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THE FIRST, INDUSTRY MADE, MODEL MAGNET FOR
THE CERN LARGE HADRON COLLIDER

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Abstract

CERN intends to order from industry all magnets and auxiliary components for a future Large Hadron Collider (LHC) to be installed in the LEP tunnel. Industry is, therefore, associated from the beginning to the R. & D. effort not only in the development of components, but also in the design and construction of advanced technology magnet models.

The first magnet model for the LHC has been designed and built as a joint venture by CERN and the firm Ansaldo Componenti, Genova, Italy. The model is a single aperture, 1 m long, dipole magnet based on the NbTi cable technology and designed for 8 Tesla nominal field at 2 K. It reached and passed its nominal field without any quench and attained 9.1 Tesla where it operated happily without quenching, before the first campaign of tests was voluntarily stopped. In a second test campaign a 9.3 T central field was attained.

1. Introduction

A high-energy proton-proton collider is proposed at CERN as one of the next possible facilities to push further the frontiers of particle physics. This Large Hadron Collider (LHC)¹ would be installed in the ~ 27 km long tunnel of the Large Electron Positron colliding beam accelerator (LEP) which is now being completed. As in a given tunnel circumference the attainable beam energy is directly proportional to the bending magnetic field, it is important to push the technology of superconducting magnets towards the highest possible field. The envisaged field level is in the range 8 to 10 T. In order to prepare for the construction of the LHC, which will require about 2000 twin-aperture, 10 m long, dipole magnets, an R. & D. programme has been started in close collaboration with several European laboratories and industries². Both presently possible routes to high-field/high-current density magnets, i.e. using NbTi superconductor at about 2 K and Nb₃Sn at 4.5 K are being pursued, with the development of suitable conductors, 1 m long model magnets and 10 m long prototypes.

Subject of this report is a superconducting model magnet which was made with the purpose of testing the main design and fabrication concepts of the high-field dipole magnets for the LHC.

With it a new style of CERN-Industry co-operation has been successfully inaugurated, whereby CERN provides most of the scientific and technical know-how while industry participates in the design feeding into it its knowledge of manufacturing methods and economics, and takes then over the complete fabrication of the model or prototype.

2. Description of the magnet

The magnet model is an 8 T nominal field, single-aperture, 50 mm bore, 1 m long superconducting dipole using NbTi conductor and operating at superfluid

helium temperatures. In its design^{3,4} care has been taken to choose components that could be easily procured both in terms of cost and time. So, e.g. the superconducting cable was designed such that one could make use of some strands left over from the production of the cable for the DESY-HERA project⁵, and the steel yoke is made from HERA dipole type laminations, which were machined at the vertical symmetry plane to fit into the different mechanical structure of the CERN model. The assembled magnet is shown in Fig. 1 and a list of the main parameters is presented in Table I.

Figure 1. The first LHC model magnet

Figure 2 shows a cross-section of the magnet. Each coil consists of two concentric shells wound with the same superconducting cable. There is therefore no adaptation (grading) of the current density to the maximum field seen by the winding, which is considerably lower in the outer shell. Current density grading is in fact adopted for the LHC 10 tesla models, but it would have required thinner strands in the outer shell and for this first magnet it was preferred to use the same cable, made from HERA type strands which were readily available. Nevertheless, the effect of current grading on the mechanical behaviour of the structure was simulated by increasing the number of turns in the second layer beyond what would have provided an optimum field distribution in the aperture. There are two wedges in the coil inner layer and one in the outer layer. The two larger wedges are made from copper, the smaller one is a glass-epoxy laminate. The coil ends are of approximate constant perimeter profiles with end spacers made from glass-epoxy.

The coils are surrounded by 3 mm thick laminated aluminium alloy collars which are clamped together by longitudinal stainless steel tie rods as in the HERA dipoles. The iron yoke is vertically split in two symmetric parts which are mounted around the collars under a pre-determined horizontal compressive force and with a ~ 0.5 mm vertical gap between them at room temperature. They are clamped around the collars by a stainless steel shrinking cylinder which, thanks to its higher thermal contraction, pushes the iron

halves to close their gap during cool-down and applies then the necessary pre-compression to the mating iron faces. The way of working of this special mechanical structure, first proposed in 1985, has been described elsewhere³. With respect to other structures in which the coils are supported only by the collars, it has the advantage of a much higher rigidity in cold condition and, therefore, of a considerable reduction of coil movement under the action of the electromagnetic forces. E.g. the radial displacement of the coil inner edge at the median plane at $B_0 = 9.5$ T is only 0.04 mm. Azimuthal stresses in the winding are also greatly reduced.

TABLE I Main Parameters of model magnet

Coil inner diameter	50.0	mm
Coil outer diameter	102.6	mm
Yoke inner diameter	176.8	mm
Yoke outer diameter	396.0	mm
Shrinking cylinder outer diameter	412.0	mm
Coil straight length (inner layer)	800.0	mm
Overall coil length (outer layer)	1'060.0	mm
Magnet length (without connections) ...	1'265.0	mm
Overall magnet length	1'353.0	mm
Weight	1'210	kg
Nominal induction B_0	8.0	T
Peak field in winding at B_0	8.3	T
Operation current at B_0	9'180	A
No of turns per pole inner shell	21	
No of turns per pole outer shell	21	
Total No of turns	84	
Stored energy at B_0	160	kJ
Stored energy at $B_0 = 9.3$ T	216	kJ
Resultants of e.m. forces in the ... ΣF_x	194	t/m
First coil quadrant at $B_0 = 9.5$ T ... ΣF_y	-103	t/m
Cable geometry		
(soldered with Sn, 4.5 % In) 1.31,1.66 x 12.6 mm ²		
No of strands	30	
Strand diameter		
(including 0.005 mm AgSn lining)	0.84	mm
NiTi filament diameter	10	μ m
No of filaments	2'460	
Cu/Sc ratio	1.8	
Twist pitch of the strand	25	mm
Transposition pitch of the cable	114	mm
Insulation	2 x 0,025 mm Kapton 50 % overlapped + 0,12 mm glass fiber, B-stage epoxy helicoidally wound with 2 mm spacing

Figure 2. Cross-section of the magnet

One half of the axial electromagnetic force (~ 200 kN at $B_0 = 9.5$ T) acting on the magnet ends is supported by thick stainless steel plates that are welded to the shrinking cylinder.

3. Characteristics of the cable

The superconducting cable, supplied by Vacuumschmelze GmbH (Germany), is fully soldered with a $3.5 \times 10^{-8} \Omega$ m (at 4.2 K) resistivity solder. It has a $2 \times 0.796^\circ$ keystone angle and an 8.45 width to thickness ratio. The Ti content in the superconductor alloy is 47.2 ± 47.5 %. The geometrical characteristics of the cable are listed in Table I.

The critical currents of the strands have been measured at various fields prior to cabling and after cabling. Critical measurements on the finished cable have been performed at BNL and FNAL. Table II shows the critical currents of the cable calculated by adding together the currents of individual strands. It appears that the mean degradation due to cabling is 4.2 %. The residual copper resistivity ratio in the finished cable is 70. Figure 3 shows the critical currents calculated by the addition of the individual current strands and the measured currents at BNL and FNAL at 4.2 K. At the lower temperatures of 2 K and 1.6 K, the critical currents have been scaled by shifting the short sample curves by the corresponding variation of B_{c2} with the temperature.

Table II Characteristics of cable (Addition of the individual strand critical currents at 4.2 K)

B(T)	5	6	7	8
Prior to cabling				
$\Sigma I_c(A)$	14706	11772	8760	5849
$\langle J_c \rangle$ (A/mm ²)	2476	1982	1475	985
After cabling				
$\Sigma I_c(A)$	14132	11260	8421	5571
$\langle J_c \rangle$ (A/mm ²)	2380	1896	1418	938

4. Manufacturing tools

High-quality tools had to be prepared for coil manufacture and the assembly of the magnet structure. Only the main components are briefly described here.

The winding machine consists of a vertical axis rotary table on which a horizontal winding mandrel can rock. The movements are interlocked via a control console.

The conductor is tensioned by a brake that pinches the insulated cable by means of rubber ribbons which are actuated by a compressed air servomechanism. The tension is provided by the torque of a direct-current motor. When the winding machine works, this device produces a nearly constant tension irrespective of the speed of the cable, the braking force being precisely regulated by an electronic system. The maximum force is 120 daN, but the mean winding tension was about 40 daN. To avoid possible cable

deformations during winding, the brake can move horizontally in transverse direction to the cable on ball bearings. After winding, the coils are polymerized in moulds made from stacked precise profile laminations. Curing is performed by heating both the mould and the mandrel with diathermic oil at approximately 150-160°C temperatures.

The main assembly tool is a press which is used both for coil collaring and for final assembly of the magnet.

Figure 3. Curing mould and collaring press

This press, of 560 mm x 600 mm useful transverse dimensions, is of modular construction, so that it can be extended in length at will. The maximum force capacity is 10 MN/m. It is of remarkable stiff construction, the deflection in the centre being less than 0.1 mm under maximum load. The force used for coil collaring was 5.5 MN. At magnet assembly the compressive force applied to the two yoke-halves before welding the shrinking cylinder was 2.2 MN.

5. Performances of the magnet

5.1 Test set-up and campaigns

The magnet was tested in a vertical cryostat in which the temperature of the superfluid helium bath could be adjusted between 1.6 K and 2.1 K. A description of the test station may be found in Ref. 6.

Two test campaigns took place. In the first one the maximum field was voluntarily limited at 9.1 T, which was reached after the third quench and at various temperatures between 1.6 and 2.0 K without quenching. The magnet was subsequently warmed up to room temperature where it was kept for about a week and then cooled down again for the second campaign of tests.

5.2 Training behaviour and fields obtained

The history of quenches can be seen in Fig. 4 and Fig. 5. The first quench occurred at 8.55 T and the last quench at 9.3 T central field and at a bath temperature of 1.6 K to 1.7 K. At the second cool-down, the first quench occurred at 8.74 T. Fig. 4 shows that, at high field, the magnet attains the short sample limit of the cable and is not yet limited by the mechanical structure. The maximum field on the conductor is estimated at 9.6 T. The magnet model can

be safely operated at 8.5 T. The first training quench occurred above this operational field.

Figure 4. Critical currents of the superconducting cable and load line of the magnet

Figure 5. History of quench

5.3 Behaviour of the magnet at varying currents

The magnet has been discharged at various speeds to see its behaviour in superfluid helium with the high a.c. losses of a high aspect ratio and soldered cable. The magnet was discharged from 9 T at a speed of 0.13 T/s (6.8 s) without initiating a quench. At this speed, the total dissipated power amounts to

~ 19 W, this value is in good agreement with the strand coupling time constant which has been measured to be 4.7 s. Temperature measurements in the helium bath have shown that the major part of the power dissipated in the coils goes into the central bore of the magnet.

5.4 Tests with heaters

Heaters, which were spare parts of a previous long magnet⁷, have been mounted on the outer coil layer. They consist of a 30 μ m stainless steel alloy meander insulated by a 25 μ thick Kapton sheet and cover only 20 cm² of the winding surface. With 88 Joules energy discharged in one heater, the delay between the heater trigger pulse and the appearance of a quench is 34 ms at 7.9 T. The time constant of the heater circuit is 12 ms and the maximum current in the heater is 55 A.

6. Conclusions

The first model magnet for the LHC is a great success of the new style budding CERN-Industry collaboration, in which industrial firms participate from the beginning in the most crucial technological developments for future projects.

The model has confirmed in practice the merits of the new "vertically split iron" structure showing that it is adequate to efficiently support the windings up to 9 $\pm$ 10 T fields.

Finally, this success is a first encouraging milestone in the technical preparation for a future Large Hadron Collider at CERN.

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