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RECENT STATUS OF LHC MAGNETS

LHC Magnet Team, presented by N. Siegel

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Abstract - CERN is proceeding with the design and development of a new high energy accelerator collider, the Large Hadron Collider (LHC), consisting of a double ring, enabling the circulation of counter-rotating beams of particles of like sign. This machine is to be installed in the existing 27 km long tunnel of LEP, the electron-positron collider in operation at CERN since 1989. To fit available tunnel space and reach the collision energy of interest, twin-aperture magnets with central bore fields between 8 and 10 Tesla are in development. The magnet system comprises about 1300 twin-aperture, up to 13.5 m long dipole units, about 500 twin-aperture, 250 T/m, 3.2 m long quadrupole units and a large number of other superconducting magnetic elements. A considerable magnet R & D programme is underway, comprising the construction of short models and full length prototypes. The short twin-aperture model dipoles were tested successfully up to cable short sample current at 4.2 K, but exhibited substantial training in reaching that limit at 1.8 K. The causes of this behaviour are under investigation and a programme of new model magnets has been started. The construction of ten 10 m dipole prototypes and of two 3 m quadrupole prototypes is progressing, and, after testing, they will be assembled into a test lattice cell of the LHC. The paper describes the present state of the R & D work for the LHC magnets, reviewing their features, recent test results and aims of future developments.

I. INTRODUCTION

Provisions have been made at CERN already in the planning and construction phase of the Large Electron-Positron Storage Ring (LEP), for the installation of a second machine in the same underground tunnel. This new machine, a high energy accelerator collider, the Large Hadron Collider (LHC) [1], will consist mainly of a double ring of technologically advanced high field superconducting magnets, installed together with the other machine equipment above the components of the LEP collider.

The structure of the LHC is made up, as for LEP, of eight arcs separated by eight straight sections. In the arcs and over most part of the straight sections, the two counter-rotating beams circulate in two separate, horizontally spaced, magnetic channels. The two beams alternate from inner to outer magnetic channel in successive arcs, crossing each other in the middle of the straight sections at a small horizontal angle by means of two sets of recombination dipoles.

Proton beams can be brought to collide in the crossing regions; of which six could be used for physics experiments and two are reserved for technical services, i.e. the beam cleaning system and the beam dumping system respectively.

In addition to proton-proton collisions, the presence of LEP in the same tunnel allows the possibility of high energy electron-proton collisions, and with the facilities of the CERN heavy ion programme, the collision of sulphur and later of lead ions will be possible at little extra cost.

The LHC benefits fully from the existing accelerator infrastructure of CERN which will provide injection beams of the required characteristics. Also, since the accelerators in the injection chain are classical fast cycling machines, the LHC can be filled in the relatively short time of about 7 minutes, thus reducing the time at which it has to remain at injection field level, where particle stability is more problematic, due to the circulation of persistent currents in the superconducting magnets.

The main performance parameters of the LHC for p-p collisions are given in Table 1 below.

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 fields to reach highest collision energies. The dimensions of single magnets operating in the range of 8 to 10 Tesla, as planned for the LHC, 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 in which two magnetic apertures are placed in a common yoke and cryostat assembly, leading to smaller cross-sectional dimensions and to a more economic solution [2] [3].

It is planned that for the LHC machine magnets made with NbTi superconductors operating at superfluid helium temperature will be used. The use of Nb_3Sn superconductors operating at 4.2 K is still being investigated, and a short dipole model is under construction (See Chapter 3), but further development of conductor and coil construction techniques would be necessary for such an option on.

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

TABLE 1
THE LHC p-p PERFORMANCE

Maximum proton beam energy	7.7 TeV
Number of bunches	4725
Particles per bunch	10^{11}
Stored energy	583 MJ
Luminosity	1.7×10^{34} cm^{-2}s^{-1}

magnet coils. A very efficient beam cleaning system is foreseen, still in the most exposed conductor an energy deposition of about 10 mW cm^{-3} has been estimated which must be conducted away within a limited temperature margin. To optimize in this respect the insulation parameters, experiments studying heat transport of insulated cables cooled by superfluid helium are proceeding at CEN, Saclay, (F) [4].

II. THE MAGNET SYSTEM

The LHC lattice is designed to lie in a beam plane exactly 1.21 m above that of LEP and both machines will be co-linear in plan view, except for small radial deviations in the straight section quadrupoles. In the long arcs, which have a length of 2.5 km and make a deflection of 701 mrad, the machine is made up of regular cells of a bending/focusing configuration which is repeated periodically around the rings. In addition to the regular arcs, there are other magnets in the dispersion suppressor sections and on either side of each crossing point. In total, about 24 km of the LHC circumference will be occupied by superconducting magnets of different types. A detailed description of the complete magnet system is given in references [1] and [5].

As a result of further studies of correction strategies and with the aim of maximizing global dipole occupancy inside the arcs, a new layout of the standard cell has been developed recently. It is based on reducing the number of half cells from 50 to 48, reducing the number of main dipole magnets from four to three per half-cell, increasing their length correspondingly, and replacing the "central corrector" MDOS by short magnets, one sextupole and one decapole corrector, appended respectively at each end of the main dipoles. The central octupole corrector could be suppressed since the perturbation due to this multipole error is self compensating over two successive arcs, given its antisymmetric distribution between inner and outer channel.

The layout of the previous and of the new standard half cell is shown in Fig. 1 below.

With the new layout, the number of twin-aperture dipoles is reduced from 1792 to about 1300 units, but the total

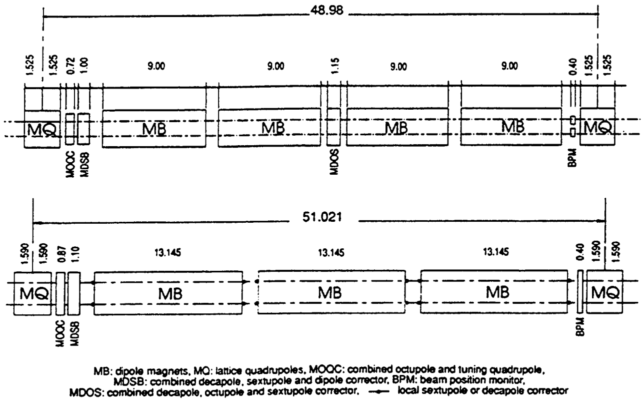

Fig. 1 The LHC half-cell
Upper: previous layout with four dipoles and a central corrector
Lower: new layout with three dipoles

integrated dipole field length is increased in the arcs by approximately 5%. Thus the central bore dipole field necessary ro reach the maximum beam energy of 7.7 TeV is 9.5 T. The number of main twin-aperture quadrupoles in the arcs is reduced from 392 to 384, their length being slightly increased.

III THE DIPOLE MAGNETS

An important R & D effort started at CERN a few years ago and is in progress for the high field magnets of the LHC, in particular for the dipoles. Many institutions and laboratories collaborate in this effort together with a substantial participation of industrial firms [5].

The main items of the dipole programme are the following:

- Conductors.
- Short models:
  Single-aperture models, two in NbTi and one in Nb3Sn, made by European industry are completed and successfully tested [6]. One model, in NbTi, developed by KEK and made in Japan is presently being tested at CERN. Four twin-aperture models, so-called MTA1, have been made by European companies and tested at CERN [7].
  One twin-aperture model, developed by KEK, is now being manufactured [8].
  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 prototypes:
  A twin-aperture prototype (TAP) [9], using HERA type dipole coils, 10 m long, was made and recently tested at 1.8 K.
  Ten, 10 m long, prototypes are in the process of being manufactured by European industry.

A review of the dipole programme, presenting design characteristics and test results has been reported recently in ref. [10]. A summary of the more outstanding features and results is given below.

A. Superconducting cables

The dipole coils are made of two layers. The inner layer cable has 26 strands of 1.29 mm diameter and a 2.02/2.50 x 17 mm^2 cross-section. The outer layer cable has 40 strands of 0.84 mm and a 1.30/1.65 x 17 mm^2 cross-section. The design Cu/Sc ratio is 1.6 and 1.8 for inner, respectively outer layer. About 20 km of inner layer cable and 35 km of outer layer cable have been ordered to European firms for the model and prototype dipoles. Part of these quantities have been delivered and tested. Some of the measured parameters are shown in Table 2 below.

B. Short models

1) MTA1 models: Four such models have been built by four different European firms (Fig. 2); their main parameters are given in Table 3.

TABLE 2
PRESENT CHARACTERISTICS OF LHC DIPOLE STRANDS

Firm	Strand diameter (mm)	Number of filaments	Filament diameter (μm)	Jc A/mm^2 at 10^{-14} Ωm	
				6T 4.2K	8T 4.2K
1	1.29	21780	5.4		1087
1	0.84	9438	5.1	2195	
2	0.84	9438	5.1	2248	
3	1.29	28158	4.7		1070
4	1.29	27954	4.8		937
4	0.84	10164	5.0	1960	
5	1.29		7÷8		1005
5	0.84		7÷8	2185	

A certain number of technical variants, introduced in the construction to check different design ideas and compare their relative merits, are described in Table 4. The value of Bss in the table is the central field corresponding to a peak field in the coil equal to cable short sample.

It is worthwhile noting that the cables used for these models were at an earlier stage of development and presented lower performances than the present ones.

The four magnets were tested and measured in a vertical cryostat [11]. All four reached short sample field at 4.2 K within a few quenches, however at 1.8 K all magnets exhibited substantial training above 9 T. The training was completed for the MTA1 "JS" model which went to its cable short sample limit corresponding to 10 T in the central bore. The magnets also show retraining after a thermal cycle to room temperature. A novel method to determine the origin of quenches was implemented, based on small pick-up coils distributed in the aperture near the windings. Very small

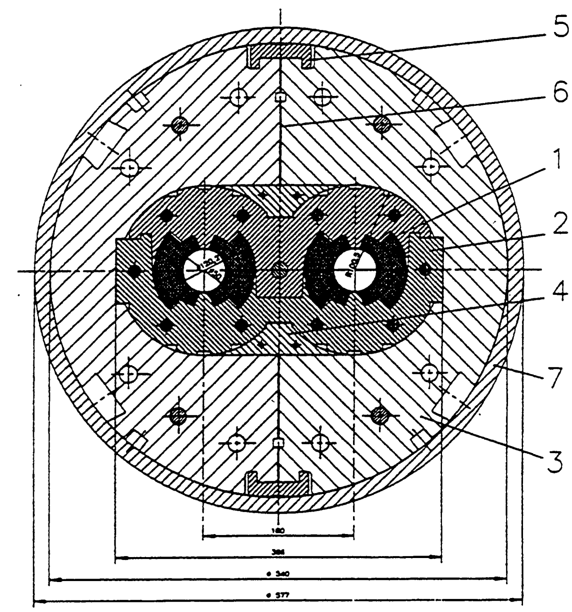

Fig. 2 Cross-section of a twin-aperture dipole
1. Coils, 2. Collars, 3. Yoke, 4. Iron insert, 5. Clamp, 6. Gap, 7. Outer shrinking cylinder

TABLE 3
DIPOLE MAIN PARAMETERS

Field B_0 (2 K)	10	T
Current	14730	A
Coil inner diameter	50	mm
Coil outer diameter	120.2	mm
Distance between apertures	180	mm
Collars outer horizontal dimension	380	mm
Iron outer diameter	540	mm
Stored energy for both channels combined	684	kJ/m

variation of flux can be measured which can then be traced back to conductor movements or current redistribution within the cable. With this method, which is a valid complement or alternative to voltage taps, it was found that most of the quenches are produced in the ends or in the transition region between straight and curved parts in the first or second turn of the coil inner layer and a few occur in the straight part at the first turn of the inner layer where the field reaches its peak value.

The coil/collar assembly of magnet MTA1 "H" was tested before mounting it into the yoke. This assembly behaved in a similar way to the completed magnets, except that it reached lower field levels corresponding to the absence of the steel. This result confirmed that the training behaviour is not coming from the interaction of the collar and yoke structure but stems mainly from problems in the coil/collar interface or in the coils themselves, especially at the ends. Possible defects in design or manufacture are being investigated to understand and eliminate the causes of premature quenches.

Further tests included measurements of dissipated and stored energy, of field multipoles 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. An example of energy loss measurement as a function of ramp rate is shown in Fig. 3. 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}.

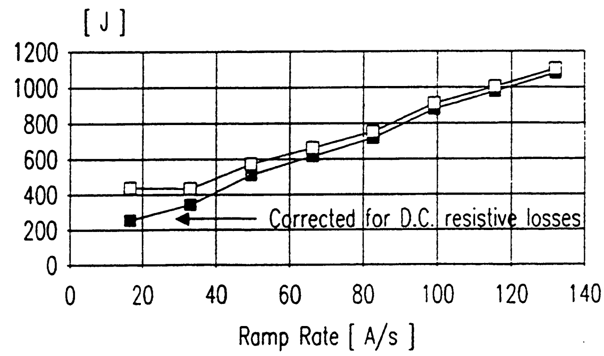

Fig. 3 Measurement of energy loss as function of ramp rate for current ramps between 2 T and 7.5 T in the MTA1 model

TABLE 4
TECHNICAL VARIANTS OF THE MTA1 MODELS

Model / Components	A	E	JS	H
Cables				
Inner layer	Partially soldered	Unsoldered	Partially soldered	Unsoldered
Outer layer	Soldered	Soldered	Partially soldered	Unsoldered
Elec. insulation				
22% B-stage epoxy	Glass-fiber cloth	Glass-Kevlar™ cloth	Glass-fiber ribbon	Glass-fiber cloth
Coils				
End spacers	G11	Bronze	G11	G11
Collar Material	Al 2014 T6	Al 5083 G35	Al 2014 T6	Al 5083 G35
Shape	Common collars	Separate collars	Common collars	Common collars
Assembly	Rods	Lateral keys	Lateral keys	Rods
Yoke				
Glued	No	No	Yes	No
Outer cylinder				
Material	Stainless steel 316LN	Al 5083	Al 5083	Al 5083
Assembly	Lateral welds	Warm shrink fitting	Warm shrink fitting	Warm shrink fitting
Bss (1.9 K)	9.8 T	9.8 T	10.0 T	9.9 T

The multipole content and their variation with field were measured and correspond well with the computations (Fig. 4).

The models will be re-assembled by the manufacturers after introducing a number of corrections and will be re-tested thereafter at CERN.

2) *New CERN models:* A programme to test new models has been started at CERN. The main features concerning design, components and materials to be tested are:

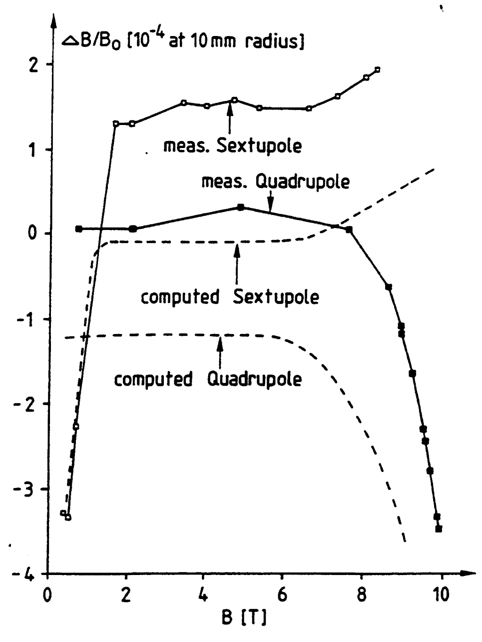

Fig. 4 Quadrupole and sextupole components in MTA1 "JS" magnet at r = 1 cm in 10^{-4} units (measurements were taken 18 min after current stabilization)

- Individual collaring of coils, allowing pairing of collar/coil assemblies according to their multipole error content measured at room temperature.
- Closing the yoke gap(s) as far as possible at room temperature to avoid uncertainties in the collar/yoke structure due to friction.
- Variants with stainless steel and with aluminium alloy collars.
- The stainless steel collars feature a slotted central "nose" which deforms elastically giving better pressure distribution and lower initial pre-stress.
- Yoke split vertically in three (stainless steel collars) or in two (aluminium alloy collars) parts. The cross-sections of these variants are shown in Figs 5 and 6 respectively.
- A variant with a horizontally split yoke is under study.
- Single aperture models are also in manufacture to check specific variants of design and materials.

In the meantime, calculations of new coil geometries are actively pursued. They address the questions of the reduction of multipole error components and the increase in coil aperture which were highlighted in studies and reviews of machine performance and aperture requirements. Mathematical optimization techniques have been developed and applied to find best conductor and coil block arrangements [12]. Conductor distributions have been found with low b7, b9 and b11 multipoles, which satisfy the stringent LHC requirements, and a cross-section with 56 mm aperture has been calculated and optimized. A collaboration is now underway with Finnish and Swedish Institutions for the design and manufacture of a 56 mm twin-aperture model dipole [13].

Also the inverse problem of evaluating errors in the conductor positioning from a given multipole content has been addressed and techniques are under development which should allow from the knowledge of the magnet field distribution to indicate probable problem areas permitting better specification

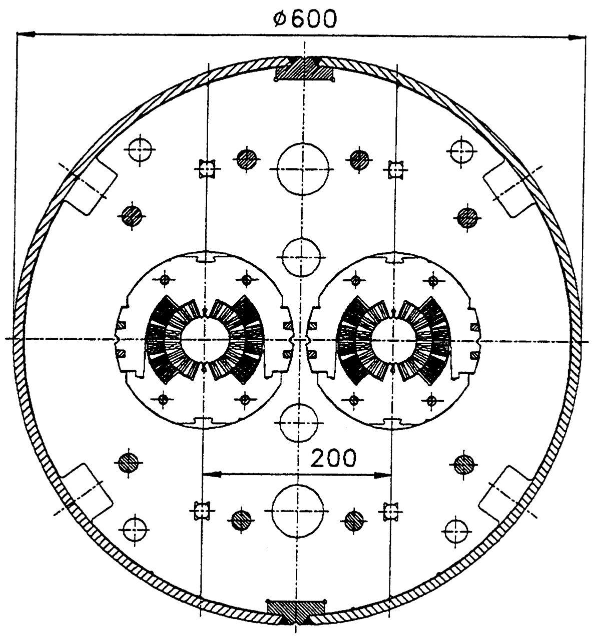

Fig. 5 Preliminary cross-section of LHC dipole model with stainless steel collars and yoke in three parts

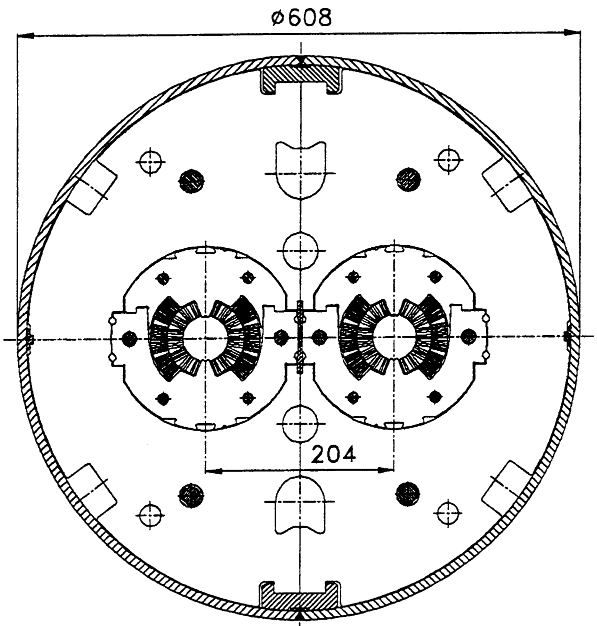

Fig. 6 Preliminary cross-section of LHC dipole model with aluminium alloy collars and yoke in two parts

of the appropriate tolerances for conductor and coil block placement [14].

3) KEK model dipoles: 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 (Fig. 7). Although similar in their overall conception to the MTA1 models, the design differs in a number of features [15]:

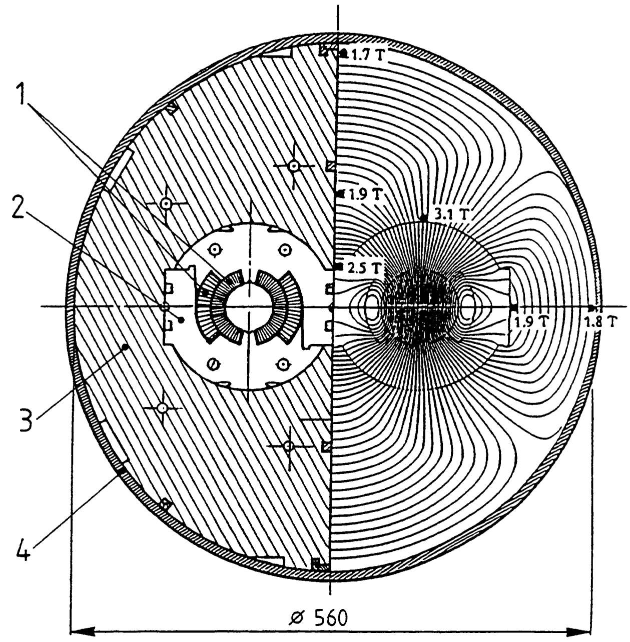

Fig. 7 Cross-section of twin-aperture KEK dipole model
1. Coils, 2. Collars, 3. Yoke, 4. Outer shrinking cylinder

- highly keystoned cables (15 mm high, 4.6° in the inner layer cable) achieving sector shaped coil layers, hence,
- no spacers inside coils and better coil filling factor,
- sandwiched Mn steel/aluminium/Mn steel collar material,
- suppression of separate yoke insert.

The single-aperture unit has been tested successfully at 4.2 K at KEK [16], reaching short sample limit of the cable in three quenches, and is now undergoing tests at 1.8 K at CERN. First results indicate that the behaviour is similar to the MTA1 models in the training performance. The origin of quenches is mainly in the coil ends, no quench has been observed in the central part of the magnet. Testing and analysis of results are currently in progress.

4) FOM-UT-NIKHEF-CERN model: This Nb_3Sn, 11.5 T, twin-aperture dipole model is presently being built in the Netherlands [17] and will provide further experience with this route towards high field magnets. The coils are potted and separately prestressed using shrink-fitted ring-shaped aluminium alloy collars giving smooth distribution of the pressure. A short mechanical model has given encouraging results.

D. Long prototypes

1) Twin-aperture prototype using HERA type coils (TAP): This 10 m long prototype, designed by CERN and built by industry, using for reasons of time and economy HERA dipole magnet coils, was made to gain experience with full scale, high field magnets, operated at 1.8 K [18]. The magnet was recently tested with success at CEN, Saclay, (F). At 4.5 K it reached 98% of its cable short sample limit (5.8 T central field) on first quench, behaving as the single aperture HERA dipoles. At 1.8 K, nominal field (7.5 T central field) was passed after two quenches and cable short sample limit was reached within five quenches (about 8.3 T central field). The load lines and quench history are shown in Fig. 8.

2) Ten metre long prototype dipoles: Ten, 10 m long, prototypes are being built in four European companies or consortia. Two of the magnets were ordered by INFN, (I) [19], and eight by CERN. The general conception and coil design will be the same for the ten units, but three different variants of the mechanical support structure have been decided. The cross-section of five magnets will be with a common aluminium alloy collar for both apertures, as the MTA1 magnets and shown in Fig. 3. One unit will have separate stainless steel collars and the yoke split vertically into three parts (Fig. 5) and another will have separate aluminium collars and the yoke split vertically in two parts (Fig. 6). The structure of the three others will be defined shortly. All dipoles will be fully equipped and delivered with their cryostat (Fig. 9). Completion of the first unit is foreseen early 1993, with the other units following at a two monthly rate.

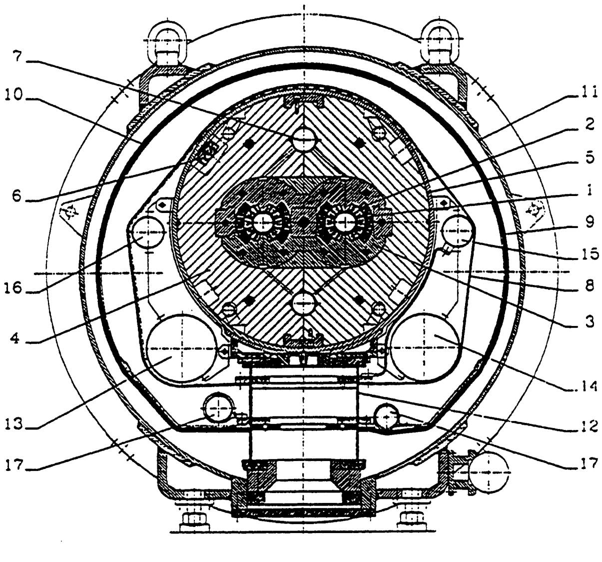

Fig. 9 Cross-section of the LHC prototype dipoles
1. Vacuum chamber, 2. Coils, 3. Al collars, 4. Iron yoke, 5. Shrinking cylinder, 6. Bus-bars, 7. Bore for HeII heat exchanger, 8. Radiative insulation, 9. Thermal shield, 10. Superinsulation, 11. Vacuum vessel, 12. Support post, 13. 1.8 K GHe pipe, 14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

IV. QUADRUPOLES

A. *LHC main quadrupoles*

The main parameters of the lattice quadrupoles are given in Table 6 and their cross-section is shown in Fig. 10

The superconducting cable for the main quadrupoles consists of 24 NbTi strands of 1.09 mm diameter and has a 1.89/2.35 x 13.05 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.

TABLE 6
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

The superconducting cable for the main quadrupoles consists of 24 NbTi strands of 1.09 mm diameter and has a 1.89/2.35 x 13.05 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 [20] and of a measurement at 1.8 K [21] are presented in Table 7.

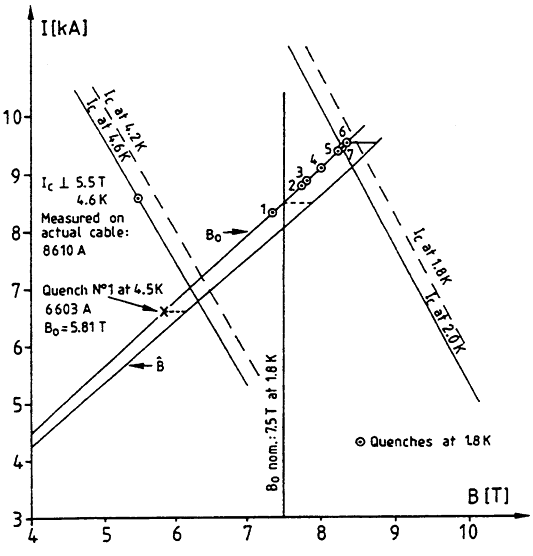

Fig. 8 Load lines and quench history of TAP magnet
Load line computed with 95% stacking factor

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 them in series with the main dipole magnets. The two quadrupoles of each unit are combined in a focusing/defocusing configuration, the only possible to avoid excessive magnetic saturation effects. The containment of the electromagnetic forces in the coils is

TABLE 7
CRITICAL CURRENT DENSITY IN LHC QUADRUPOLE STRANDS

	Jc A/mm^2 at 10^{-14} Ωm		
	5T, 4.2 K	6T, 4.2 K	9 T, 1.8 K
Specified values	2710	2160	2160
Measured before cabling	2698	2136	2080
Measured after cabling	2603	2072	

provided only by the collars, made of stainless steel, prestressed 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.

Two twin-aperture prototypes are being built [22]. The design was carried out by a CEA, Saclay team in collaboration with CERN. The components and tooling have been specified by the CEA, Saclay team and ordered by CERN to industry. 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. Five coils made of "dummy" conductor have been made and used for collaring tests. The winding of the superconducting coils has started and the completion of the first prototype is foreseen for the end of 1992.

B. Tuning quadrupoles and octupole correctors

The prototype tuning quadrupole (± 120 T/m, ± 1600 A, 0.8 yoke length) and octupole corrector (± 10^5 T/m^3, 216 A) are being built in Spain. A nested construction (Fig. 11) is foreseen [23].

Completion of the tuning quadrupole is towards the end of 1992.

C. Insertion quadrupoles

All insertion quadrupoles are of twin-aperture design, except the single bore inner triplet quadrupoles in the insertions for experiments. The principal constraints are twofold: firstly, the large values of beta functions in the quadrupoles of the cleaning and dump insertion and of the inner triplet impose on them a strict limitation in the content of multipole errors to avoid deleterious effects on beam performance. Secondly, the insertion quadrupoles come in different strengths and require separate adjustment during the machine cycle. A further constraint lies in the strong radiation near collimators and interaction points.

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 [24]. Both, a single and a twin-aperture version have been worked out. The latter version is shown in Fig. 12.

Schemes for the other insertion quadrupoles include lattice type ones, series connected with the dipoles with local low current tuning quadrupoles or alternatively individually powered quadrupoles designed for lower excitation currents.

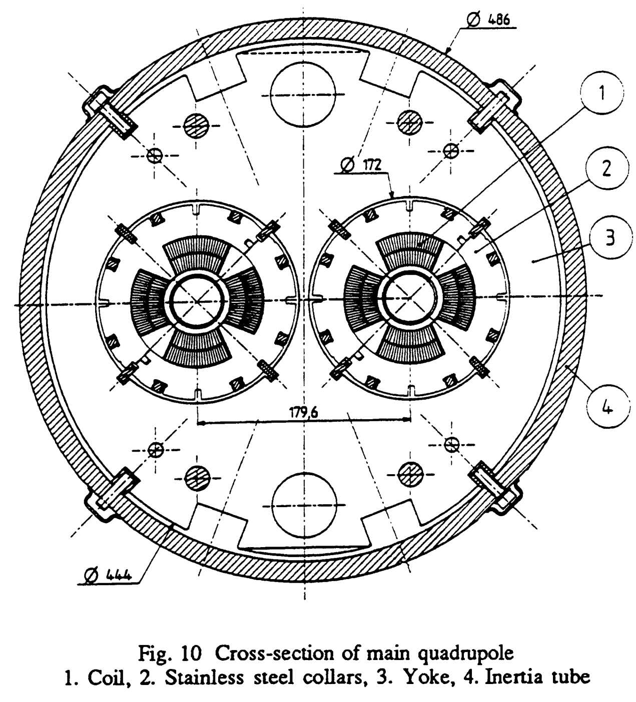

Fig. 10 Cross-section of main quadrupole
1. Coil, 2. Stainless steel collars, 3. Yoke, 4. Inertia tube

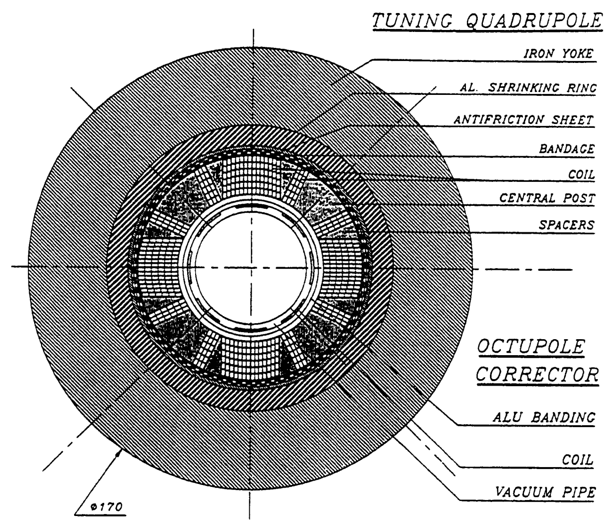

Fig. 11 Cross-section of tuning quadrupole and octupole

V CORRECTOR MAGNETS

All correctors are single elements installed in pairs in the two rings and magnetically decoupled to allow separate and independent control and adjustment for each beam.

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/m^2, ± 458 A) corrector [25] was made in UK and tested successfully at RAL at 4.2 K [26] and later at 1.8 K at CERN. At 1.8 K, the magnet runs over the full range of operating currents. A cross-section of this magnet is shown in Fig. 13.

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

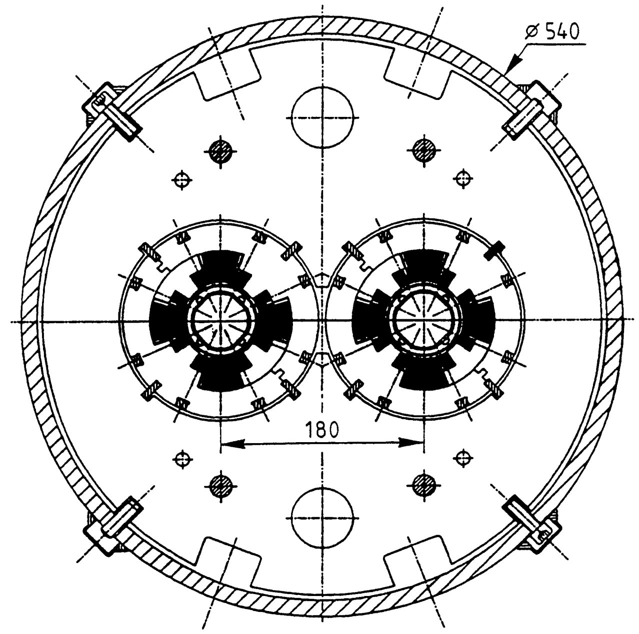

Fig. 12 Cross-section of a twin-aperture quadrupole for the LHC cleaning and dump insertions

VI PROTOTYPE LATTICE CELL

An important milestone in the LHC R & D programme of prototypes is the installation and testing of a regular cell of the machine lattice in 1993. It will be used to test under realistic conditions the installation, cooldown and operation at1.8 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, the cooling loop, steady state and transient mode, quench recovery, the cryostats, the controls and data acquisition, all in tunnel type environment. Since the delivery of magnets is gradual, operational tests are foreseen after completion of the first half cell, representing 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.

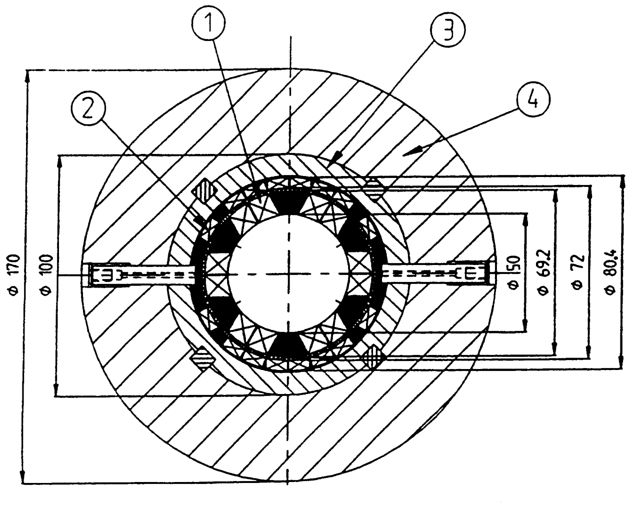

Fig. 13 Cross-section of a prototype sextupole-dipole corrector
1. Sextupole coil, 2. Dipole coil, 3. Al shrink ring, 4. Iron yoke

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