THE LHC MAGNET SYSTEM AND ITS STATUS OF DEVELOPMENT

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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 two superconducting magnetic beam channels, 27 km long, to be installed in the existing LEP tunnel.
The magnetic system comprises about 1200 twin-aperture dipoles, 13.145 m long, with an operational field of 8.65 T, about 600 quadrupoles, 3 m long, 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 also describes the present state of the magnet R & D programme. Results from short model work, as well as from full scale prototypes will be presented, including the recently tested 10 m long full-scale prototype dipole manufactured in industry.

1. Basic choices and main constraints of the LHC Collider

The new machine, a high-energy accelerator collider, consists essentially of a double ring of high-field superconducting magnets installed, together with the other machine components, in the same 27 km long underground tunnel, which houses the existing LEP collider [1].
Particles circulating in counter sense in the rings can be brought to collide in intersecting points.
The main performance parameters of the LHC for proton-proton and for Pb ion collisions are given in Table 1.
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 a quest for compact magnets operating at the strongest possible field to reach the highest collision energies. The dimensions of single magnets operating at the projected field level exclude the possibility to install two separate magnetic rings. This constraint has led to the development of the two-in-one concept in which two sets of magnetic excitation windings are placed in a common yoke and cryostat assembly, leading to smaller cross-sectional dimensions and to a more economic solution [2].
It was also decided that, for the LHC, coils wound from NbTi alloy operating at superfluid helium temperatures will be used.

	C.m. energy for B = 8.65 T [TeV]	No. of bunches	Particles per beam	Luminosity [$cm^{-2}\ s^{-1}$]
pp	14	2835	$4.7\ 10^{14}$	10^{34}
Pb ions	1150	496	$4.7\ 10^{10}$	$1.8\ 10^{27}$

Table 1: Main parameters of the LHC [1]

2. The LHC main 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 192 times around the ring. The magnet system for the LHC has been described extensively elsewhere [14, 15].
One half of an arc cell has a length of 51 m and contains three 13.145 m long bending magnets and a 6.5 m long short straight section. In the straight section are installed: the 3.05 m main quadrupole, a beam position monitor and two corrector magnets, one with

combined dipole/sextupole windings and the other one with tuning quadrupole and octupole windings. Spool pieces containing sextupole and decapole correctors are attached to each main dipole to correct the field errors of these magnets.
Dipoles and main quadrupoles of the two rings are combined into "two-in-one" units, each pair having a common yoke and cryostat. In the present design multipole correctors are assembled concentrically on a common beam pipe.
In addition to the regular arcs, there are other magnets in the dispersion suppressor section, and on either side of each crossing point.Table 2 shows the types and numbers of superconducting 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 ~ 400 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.

2.1 Main dipoles

The design of the dipoles is made to meet the following requirements:

- Operational field: 8.65 T.
- Magnetic length: 13.145 m.
- Coil inner diameter: 56 mm.
- Distance between the axes of the apertures: 180 mm.
- Overall diameter of cold mass: ≤ 580 mm.

The resulting main parameters are listed in Table 3.
The coils are formed of two layers made with keystoned cables of the same width but of different thickness, resulting from the wanted grading of current density for optimum use of the superconducting material. The proposed filament size allows the fabrication of superconducting wires by single stacking process. The persistent current sextupole components (defined as $\Delta B/B$ at a radius of 10 mm) at injection field (0.56 T) are -3.56×10^{-4} and 0.18×10^{-4} respectively for these filament diameters.Table 4 shows the dipole strand and cable characteristics.

Type	Nominal strength	Magnetic length (m)	Number
Regular lattice			
Main dipoles	$B_0 = 8.65$ T	13.145	1280
Main quadrupoles	G = 220 T/m	~3.05	376
Tuning quadrupoles	G = 120 T/m		
+ octupoles	$B^{III} = 1 \times 10^5$ T/m3	0.72	768
Combined correctors			
Dipole	B = 1.5 T		
6-pole	$B_{II} = 3000$ T/m^2	1.0	768
Sextupole correctors	$B^{II} = 5700$ T/m^2	~0.10	1280
Decapole correctors	$B^{IV} = 4.6 \times 10^7$ T/m^4	~ 0.10	1280
Interaction regions			
Twin-aperture quads	G = 220 T/m	3.7 to 8.0	130
Single-aperture quads	G = 225 T/m	6.9	24
Separation dipoles	$B_0 = 5.2$ T	9.0	6

Table 2: Type and number of superconducting magnets

2.2 Lattice Main Quadrupoles

The main quadrupoles are designed to provide a 220 T/m field gradient over a magnetic length of 3.01 m, on the basis of the two-in-one configuration with Ø 56 mm coil aperture and distance between aperture axes of 180 mm.

The main parameters and the cable characteristics are listed in Tables 5.and 6. Their constructional features are very similar to that of the already built prototypes. The two layer coils will be wound from the same superconducting cable in the double pancake style. This technique avoids the inter-layer splices which, being numerous in the quadrupole, would be a significant load to the cryogenic system.

Operational field	8.65	T
Coil aperture	56	mm
Magnetic length	13.145	m
Operating current	12 000	A
Operating temperature	1.9	K
Coil turns per beam channel		
inner shell	30	
outer shell	52	
Distance between aperture axes	180	mm
Outer diameter of cold mass	560	mm
Overall length of cold mass	14085	mm
Outer diameter of cryostat	980	mm
Overall mass of cryomagnet	29	t
Stored energy for both channels	7.2	MJ
Self-inductance for both channels	110	mH
Resultant of e-magn. forces in the 1st		
coil quadrant ΣFx (1.80 MN/m)	23.7	MN
inner layer ΣFy (- 0.15 MN/m)	- 2.0	MN
outer layer ΣFy (- 0.62 MN/m	- 8.2	MN
Axial e-magn. force on magnet ends	0.55	MN

Table 3: Dipole parameters

	Inner Layer	Outer Layer
Strand		
Diameter (mm)	1.065	0.825
Cu/Sc ratio	1.6	1.9
Filament size (mm)	7	6
Twist pitch (mm)	25	25
Critical current (A)		
10 T, 1.9 K/9 T, 1.9 K	≥ 510	≥ 370
Cable		
Number of strands	28	36
Cable dimension		
width (mm)	15.0	15.0
thin/thick edge (mm)	1.72/2.06	1.34/1.60
Transposition pitch (mm)	110	100
Critical current (A)		
10 T, 1.9 K/9 T, 1.9 K	≥ 13750	≥ 12880

Table 4: Dipole strand and cable characteristics

2.3. Insertion Magnets

There are a total of 166 special quadrupoles in the LHC insertions and straight sections differing in type, length and integrated gradient. Of this total, 114 magnets are of the lattice quadrupole type having the same cross-section but with three different lengths. The other ones are special magnets, based on a 70 mm aperture coil which is being developed for the low-beta quadrupoles. In the experimental insertions, these are single aperture units, while for other insertions a two-in-one version is being designed, which may, however, operate at 4.5 K.

Operational field gradient	220	T/m
Coil aperture	56	mm
Magnetic length	3.01	m
Operating current	11470	A
Operating temperature	1.9	K
Turns per coil		
inner layer	4+6	
outer layer	10	
Distance between aperture axes	180	mm
Yoke, outer diameter	444	mm
Self-inductance (both apertures)	8.8	mH
Stored energy (both apertures)	580	kJ

Table 5: Main parameters of LHC lattice quadrupole magnets

Strand diameter (mm)	0.825
Number of strands	28
Cable dimensions	
width (mm)	11.60
thin/thick edge (mm)	1.348/1.60
Transposition pitch (mm)	95
Critical current at 9 T, 1.9 K (A)	≥ 10060

Table 6: Characteristics of the cable for the quadrupoles

The low-beta quadrupoles are single-bore units, 6.1 and 6.9 m long. The LHC performance depends critically on their field quality, especially on the higher order random multipole errors at low field. In order to obtain this field quality and to provide additional space for the cone of secondary particles emanating from the collisions, a novel design based on a graded coil with an aperture of 70 mm [4], wound from NbTi keystoned cables has been proposed. The design gradient of the magnet is 250 T/m for an excitation current of 5200 A. The design concept is presently being verified on a 1.3 m model magnet which is being developed in collaboration with an industrial firm.

2.4 Other Magnets

The strengths of all other magnets, i.e. tuning quadrupoles and octupoles, sextupoles and correction dipole, sextupole and decapole corrector spools are lower than those of the previous design for which prototypes have been successfully built and tested or are in the construction phase. Therefore the further R & D work on them will aim at simpler and more economical solutions.

3. Status of the LHC magnet development

The programme was mainly focused on the standard cell components and in particular on the dipoles, but included study and construction of several other magnets and items.

3.1 Quadrupoles

Two full size quadrupole magnets of final aperture (56 mm) and length (3.05 m) have been designed and built by CEA-Saclay, using s.c. cables and structural parts made in industry. Their design and construction are described in [10].

These magnets have undergone tests at 1.9 K and magnetic measurements at CEA-Saclay by the end of 1993. Both prototypes have reached the design current, the first magnet after one quench, the second one after three quenches.

After testing, the first prototype has been delivered to CERN where it is presently being installed into a "short straight section", which is an assembly of quadrupoles, sextupoles and all other types of correction magnets. This will be the first element to form the test string (one half standard cell) of the LHC which is expected to be ready for testing by end 1994.

The collaboration between CERN and CEA-Saclay has permitted to develop a set of tooling in view of the mass production to be performed in industry.

3.2 Dipoles

The R & D effort covers:

- Superconducting cables.
- Short single-aperture and twin-aperture models (~ 1.3 m long).
- Long twin-aperture prototypes (~ 10 m long).

3.2.1 Superconducting cables

Twenty-four kilometres of cable for the inner coil shell made of 26, Ø 1.29 mm strands, and 42 kilometres of cable for the outer coil shell, made of 40, Ø 0.84 mm strands, have been developed and produced by the five European manufacturers and at present satisfy all main technical requirements. The current densities in the non-copper part of the strand cross-section, taken from the finished cables at the 3 σ limit in the distribution curve of production, are 980 A/mm^2 at 8 T, 4.2 K, for the inner layer and 2000 A/mm^2 at 6 T, 4.2 K, for the outer layer. The results of the models show that the short sample quenching field of the dipole (B_{ss}) is close (within ~ 2%) to the cable short sample limit determined from strands extracted from the cables.

The total quantity produced, 14 t, is a significant amount and gives confidence that the required quality can be maintained in mass production.

3.2.2 Model magnets

A number of models of the main dipoles have been made and successfully tested [5, 6, 7]. Two magnets were built in Japan by KEK in collaboration with industrial companies. All other magnets were entirely built by European companies except one which was assembled at CERN using industry made coils and other components.

At 4.3 K, the conductor short sample limit of this magnet was attained at the second quench and no retraining occurred after thermal cycles.

At 2 K the magnet had the first quench above 9 T central field, reached 9.5 T in five quenches and finally attained the record field of 10.5 T. After thermal cycles to room temperature all quenches were above 9.75 T.

3.2.3 Ten metre long magnets

A magnet, named TAP, with a CERN twin structure but coils identical to those of the HERA dipole (75 mm aperture) was built in industry and successfully tested at CEA-Saclay at the nominal temperature of 1.9 K at which the conductor short sample limit of 8.3 T was reached [8].

Subsequently, the construction of seven higher field (cable width 17 mm), 10 m long magnets was launched in four firms or consortia. All these magnets have the same type of coils, but three slightly different mechanical structures [15].
The present status of manufacturing/testing of these higher field prototypes, referred to as MBP, is well advanced. The first one,named MBP/A #1 (CERN-INFN 1) and funded by INFN (the Italian "Istituto Nazionale di Fisica Nucleare"), has satisfactorily passed a thorough campaign of tests and measurements , and is now ready for installation in the test string [13, 15]. The next chapter will deal with this magnet. The second prototype MBP/A #2 (CERN-INFN 2) is now being tested at CERN.

4. The first tested full scale dipole prototype

4.1 General

In the present chapter a brief description is given of the main design and manufacturing aspects of the first full scale prototype MBP/A #1.
A collaboration on applied superconductivity set up between CERN and INFN in the second part of the eighties, has permitted to launch the construction of the first two full scale prototypes about 8 months in advance with respect to the CERN self-financed magnets. INFN placed their orders for the manufacture of the various components with Italian industry. The overall technical responsibility for the these prototypes remained with CERN.
As already explained in [14, 15], it should be stressed that this R&D program was the first attempt done by CERN to develop full length prototypes directly in Industry (after the positive experience with short models), without passing through a phase of in-house development followed by a technology transfer.

4.2 Technological development

At the time when the programme was launched, in spring 1990, the only results available at CERN were those of the two single-aperture 1 m long models referred to as 8TM1 and 8TM2 made with HERA type strand. The twin-aperture models (MTA1), were the first attempt to explore the two-in-one structure; they have been tested in latespring-summer 1991. Development of the TAP magnet, which permitted to assess the problems related to a 10 m long magnet, although at lower field and with larger aperture, was still going on; this magnet was tested at end 1991 - beginning 1992.
The above facts clearly indicate the difficulty of carrying out the construction of these prototypes without disposing of the results of the previous steps of the R&D programme. This was particularly true for the first full scale magnet, the MBP/A #1 prototype whose design evolved from the initial concept to the final one passing through a number of modifications suggested by the results of intermediate phases [12]. Fig. 1 shows the final cross-section of the magnet.

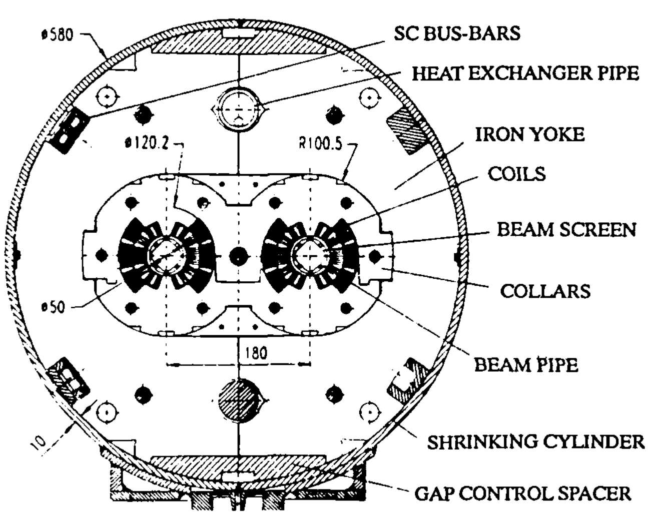

Fig. 1. Final cross-section of the first full scale prototype MBP/A #1 (CERN-INFN 1)

4.3 From design to fabrication

The design principle has already been described in [9, 11]. It is largely based on the kinematics of the structure during the cool-down from room temperature to the operating temperature of 1.9 K. The structural design calculations [11] were therefore aiming at the definition of a cross-section which would behave as expected. Detailed design analysis showed that very tight tolerances were required in the fabrication of coils and of the other magnet components. This has required strict control of the manufacturing techniques, both at the level of fabrication of the magnet itself and of the procurement of parts with the sub-contractors. A typical tolerance for the main parts like coils, collars and yoke laminations is of the order of a few tens of μm.

The collars and yoke laminations, made respectively of Al alloy and of soft steel, were obtained by fine blanking which required development of special tools and punching techniques to cope with the characteristics of the materials.

To optimize coil production and the so-called "coil collaring"(i.e. clamping the coils with their structural supports), a complete dummy coil-collar assembly was fabricated. This allowed to set-up the main parameters for the coil winding, coil curing and elastic modulus measurement operations. The main new difficulties related to these operations reside in the fact that the cables were much stiffer compared to previously made magnets and that the aperture diameter was only 50 mm. While winding and curing the first layer (fabricated with dummy cables) took months, the typical time for winding and curing of a layer of the superconducting coils for prototype MBP/A #3 was of the order of only three days.

Magnet collaring was a fundamental operation carried out under a press at loads between 6 to 10 MN for meter of press length. The average compressive azimuthal stresses in the coils were:

80 MPa in the inner layers
55 MPa in the outer layers

Preparation of the collaring operation and calibration of the pre-stress in the coils required about one month for the dummy assembly and about one week for prototype MBP/A #1. Prototypes MBP/A #2 and MBP/A #3, fabricated by the same manufacturer of prototype MBP/A #1, required less than one day (one shift) to be collared. Collaring of the mass production dipoles should not take more than a few hours.

Another interesting development was the setting-up of the procedure for welding the outer containment structure of the magnet, made of two stainless steel half cylinders joint together, so as to ensure the wanted pre-stress on the coil/collar/yoke assembly (Fig. 2). This

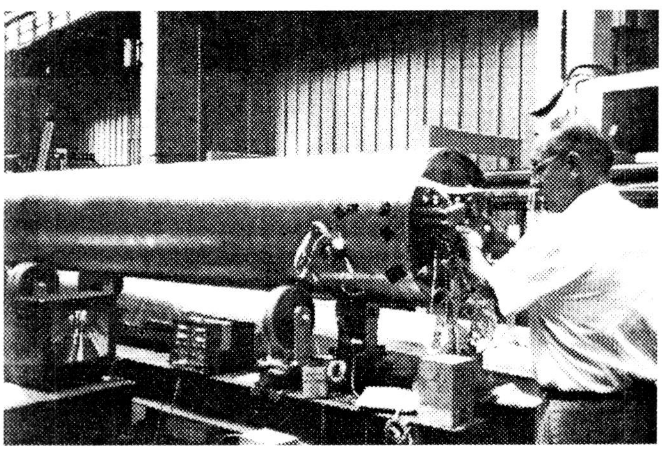

Fig. 2 . Inspection of the magnet apertures, after welding of the external shrinking cylinder.

required the fabrication of three complete models (about 400 mm long, having the real cross-section of the magnet), which were cooled to liquid nitrogen temperature to verify the kinematical behaviour of the magnet. A major design modification was introduced [9], consisting of two sets of Al bars, placed between the yoke halves, which permit a precise control of the geometry after welding and during thermal cycles. The wanted (and achieved) tensile stress in the shrinking cylinder was about 190 N/mm2.
Before being put into the cryostat, the cold mass was pressure tested at 26 bar, to assess its soundness with respect to the maximum pressure increase during a quench (max expected pressure 20 bar). It also passed a leak tightness test which proved that the leak rate was less than 10 $^{-9}$ mbar/ls. These tests were repeated after insertion of the cold mass into its cryostat.

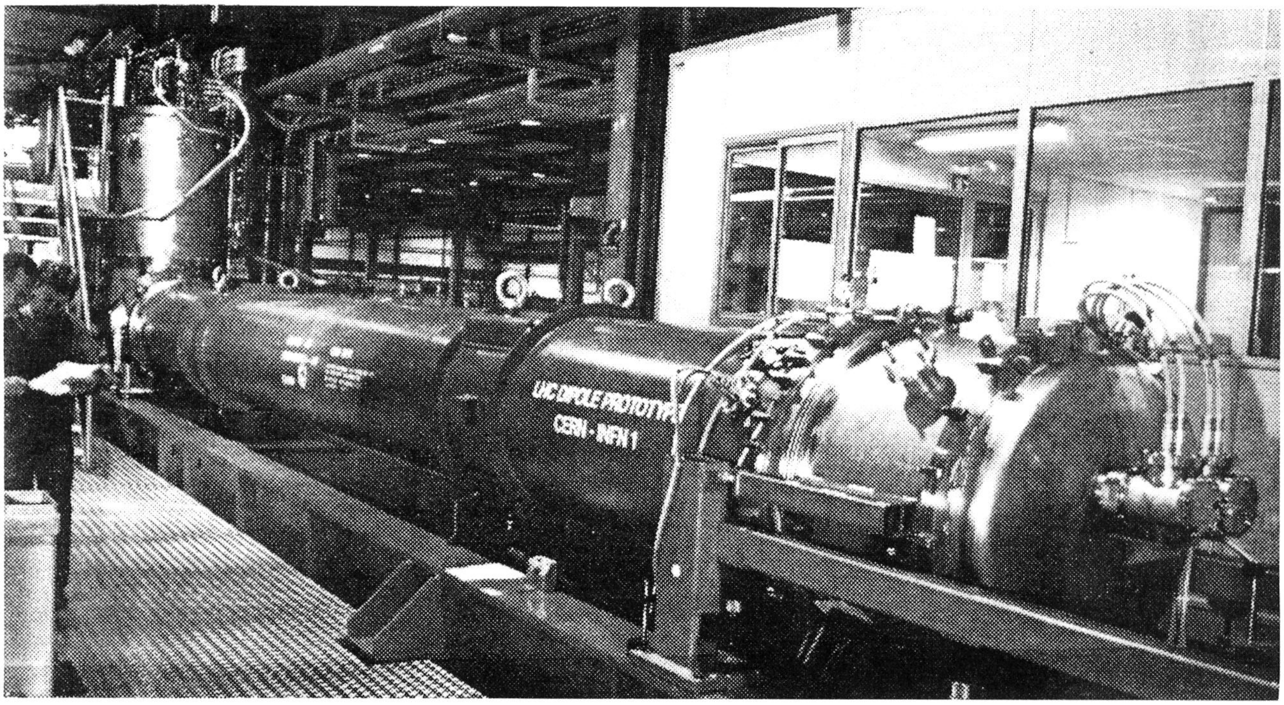

Fig. 3 . Prototype MBP/A #1 (CERN-INFN 1) on its test bench at CERN.

4.4 Testing at CERN

The first prototype was shipped to CERN in February 1994 . After one month of preparation it was mounted on the new test station (see Fig 3), developed at CERN to test the prototype dipoles. On April 1994 the magnet went through its first quenches. The first quench (see fig.4), occurred at a field slightly above the nominal field of the LHC machine, which is 8.65 T. On the third quench the magnet reached 9 T.
The magnet was then warmed-up to insert anti-cryostats in the cold bore apertures to perform precise magnetic measurements. An intense campaign of magnetic measurements was carried out [13], which showed excellent field quality in both apertures.
Following these magnetic measurements, testing was resumed on mid June 1994. The magnet behaved particularly well. It did not not show any "retraining" after the thermal cycle to room temperature and reached a field of 9.5 T after some quenches. Fig. 4 resumes the training history of the magnet.

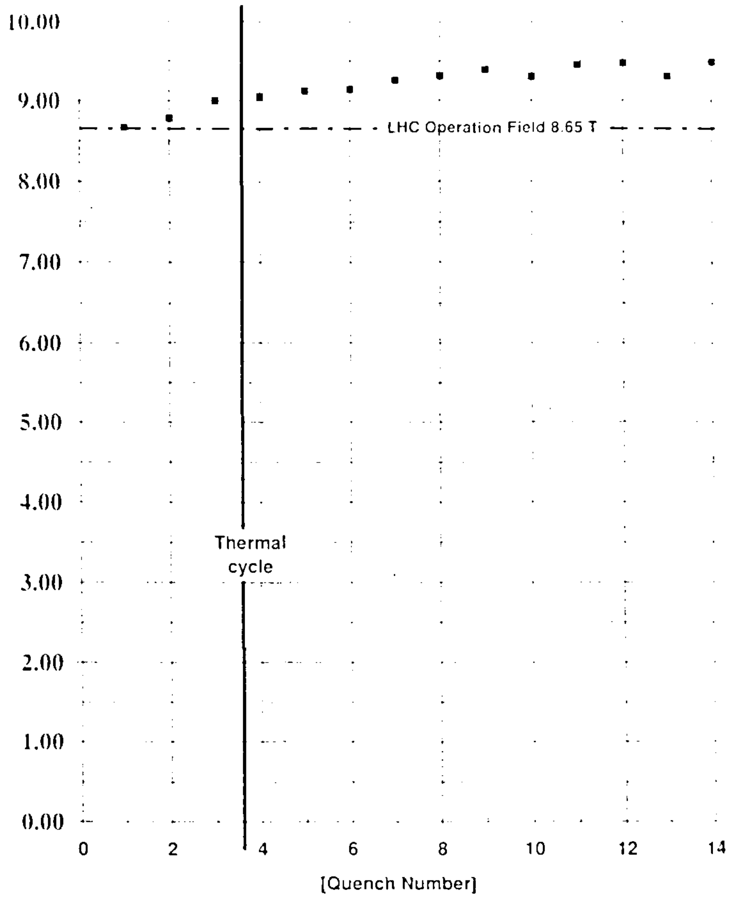

Fig. 4 . Quench history of the MBP/A #1 (CERN-INFN 1) prototype during the first and second test campaigns.

The results obtained so far with prototype MBP/A #1 are very encouraging indeed.They permit to be confident on the capability to build the LHC advanced technology magnets in industry. The evolution of the design of the LHC machine has led to dipole magnets with an increased magnetic length of 13.145 m, having a 56 mm diameter aperture. Although the increased length, together with the fact that they will be sligthly curved, will require some development, the larger aperture coupled with a smaller and hence less stiff cable should make the final magnets easier compared to the already successfully tested prototype MBP/A #1.

5. Future programmes

A decision concerning the approval by CERN Council of the LHC accelerator is expected to be taken soon . If a positive decision is taken in 1994 it is expected that, after finalization of the R&D programme and evaluation of a number of pre-production units, the mass production of the s.c. magnets will start in 1997.

6. Conclusion

The R&D programme for the superconducting magnets for the LHC is approaching the end of the first very important phase in which the following points have been confirmed:

- The technical choices for the LHC magnets are sound, including the twin-aperture configuration.
- The field levels of the LHC machine and the required field quality have been achieved in model magnets and in 10 m long prototypes made in industry.

These facts represent a encouraging base for the second phase of the R&D programme, which is aimed at finalizing the magnet design and construction techniques for the mass production.

Acknowledgment
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