DEVELOPMENT OF HIGH-FIELD SUPERCONDUCTING MAGNETS FOR THE LARGE HADRON COLLIDER

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Abstract

The development of the magnets for the CERN LHC is progressing from the stage of 1 m long model magnets to the construction of full size, 10 m long prototypes. A number of 8 to 10 T single aperture and twin-aperture, 1 m long, dipoles have been built or are being completed in industry. A twin-aperture, 10 m long prototype dipole with its 1.8 K cryostat is being assembled and will be tested soon. Design and construction of quadrupoles, correction magnets and other essential components are being actively pursued in collaboration with several European Institutions and industries.

1. Introduction

CERN is proposing a powerful proton-proton collider as its next high-energy facility. This Large Hadron Collider (LHC) would be installed above the LEP machine in the existing 27 km long tunnel [1].

The circumference of the machine being fixed, the maximum obtainable energy is related to:

- the operating field level in the dipoles which depends on the temperature of the coolant and the beam losses;
- the physical distance between the magnets which is determined by the space needed for installation and connection.

The envisaged field level in the superconducting dipoles is in the range 8 to 10 T. The design is based on two sets of superconducting coils, mounted in a common force retaining structure, yoke and cryostat, and providing opposite fields of equal value in the two beam channels according to the "two-in-one" concept.

Several items and magnets are being studied and built in the R&D programme:

(a) high aspect ratio and high current density cables,
(b) single-aperture 1 m-long dipole models following both technologies, NbTi at 2 K and Nb_3Sn at 4.3 K (8 TM1, 8 TM2, 9 TM1 magnets),
(c) twin-aperture 1 m-long dipole models (MTA1 magnets),
(d) a twin-aperture 10 m-long prototype using HERA coils for a field of 7.5 T with its cryostat working at 1.8 K (TAP magnet),
(e) 10 m-long, high magnetic field prototypes and their cryostats,
(f) main quadrupoles,
(g) prototype auxiliary magnets, such as tuning quadrupole, sextupole, dipole corrector,
(h) high-current diodes for protection,
(i) and finally a complete cell of the LHC machine.

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

2. LHC half-cell

A half-cell of the LHC lattice requires 4 dipoles, 1 quadrupole and lumped correction magnets. Main dipoles and quadrupoles are powered in series. Close to the quadrupoles, there are a combined sextupole-dipole corrector and a combined tuning quadrupole-octupole magnet. Half-way in the half-cell between the main quadrupoles there is a combined sextupole-octupole-decapole corrector. The design of this latter element has just started and, therefore, is not described here.

3. Dipoles

The main characteristics and the mechanical design of the twin-aperture dipoles can be found in ref. [2,3]. Table 1 summarizes the characteristics of the dipole, the cross-section of which is shown in Fig. 1. The length is 1.35 m for the models and 10 m for the prototypes.

Nominal field B_0 (2 K)		10	T
Operation current		15060	A
Turns per beam channel	1st layer	2 x 13	
	2nd layer	2 x 24	
Overall current density in compressed and insulated cable (A mm^{-2})	1st layer	357.5	
	2nd layer	532.9	
Coil inner diameter		50	mm
Coil outer diameter		120.2	mm
Distance between aperture axes		180	mm
Collars outer dimensions		201 x 381	mm
Iron outer diameter		540	mm
Stored energy for both channels combined		684	kJ m^{-1}
Resultant of magnetic forces in the first coil quadrant			
ΣF_x		= 2.27	MN m^{-1}
ΣF_y	1st layer	= -0.23	MN m^{-1}
ΣF_y	2nd layer	= -0.98	MN m^{-1}
Longitudinal magnetic force		0.70	MN

Table 1 - Dipole parameters

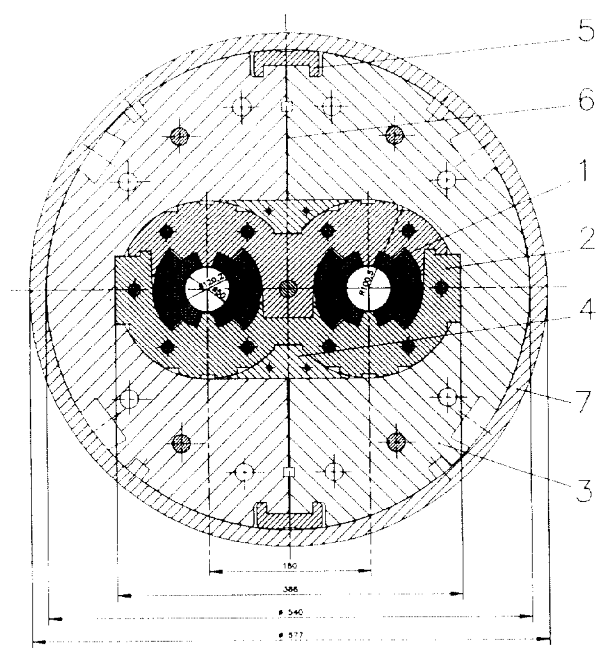

Fig. 1 - Cross-section of the LHC twin-aperture dipole
1. Coils, 2. Al collars, 3. Yoke, 4. Iron insert, 5. Clamp, 6. Gap, 7. Outer shrinking cylinder

Estimated systematic and random field errors at injection (Bo = 0.5 T) are presented in Table 2. As it can be seen, the introduction of the individual dipoles in the "two in one" geometry creates additional multipole components, especially a quadrupole. Iron inserts between the two individual dipoles reduce the quadrupolar component and the saturation effects [2]. The residual error can be eliminated by introducing a left-right asymmetry in the coils, e.g,.a wedge of 2 x 0.8 mrad. placed in the mid-plane of the central coil layers.

Multipole	Normal systematic	skew systematic	normal random	skew random
a_2		± 0.8		1.7
b_2	- 1.4 ± 1.6		1.2	
a_3		± 0.1		0.5
b_3	- 3.7		1.7	
a_4		± 0.03		0.2
b_4	± 0.05		0.15	
a_5		± 0.03		0.07
b_5	0.45		0.22	
a_7		± 0.02		0.04
b_7	0.13		0.02	
a_9		± 0.001		0.002
b_9	0.024		0.005	
etc.				

Table 2: Relative field errors at R = 1 cm in 10^{-4} units

3.1 Cable development

The dipole windings consist of two layers of conductors made of two different trapezoidal cables. The inner layer cable has 26 strands of 1.29 mm diameter and a cross-section of 2.02/2.50 x 17 mm^2. The cable for the outer layer has 40 strands of 0.84 mm diameter and a cross-section of 1.30/1.65 x 17 mm^2. The development of the superconducting cables is being encouraged by placing orders of significant lengths in European companies. In the strands of the outer layer cable, the current density of 2100 A mm^{-2}, at 9 T, 2 K required for LHC is to-day obtained. In the 1.29 mm ϕ strands for the inner cable, current densities of 1000 A mm^{-2} at 11 T, 2 K (1110 A mm^{-2} at 11 T, 1.8 K) are obtained in 10 μ NbTi filaments. The next step now engaged is to have this current density in 5 μ filaments. Strands having 28000, 5 μ ϕ, NbTi filaments in Cu matrix have already been produced with a current density of 1150 A mm^{-2}, at 8 T, 4.2 K. For Nb_3Sn, a significant length (> 100 m) of cable has been produced with a current density of 1600 A mm^{-2}, at 11 T, 4.2 K in the non-Cu part of the cross-section and in 15 μ filaments.

3.2 Single aperture models

Several single aperture models, 1 m long, have been constructed on common development programmes with industry and following the two lines of magnet development: NbTi at 2 K and Nb_3Sn at 4.3 K [5]. For both technologies, the coil winding diameter is 50 mm. Two magnets of 8 T nominal field have been built at Ansaldo with a 12.6 mm wide cable of NbTi/Cu strands. They had their first quench above 8.5 T and reached 9.3 T at 1.6 K after 4 quenches. This field was subsequently attained at 1.9 K. It has been verified that at quench the magnets can absorb their magnetic stored energy (self-protected conditions).

A Nb_3Sn model magnet has been built in Elin (A) using a 17 mm wide cable . This magnet reached 9.5 T at 4.3 K. During a second test campaign, 8 months later, the maximum bore field of 9.5 T was obtained again after two quenches. The work carried out by the CERN-Elin collaboration has demonstrated that the "wind and react" route for building high-field superconducting Nb_3Sn magnet is feasible.

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

3.3 Twin-aperture dipole models and prototypes

To demonstrate the validity of the two-in-one configuration, four one-meter long twin-aperture dipoles are under construction in industry: Ansaldo, Elin, Holec, Jeumont-Schneider. The four models which have various technical solutions for the coils, the collars, and the shrinking cylinder, will be tested at the end of 1990. In three companies, the superconducting coils are wound and ready to be assembled.

One preliminary important result is the feasibility of the winding with 17 mm wide cables. The electrical insulation, acceptable for models and prototypes, has still to be improved for mass production. Collaring of the two-in-one coils has to be well controlled to ensure the correct prestress on the coils.

Specifications of a full size (10 m long) 10 T, twin-aperture prototype have been sent to industries to have construction contracts placed in autumn 1990. Orders of cables for two prototypes have been placed.

3.4 Twin aperture prototype TAP

A twin-aperture, 10 m-long, prototype magnet [4] was designed by CERN and built by industry in order to gain experience in the construction of full scale, twin aperture, high-field magnets and with the superfluid helium operation of such a long magnet. In order to reduce the cost of development and tooling, HERA coils, operated at 1.8 K, have been used. Apart from the coils, the external dimensions and the yoke are the same as for the 10 T dipoles. The main parameters are listed in Table 3. The active part which is now completed at ABB (D) will be inserted in its cryostat at FBM (I) before being tested at CEN, Saclay (F). Fig. 2 shows the active part before the welding of the shrinking cylinder.

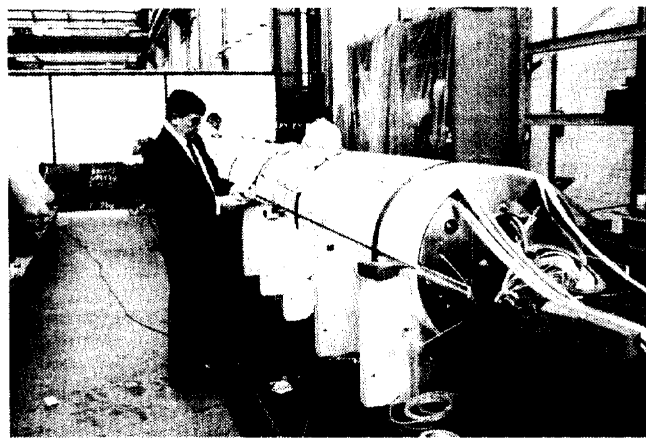

Fig. 2: Active part of TAP magnet

Magnet parameters	
Expected central field at 1.8 K	7.5 T
Excitation current at 7.5 T	8625 A
Stored energy at 7.5 T	4.06 MJ
Maximum field in winding at 7.5 T central field	8.05 T
Coil inner diameter	75 mm
Distance between aperture axes	180 mm
Resultant magnetic forces per quadrant	
horizontal component (inner and outer layer)	1.78 MN m^{-1}
vertical component (inner layer)	- 0.51 MN m^{-1}
(outer layer)	- 0.49 MN m^{-1}
Longitudinal magnetic force (total at either end)	0.55 MN
Overall length of magnet	9.15 m
Outer diameter of magnet	580 mm
Cryostat parameters	
Overall length	10.1 m
Outer diameter	1.0 m
Cold mass (magnet and helium vessel)	15000 kg
Mass of vacuum vessel	5000 kg
Number of support posts	3
Spacing of support posts	3.16 m
Liquid helium capacity	260 l
Liquid nitrogen capacity	40 l
Nominal temperature levels	80 K, 5 K, 2 K

Table 3: Main parameters of TAP magnet and cryostat

4. Main quadrupole

The main twin aperture quadrupoles are designed at CEA (Saclay) in collaboration with CERN. They are two quadrupoles arranged in a twin aperture structure with a common magnetic circuit. The current will be the same as for the dipoles. Table 4 gives their general characteristics.

The superconducting cable consists of 24 NbTi strands of 1.09 mm diameter and has a cross-section of 1.89/2.35 x 13.05 mm^2. The winding diameter of the quadrupoles has been increased to 56 mm to reduce the field error components due to coil imperfections and the 12-pole component due to magnetization currents. The integrated field is optimized so that the relative error for the 12-pole due to imperfections of the geometry is 0.04 units at R = 1 cm. The dipolar component due to the "two in one" configuration corresponds to 0.01 mm off axis displacement. From the mechanical point of view, the collars are designed to withstand the electromagnetic 1.25 MN m^{-1} forces. The completion of the prototype is foreseen by the end of 1991.

Nominal gradient	252	T m^{-1}
Nominal strength	770	T
Operation current	15060	A
Peak field in winding	7.76	T
Coil inner diameter (warm)	56	mm
Coil outer diameter (warm)	110.6	mm
Distance between aperture axes (warm)	179.6	mm
Collars outer diameter (warm)	164	mm
Iron inner diameter (warm)	172	mm
Iron outer diameter (warm)	428	mm
Length	3200	mm
Stored energy for one aperture	445	kJ
Resultant magnetic forces in the first coil octant:		
Fx	0.63	MN m^{-1}
Fy	-0.88	MN m^{-1}

Table 4: Main parameters of LHC prototype lattice quadrupole

5. Tuning quadrupole and octupole correction winding

This component is the subject of a common development with the consortium ACICA (SP). The nominal strength is 86.4 T with a gradient of 120 T m^{-1}. The design is based on individually built, magnetically decoupled quadrupoles. The aperture of the winding is 56 mm which allows to install an octupolar correction winding inside the tuning quadrupoles. The coils are made from insulated monolithic multifilamentary conductors 1.35 x 2.30 mm^2 and vacuum impregnated with epoxy resin. The coils, 15.1 mm thick, are surrounded by glass epoxy bandages and an antifriction sheet. They are placed in an 30 mm thick Al alloy shrinking cylinder which gives the required prestress and supports the electromagnetic forces of 0.12 MN m^{-1} per octant. The overall diameter of an individual tuning quadrupole is 170 mm. The stored energy is 12.85 kJ and the current 1600 A. The peak field in the winding amounts to 3.8 T. The completion of one prototype is foreseen by mid 1991.

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

6. Combined sextupole-dipole corrector

This combined sextupole-dipole corrector [6] is fabricated in a common development programme with Tesla Engineering and Rutherford Appleton Laboratory. The straight section lengths of both magnets are 1.0 m. The 1.5 Tm dipole is made of 1200 turns per coil of a 0.35 mm diameter NbTi/Cu composite wire. The coils are wound with a preassembled and shaped ribbon of 12 wires in parallel. The power consumption of the 25 junctions will be 3.6 mW at 1.8 K for the operating current of 47 A (at 65% of short sample limit). The peak field reaches 3.5 T. The self-inductance of the dipole is 4.6 H and the stored energy 5 kJ.

The sextupole corrector is designed for a strength of 4000 T m-2. The winding consists of 104 turns per coil of a 0.7 x 1.2 insulated NbTi/Cu composite conductor. The operating current is 458 A, the self-inductance 59 mH, the stored energy 6 kJ and the peak field in the windings 4.2 T.

The sextupolar winding has an inner radius of 25 mm and a thickness of 9.6 mm. The dipole winding, which is placed around the sextupole, is 4.2 mm thick. The coils are vacuum impregnated and placed in aluminium alloy shrinking rings, giving the requested precompression after cooldown. The yoke for the combined sextupole dipole corrector is a low carbon tube having a 100 mm inner diameter and a 170 mm outer diameter. The coils/shrinking rings assembly is centered in the yoke by means of keys.

The mechanical structure has been designed to cope with the various distribution of forces and bending moments due to the various possible modes of operation of sextupole and dipole. The construction of the prototype is progressing actively and the magnet should be ready for tests at RAL and at CERN in the middle of 1990.

7. High-current by-passing diodes

High-current diodes are foreseen across the superconducting dipoles and quadrupoles to by-pass a quenching magnet while the machine is discharged. These diodes work at low temperature and have to sustain a peak current of 15 kA and an integrated I^2 dt of about 10^{10} A^2s when the whole magnet ring is deenergized with a time constant of 100 s. The energy absorbed by the diode arrangement amounts to 1.5 MJ. A development programme is pursued with companies as ABB (CH), Marconi (UK) and Siemens (D) to deliver single diodes filling the specification. Tests have been carried out with two commercially available diodes (ABB) arranged in parallel connection. At 77 K, the diode pair can carry a current up to 16.5 kA during 60 sec. and with a current distribution between the two diodes of 40% to 60%. At 1.8 K, the current distribution is unfortunately worse and a diode may burn out due to overheating. A new mechanical/thermal arrangement of the diodes and a current balancing circuit are now under construction to improve the current sharing between the two diodes. Irradiation tests are made at 77 K with the diodes placed in an external beam of the SPS. After a dose of 93 Gy, it has been observed that the electrical capacitance of the diode is decreased by 1.7%, the voltage drop increased by 2.2% at 500 A, and 4.8% at 5 kA. The increase of the reverse blocking voltage by about 0.15% is almost negligible. It seems that the variation of the diode characteristics is linear with the irradiated dose. An experimental programme is now set-up to rejuvenate the irradiated diodes by annealing them.

8. Conclusions and future programme

In the first phase of development of high-field superconducting magnets for LHC, encouraging results have been obtained with the models, which show the validity of the magnet design. An intense and wide collaboration with industry has been set-up under various forms already at the model time. The twin aperture magnet, 1 m long and 10 m long, will be tested soon as well as a long superfluid helium cryostat. The work will proceed with the construction in collaboration with industry of all the cryo- magnets of a complete LHC cell: dipoles, quadrupoles, correction magnets, auxiliary equipment and cryostats. The test of a complete LHC cell is the next R&D programme to verify the technological basis for the construction of the LHC.

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