Review of R & D towards High-Field Accelerator Magnets

R. Perin
CERN
CH - 1211 Geneva 23

Abstract

The great success of HERA and the results recently obtained with SSC and UNK prototype magnets have shown that the technology of accelerator superconducting magnets for intermediate fields in the range 4 to 6 T is now reliable for large scale applications.

For the 8.5-10 T range, the major effort is devoted to developing the magnets for the Large Hadron Collider (LHC). CERN has an important programme of construction of short models and full length prototype magnets in collaboration with several European Institutions, laboratories and industrial firms. Outside Europe, a non-negligible effort for building LHC model dipoles is also carried out in Japan. After the success of single-aperture models, four twin-aperture 1 m long dipole magnets were built by European industry and tested at CERN. All four magnets reached cable short sample performance at about 8 T central field at 4.2 K, and they went to central fields up to 10 T corresponding to the short sample limit at superfluid helium temperatures, but with training. A programme of modifications of existing models and construction of new models was launched. In the meantime, ten full length (~ 10 m) dipole prototypes are being built in industry. Eight of them will be assembled in a LHC prototype lattice cell.

1. Introduction

The technology of accelerator superconducting magnets has been applied with an extraordinary success on a large scale in the HERA project[1] and the excellent results recently obtained with dipole prototypes for SSC and UNK confirm that the technology is now mature for fields up to 6.6 T.

The evolution in design field and field gradient of superconducting magnets for accelerators is summarized in Table 1. With each new project an important progress was made. The HERA proton ring was designed for a 4.7 T bending field, but the magnets behave so well that they will certainly be run above 5 T. The RHIC case is a special one because the field level is limited to the specific requirements of the machine which will be installed in an existing tunnel. This has permitted the RHIC magnet designers to conceive a clever economical structure with only one coil layer and a simple coil clamping system without the use of collars[2]. The step to the LHC field levels appears to be rather bold, but it is explained by the use of the new superfluid helium technique which allows to lower the operation temperature to 1.8 ÷ 2 K.

The quest for higher fields continues to be motivated by economy in space, capital investment and operation costs[3].

2. Recent Results From SSC and UNK Magnets

2.1 SSC

After the decision to increase the aperture of the SSC dipole magnets from 4 to 5 cm, a large design and building effort was made at Brookhaven National Laboratory (BNL) and Fermi National Accelerator Laboratory (FNAL). The two teams worked out two somewhat different designs of the force containment structure (horizontally split yoke and stainless steel collars at the ends at BNL, vertically split yoke and special "collet" and clamp at FNAL) and of some details in coil construction (internal splice between the inner and outer layer conductors at BNL, external splices in the end clamp at FNAL).

In autumn 1991, BNL and FNAL completed the production of the first 5 cm-aperture, 15 m-long dipole prototypes and three of the BNL magnets and five FNAL magnets have been already tested. Their behaviour with respect to training was excellent[4].

The BNL and FNAL magnets appear to be equally successful from the quench performance point of view with no or very little training, quenching regularly at 7200 ÷ 7400 A at 4.35 K. It has to be noted that the nominal current corresponding to 6.6 T central field is about 6550 A, so that the operation margin should be more than 10%. These results are remarkable because they have been obtained with such a different approach for the clamping provided by the yoke to the coil-collar assembly.

Table 1
Design parameters of superconducting main magnet units in accelerator/colliders

	Dipoles			Quadrupoles			Operation temperature
	Central field (T)	Coil aperture (mm)	Eff. length (m)	Field gradient (T/m)	Coil aperture (mm)	Eff. length (m)	(K)
TEVATRON	4.4	76.2	6.1	75.8	88.9	1.7	4.6
HERA	4.7	75	8.8	91.2	75	1.9/1.7	4.5
RHIC	3.5	80	9.5	71.8	80	1.1	4.6
UNK	5.0	80	5.7	96.1	80	3.0	4.6
SSC	6.6	50	15.2	206	40	5.2	4.35
LHC	9+10	50	9(13)	250	56	3.05	2.0

2.2 UNK

A number of full size UNK superconducting dipoles have been tested[5]. The results with respect to training, ramp losses and reproducibility were satisfactory. All quenches of the first four tested magnets were well above the 5 T nominal field and most of them above 6 T indicating an operation margin of about 12% in field. The field quality is also within the requirements, with the exception of the "skew" quadrupole component, for which a reduction is needed.

3. MAGNETS FOR THE LARGE HADRON COLLIDER

The most important R & D effort for fields higher than the SSC level (6.6 T) is at present on the magnets for the LHC[6] and, in particular, the dipoles[7].

Two NbTi and one Nb_3Sn single aperture model magnets have been built and tested in Europe[8] and one NbTi model was built in Japan.

Four twin aperture magnets (MTA1) have been built by European companies and further short models are being assembled at CERN with components manufactured by industry.

A twin-aperture 10 m-long prototype magnet[9] making use of HERA type coils has been designed at CERN, built in industry, and recently tested at CEN, Saclay.

Ten full size twin-aperture dipole prototypes are being manufactured in industry.

The design of the main quadrupole is completed and two prototypes are being assembled at CEN, Saclay.

A prototype tuning quadrupole is nearly completed, and a sextupole-dipole corrector was built and successfully tested.

3.1 Superconducting cables

The dipole windings consist of two layers. The inner layer cable has 26, ø 1.29 mm, strands and a 2.02/2.50 x 17 mm^2 cross-section. The cable for the outer layer has 40, ø 0.84 mm, strands and a 1.30/1.65 x 17 mm^2 cross-section. About 20 km of the inner layer cable and 35 km of the outer layer cable have been ordered and parts of these supplies have been delivered and measured. Some parameters of the commercially produced strands and their measured critical current density in the non-copper part are presented in Table 2.

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 Cu/Sc ratio is 1.8 and the filament diameter 5 μm. All the cable for the two prototypes (2.8 km) has been delivered. Preliminary results are presented in Table 3 which gives the average non-copper critical current density before cabling. Degradation due to cabling measured at 6 T, 4.2 K is about 3%.

3.2 Twin-aperture dipole models

3.2.1 MTA1 models

Four twin-aperture model magnets (MTA1) were built and tested. Their basic cross-section corresponds to that of the cold mass in Fig. 6 and Table 4 shows their main parameters.

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	

Table 3
Critical current density in LHC quadrupole strands

Field	Temperature	Jc (A/mm^2, 10^{-14} Ωm)	
(T)	(K)	Specified	Measured
5	4.2	2710	2698
6	4.2	2160	2136

More details of design and characteristics may be found in refs 10 and 11.

The four magnets were built with a number of technical variants (Table 5) identified with the letters A, E, JS and H (Bss is the central field corresponding to a peak field in the coil equal to the cable short sample). The most significant of these variants are presented by model MTA1"E" in which the coils of each magnet aperture are separately collared[12].

Table 4
Dipole parameters at 2 K

Nominal field B_o (2 K)	10	T
Operation current	14730	A
Coil inner diameter	50	mm
Distance between apertures	180	mm
Yoke outer diameter	540	mm
Stor. energy for both channels combined	684	kJ/m

Tests of the four magnets were performed at CERN[13]. 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 and went slightly beyond a **10 T** central field. In order to determine the origin of the quenches, a novel method based on a large number of small pick-up coils, distributed axially and azimuthally in the aperture near the magnet windings, was devised. The method is a valid complement to voltage taps, having the advantage of avoiding galvanic connections to the magnet coils. It was found 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 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. Correlation to defects in design or manufacture are being studied. 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 the MTA1"A", 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 (Fig. 1) and correspond well to computations[13].

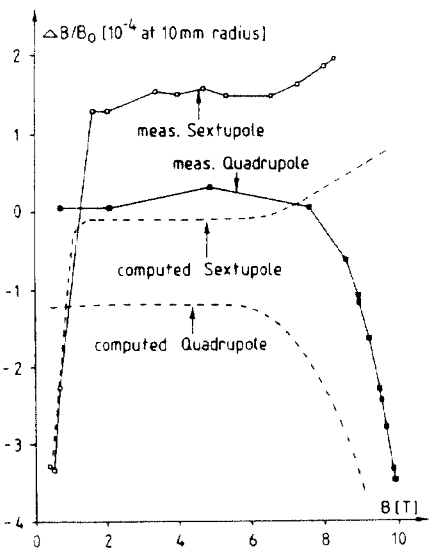

Fig. 1: Quadrupole and sextupole components in MTA1"JS" magnet at r = 1 cm in 10^{-4} units (measurements were taken 18 min after current stabilization).

3.2.2 New CERN models

The first of these new 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) at room temperature, 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 (Figs 2 and 3).

Solutions have been found in which the error multipole components including b_7, b_9 and b_{11} satisfy the LHC requirements.

3.2.3 KEK models

A twin-aperture model magnet for the LHC is being developed at KEK[14]. The particularities of this model magnet are:

- Double shell coils having no wedges, thanks to high keystone angle cables (4.6° in the coil inner layer cable).
- Symmetric separated coil/collar assembly mounted in a yoke which is vertically split into 2 parts.

The higher filling factor of the winding (no wedges) allows to reduce the cable width from 17 to 15 mm. A first coil/collar assembly in a single aperture magnet configuration has recently been tested at 4.29 K with great success: the magnet has reached the short sample limit of the cable at 8 T in three quenches[15]. The single aperture magnet will be soon tested at superfluid helium temperatures at CERN.

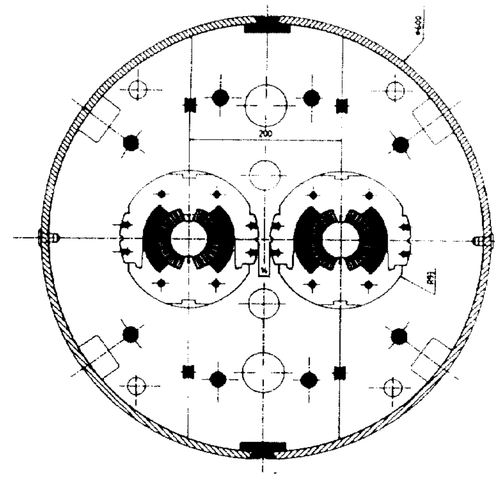

Fig. 2: Preliminary cross-section of LHC dipole model with stainless steel collars and yoke in three parts.

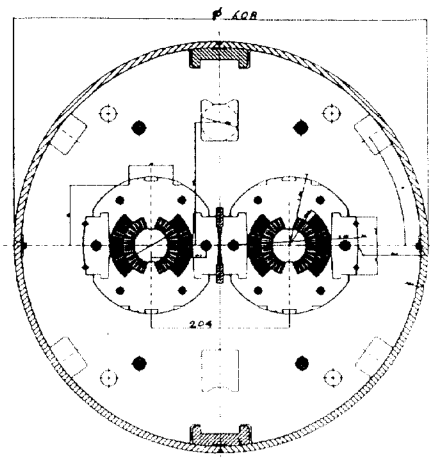

Fig. 3: Preliminary cross-section of LHC dipole model with aluminium alloy collars and yoke in two parts.

3.2.4 FOM-UT-NIKHEF-CERN model

To explore further the Nb_3Sn route, a high field (11.5 T) twin-aperture model magnet is being built in the Netherlands[16]. The vacuum impregnated coils will be collared by means of ring-shaped al alloy collars heat-shrink fitted around them.

3.3 Twin-aperture prototype with HERA type coils (TAP)

A twin-aperture, 10 m-long, prototype magnet was designed by CERN and built by industry. HERA type coils were used for reasons of economy, but the yoke and the external dimensions are the same as for the 10 T dipoles[9]. The magnet (Fig. 4 and Table 6) was tested and measured at CEN, Saclay[17]. At 4.5 K the first quench occurred at 5.8 T

Table 5
Technical variants of the MTA1 magnets

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 mat.	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		9.8 T	9.8 T	10.0 T	9.9 T

Table 6
Main parameters of TAP magnet and cryostat

Coil inner diameter	75	mm
Outer diameter of magnet	580	mm
Overall length of magnet	9.15	m
Overall length of cryostat	10.1	m
Outer diameter of cryostat	1.0	m
Nominal temperature levels	80 K, 5 K, 2 K	

central field, a value within 2% of the short sample limit of the cable, showing no difference with respect to the behaviour of the single aperture HERA magnets. The bath temperature was then lowered to 1.8 K. Nominal field was passed at the second quench and cable short sample limit was reached on the fifth quench at about 8.3 T central field (Fig. 5).

3.4 Full size 10 T prototypes

Ten full size prototypes are being built in industry, two of them were ordered by INFN (I)[18] and eight by CERN. These magnets, see Fig. 6, will be completed with their cryostats and other components as the final LHC magnets.
General conception and 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. 6. One magnet will have separate stainless steel collars and the yoke subdivided into three parts, as shown in Fig. 2, and another one will have separate al alloy collars and the yoke split into two parts as shown in Fig. 3. Delivery of the first prototype is foreseen for early 1993, the other magnets should follow at two months intervals.

3.5 LHC main quadrupoles

The design of the lattice quadrupoles is based on a coil aperture of 56 mm, and two-in-one geometry with 180 mm spacing between magnet axes[19]. Nominal gradient is 250 T/m and the effective length 3.05 m. The force containment is provided only by stainless steel collars which are pre-stressed and locked in position with tapered keys. Two twin-aperture prototypes are being built. The design was carried out by a joint CEA, Saclay/CERN team. Assembly and testing of the magnets is carried out in Saclay. Testing of the first prototype is foreseen for autumn 1992.

3.6 Prototype lattice cell and other components

A prototype cell of the LHC regular lattice will be built and installed in 1993. Its construction will be gradual and when completed it will include eight twin-aperture dipoles, two twin-aperture quadrupoles, all correcting elements, etc. The first prototype tuning quadrupole[20] will be ready in June 1992. The prototype combined sextupole-dipole corrector[21] has been already successfully tested.

Studies have been started on the design of the special magnets for the LHC interaction region[22].

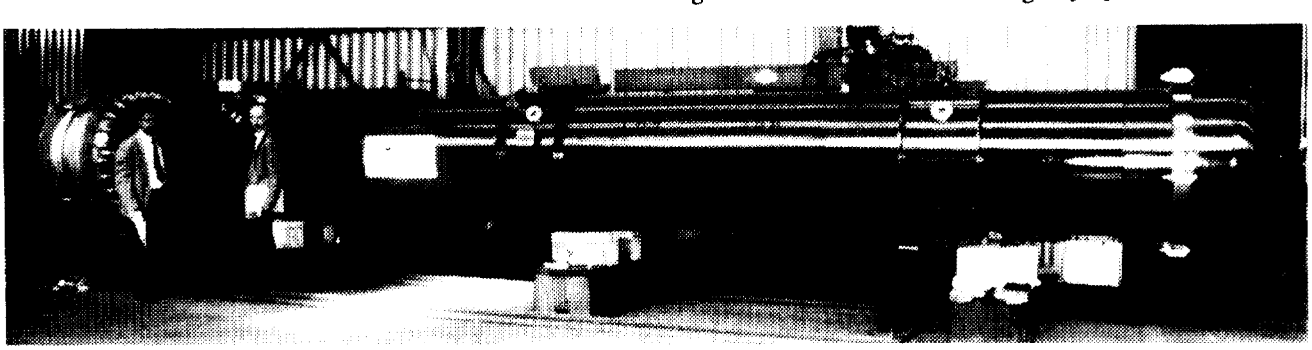

Fig. 4: Twin-aperture prototype (TAP) in its cryostat.

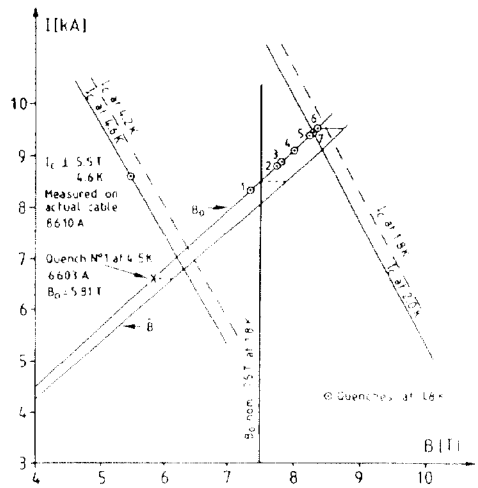

Fig. 5: Load lines and quench history of TAP magnet.

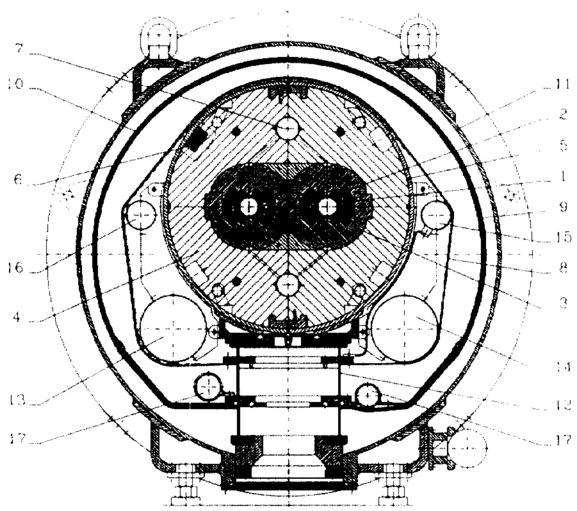

Fig. 6: Cross-section of LHC prototype dipoles
1. Vacuum chamber, 2. Coils, 3. Al collars, 4. Iron yoke, 5. Shrinking cylinder, 6. Bus-bars, 7. Bore for HeII heat exchanger, 8. Radiative insulation, 9. Thermal shield, 10. Superinsulation, 11. Vacuum vessel, 12. Support post, 13. 1.8 K GHe pipe, 14. 10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

4. CONCLUSIONS

The following conclusions can be drawn:

- The R & D for dipole magnets with field **up to 6.6 T has attained its goals**.
- The **10 T field has been reached** for the first time in accelerator dipoles and in the twin-aperture configuration foreseen for the LHC.
- It appears that the **twin-aperture configuration**, even with common collars, **does not adversely affect the quench performance** as compared to single-aperture magnets, at least for fields up to 8 T, as shown by the results of the TAP magnet.
- More detail work is necessary on 9 to 10 T magnets to eliminate training.

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