manufactured with well proven $\varnothing$ 0.84 mm strands left over from the production for the HERA project. The behaviour of these magnets was excellent: 8.55 T at the first quench, 9 T at the third quench and cable short sample limit at 9.3 T after a few further quenches. They also showed practically no re-training after thermal cycles and half year storage at room temperature: 8.9 T at the first quench and short sample limit at the second quench (Fig. 4).

4.3.2 Twin-aperture MTA1 models. A first set of four twin-aperture, 1.3 m long, model magnets (MTA1) was built in industry and tested at CERN. Their basic cross-section and main parameters correspond to Fig. 3 and Table 2. Details of design, characteristics and performance may be found in refs 10) and 11).

In order to test different ideas, the four magnets were built with a number of technical variants concerning type of cable, electrical insulation, details in the coils, material, shape and assembly method of the collars, material of the outer shrinking cylinder.

It is worthwhile noting that the cables used in these models were still at an early development stage and had lower performances than the present ones.

At 4.2 K all magnets reached their short sample field of about 7.9 T in a few quenches (typically two to four). At 1.8 K and at fields above 9 T, all magnets showed a long training which was completed only for the MTA1"JS"magnet, which attained **10.02 T central field**. The training history of this magnet is shown in Fig. 5. The difference in behaviour with respect to the previous 8 TM models is striking.

It was realized that the problems are mainly at the coil/collar interface or in the coils themselves especially at the ends. This was confirmed by the test of the coil/collar assembly of one magnet (MTA1"H") before mounting the yoke and the shrinking cylinder. It behaved in a similar way to the complete magnets, albeit of course at a lower field (1st quench 6.6 T, plateau 8.4 T),

corresponding to the absence of the yoke. The training curve of this magnet after completion of assembly is given in Fig. 6.

Figure 4: Quench history of 8 TM1 magnet

Figure 5: Training of the MTA1-JS magnet

In order to determine the origin of the quenches, a novel method based on a number of pick-up coils, distributed axially and azimuthally in the aperture near the magnet windings, has been devised¹²⁾. With these coils, it is possible to detect small magnetic flux variation originated by sudden movements of wires or cables or other disturbances. The method is a valid complement or alternative to voltage taps, having the advantage of avoiding galvanic connections to the magnet coils. It was found out that most of the quenches occur at the ends or in the transition region between straight and curved parts in the first or second turn of the coil innerlayer and a few occur in the straight part at the first turn of the inner layer where the field reaches its peak value. Correlation to defects in design or manufacture are being studied to

Figure 6: Quench history of the MTA-H magnet with the iron yoke mounted

understand and eliminate the causes of premature quenches. E.g. it was found that in all four magnets pre-stress was not correctly applied at the inner edge of the first two turns of the inner layer. In one magnet the G-11 spacers on the non-connection end were found broken: this is the place where the diagnostic system had indicated the origin of most of the quenches.

The multipole components were measured in all magnets and correspond well to the design computations.

Further tests included measurements of dissipated and stored energy and time dependence of persistent currents. A new method has been developed to determine with high precision simultaneously stored energy (and hence inductance), energy loss and d.c. resistance by integrating continuously voltage and current over one complete current cycle of the dipole. As an example, Fig. 7 shows the measured energy loss as a function of ramp rate in one MTA1 magnet. At 12 A s^{-1} , corresponding to the acceleration of the LHC, the power density dissipated in the winding is about 0.03 mW cm^{-3} . Quenches as a function of ramp rate (Fig. 8) were performed to gain knowledge about the cooling in the coils and their aptitude to withstand heat deposition by beam losses.

Figure 7: Measurement of energy loss as function of ramp rate for current ramps between 2 T and 7.5 T in a MTA1 model

Figure 8: Quench field as a function of the ramp rate for three magnets. The bath temperature is at 2 K. The ramp is always started at 2 T.

These first four magnets are being re-assembled by the manufacturers incorporating the necessary corrections.

4.3.3 New CERN models. A campaign for building new models has been launched at CERN in order to test different designs and variants in components and materials. The first of these models are designed on the basis of the following ideas:

- Separated coil/collar assembly. Individual "single" collared coils could then be measured at room temperature and paired according to their multipole error contents. This would make sorting of the magnets for their installation in the machine more efficient.
- Closing the yoke gap(s) already at room temperature or otherwise controlling gap(s) closure, so as to avoid uncertainties due to friction at cooldown.

Two solutions are being pursued in parallel, one with stainless steel collars, the other with aluminium alloy collars. The yoke is split in 2 or 3 parts. The respective cross-sections are shown in Figs 9 and 10.

Figure 9: Cross-section of LHC dipole model with stainless steel collars and yoke in three parts

Figure 10: Cross-section of LHC dipole model with aluminium alloy collars and yoke in two parts

The stainless steel collars feature a slotted central "nose" which deforms elastically giving a better pressure distribution and lower initial prestress on the coils. In the version of Fig. 10 the aluminium collars are clamped by pairs of rods to increase the stiffness of the assembly and the yoke halves feature elastic fins which are deflected and welded together at assembly before mounting the shrinking cylinder. The vertical gap between the yoke halves will thus remain partially open at room temperature and close under controlled conditions at cooldown.

A number of single aperture models are also foreseen to test individual coil/collar assemblies.

In the meantime, calculations of new coil geometries are actively pursued. Mathematical optimization techniques have been developed and applied to find best conductor and coil block arrangements and conductor distributions have been found with low b_7 , b_9 and b_{11} multipoles, which satisfy the stringent LHC requirements. Also the inverse problem of evaluating errors in the conductor positioning from a given multipole content has been addressed¹³⁾.

4.3.4 KEK models. The programme at KEK for the development of LHC dipoles includes one single and one twin-aperture short models with both the cable and the magnet being manufactured by Japanese industry. Although similar in their overall conception to the MTA1 models, the design differs in a number of features¹⁴⁾:

- highly keystone cables (15 mm high, 4.6° in the inner layer cable) achieving sector shaped coil layers, without insertion of spacers, hence better filling factor,
- sandwiched Mn steel/aluminium/Mn steel collar material,
- symmetric separated coil/collar assemblies mounted inside a vertically split yoke composed of two parts.

The single-aperture unit was first tested at 4.2 K in KEK, reaching the cable short sample limit in three quenches, and then has been tested at 1.8 K in CERN. It reached a maximum central field of **9.87 T** after 25 quenches and showed an unstable behaviour above 9.5 T. It kept the training "memory" after thermal cycling, reaching **9.5 T** at the first quench. Most of the quenches were initiated at the coil ends. The fact that it can accept relatively high ramp rates (200 A/s) without lowering the quenching field (Fig. 8) shows that there is still a margin on the current the conductor can carry and that the quenches are due to mechanical reasons, such as wire movements especially at the ends. So it can be said that in general the training behaviour of this single-aperture magnet is similar to that of the twin-aperture MTA1 magnets.

4.3.5 Other models. To explore further the Nb₃Sn route, a high field (11.5 T) twin-aperture model magnet is being built in the Netherlands by a FOM-UT-NIKHEF-CERN collaboration. It will use separated collar/coil assemblies and closed collars. The vacuum impregnated coils will be collared by means of ring-shaped Al alloy collars heat-shrink fitted around them. In this way, all collars will be in contact with the coil over the entire circumference and the stress distribution will not be interrupted by pins or keys. A short mechanical model has given encouraging results¹⁵⁾.

A twin-aperture model magnet with 56 mm diameter coil bores is being designed and will be built by a Finnish-Swedish-CERN collaboration. A distinctive feature of this magnet will be the use of ternary alloy, NbTiTa, superconductor.

4.4 Long Prototype Magnets

4.4.1 Twin-aperture prototype with HERA type coils (TAP). A 10 m-long prototype magnet in which two sets of HERA type coils are incorporated into an LHC structure was built in order to gain experience in the construction of full scale, twin aperture, high-field magnets and with the superfluid helium operation in a long horizontal cryostat^{16), 17)}.

The magnet was tested and measured at CEN, Saclay. At 4.5 K the first quench occurred at 6603 A corresponding to 5.8 T central field, a value within 2% of the short sample limit of the cable, behaving exactly as good single aperture HERA magnets. At 1.8 K, nominal field (7.5 T) was passed at the second quench and cable short sample limit was reached on the fifth quench at 8.3 T central field.

4.4.2 Full size prototypes. Ten, 10 m long, LHC dipole prototypes are being built in four European companies or consortia, two of them were ordered by INFN (I)¹⁸⁾ and eight by CERN. These magnets will be completed with their cryostats and fitted with all auxiliary components as the final magnets will be in the LHC. In addition, they will be equipped with voltage taps, strain gauges, pressure gauges, thermometers, etc. for diagnostic purposes. Eight prototypes will be installed in the LHC test cell.

The general conception and the coil design will be the same for all ten magnets, but three different variants for the mechanical support structure have been decided. The cross-section of five magnets will be with a common collar system for both apertures, as shown in Fig. 3. One magnet will have separate stainless steel collars and the yoke subdivided into three parts, as shown in Fig. 9, and another one will have separate alloy collars and the yoke split into two parts as shown in Fig. 10. The final structure of the three other magnets will be defined in the near future.

Manufacturing is already quite advanced. Delivery of the first complete prototype in its cryostat is foreseen for spring 1993, the other magnets should follow at about two months intervals.

5. THE QUADRUPOLE MAGNETS

5.1 Main Quadrupoles

The main parameters of the lattice quadrupoles are given in Table 4 and their cross-section is shown in Fig. 11.

The main quadrupoles are designed on the basis of the two-in-one geometry, coil aperture of 56 mm, distance between the magnet axes of 180 mm and powering in series with the main dipole magnets. The containment of the electromagnetic forces in the coils is provided only by the collars, made of stainless steel, pre-stressed and locked in position by a set of tapered keys. The yoke is made of single piece laminations, interlocked by pins and keys with the two quadrupole assemblies, fixing their relative position. The straightness, stiffness and position of the completed magnet is achieved by inserting it into a rigid tube to which it is attached by precise locating pins.

The superconducting cable for the main quadrupoles consists of 24 NbTi strands of 1.09 mm diameter and has a $1.89/2.35 \times 13.05 \text{ mm}^2$ cross-section. The design Cu/Sc ratio is 1.8 and the filament diameter is 5 μm . The cable for two prototypes (2800 m) has been delivered and measured. Averages of the non-Cu critical current density measured on 12 strand samples at 4.2 K before and after cabling and of a measurement at 1.8 K are presented in Table 5.

Figure 11: Cross-section of main quadrupole
 1. Coil, 2. Stainless steel collars, 3. Yoke, 4. Inertia tube, 5. Bore for heat exchanger,
 6. Bus-bar slot

Two twin-aperture prototypes are being built¹⁹⁾. The design was carried out by a CEA, Saclay team in collaboration with CERN. Coil winding, assembly and testing are carried out at Saclay. At present, the magnet design is completed and almost all the tooling and components are delivered. The winding of the superconducting coils has started and the completion of the first prototype is foreseen for the end of 1992.

Table 4: Main parameters of the LHC lattice quadrupoles

Gradient at nominal current	250	T/m
Current	15	kA
Effective length	3.05	m
Maximum induction in coils	7.8	T
Coil aperture	56	mm
Overall yoke length	3.22	m

Table 5: Critical current density in LHC quadrupole strands

	Jc A/mm ² at 10 ⁻¹⁴ Ωm		
	5 T, 4.2K	6 T, 4.2K	9 T, 1.8K
Specified values	2710	2160	2160
Meas. before cabling	2698	2136	2080
Meas. after cabling	2603	2072	

5.2 Tuning Quadrupoles and Octupole Correctors

The prototype tuning quadrupole (± 120 T/m, ± 1600 A, 0.8 yoke length) and octupole corrector ($\pm 10^5$ T/m³, 216 A) are being built in Spain. A nested construction is foreseen²⁰⁾. Completion of this prototype tuning quadrupole is expected towards the end of 1992.

5.3 Insertion Quadrupoles

Special requirements must be met by these magnets. The large amplitude of betatron oscillations in the insertions require that their random multipole errors be lower by a factor of five

than the corresponding errors in the lattice regular cell quadrupoles. The insertion quadrupoles will operate at different strengths and need, therefore, to be individually powered and as a consequence a relatively low excitation current. Moreover, as they are located in the vicinity of the interaction points, they will be subject to strong radiation which they must withstand from the stand points of integrity and heat deposition in the coils. For the quadrupoles requiring low content of multipoles, an increased aperture of 70 mm is foreseen. A novel approach to reach a gradient of 250 T/m with NbTi cables at 1.8 K is developed, using a suitable combination of low and high current density coil blocks, achieving both field quality and quadrupole strength and an excitation current of 5 kA. A design concept has been worked out for both the single and the twin-aperture versions²¹). A short (~ 1 m long) model of these quadrupoles will be built in collaboration with industry.

6. CORRECTOR MAGNETS

The combined dipole-sextupole-decapole corrector, placed near each lattice quadrupole, is made in the form of coaxial coils surrounded by common shrinking cylinder and yoke structure. A prototype 1.3 m long combined dipole (± 1.5 T, ± 47 A)/sextupole (± 8000 T/m², ± 458 A) corrector was made in UK and tested successfully at RAL at 4.3 K and later at 1.8 K at CERN²²). At 1.8 K, the magnet runs over the full range of operating currents.

The local sextupole and decapole correctors placed at the ends of the main dipoles are being developed by a RAL/CERN collaboration.

7. PROTOTYPE LATTICE CELL

An important milestone in the LHC preparation is the installation and testing of a regular cell of the machine lattice in 1993. It will test under realistic conditions the installation, cooldown and operation at 1.8 K of a representative string of machine components. Primary systems to be checked out are the magnets, their excitation, cooling by superfluid helium, quench behaviour and protection, the cryogenic system in steady state and transient mode (cool-down and quench recovery), the cryostats, the controls and data acquisition, all in tunnel type environment. Since the delivery of magnets will be gradual, operational tests are foreseen after completion of the first half cell, which represents the basic building block of the lattice. Once completed, the facility will include eight twin-aperture 10 m long dipoles, two main quadrupoles and all correcting magnets.

8. CONCLUSIONS

The R & D programme for the LHC magnet is approaching its goals and has already answered a number of fundamental questions on the crucial choices for the LHC:

- **The superfluid helium, 1.8 K, cooling of the LHC magnets in long horizontal cryostats has been proved feasible and easier than expected.**

- It is now demonstrated in short and long magnets that **twin-aperture (two-in-one) magnets behave as well as single-aperture magnets** with respect to quench/training performance.
- The **10 T field** has been passed for the first time in an accelerator dipole and in the twin-aperture configuration foreseen for the LHC.
- Training of the model magnets can be traced to movements of conductors, particularly at the coil ends. A better mechanical support has been studied and is being implemented in the new short models and in the long prototypes. Possible influences of strand and cable size are also being investigated.
- The **industrialization** of the dipole magnets, already started with the models, is well underway with the manufacturing of ten full size prototypes.

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