EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 160

Design, Fabrication and Initial Testing of a Large Bore Single Aperture 1 m Long Superconducting Dipole Made with Phenolic Inserts

H. Boschman[1], R.L. Dubbeldam[1], G. Kirby[2], J. Lucas[2], R. Ostojic[2], S. Russenschuck[2],
A. Siemko[2], I. Vanenkov[2] and W. Weterings[2]

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1 HOLEC Ridderkerk, Ridderkerk, The Netherlands
2 CERN LHC-ICP Division

Presented at MT-15 - 15th International Conference on Magnet Technology
20-24 October 1997, Beijing, China

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 2 December 1997

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G. Kirby, J. Lucas, R. Ostojic, S. Russenschuck, A. Siemko, I. Vanenkov and W. Weterings,
CERN, European Organization for Nuclear Research, Geneva, Switzerland.
H. Boschman, R.L. Dubbeldam,
HOLEC Ridderkerk, Ridderkerk, The Netherlands.

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I. INTRODUCTION

In the present layout of the Large Hadron Collider (LHC) [1], a pair of superconducting dipoles D1 and D2 bring the beams onto colliding orbits in the four experimental points. One of the options considered for the single aperture D1 is a magnet featuring only the outer layer winding of the LHC main dipole. This type of single layer coil can provide a field of 4.5 T in a 88 mm aperture at 4.2 K. An identical coil could also be used in the twin aperture D2, to give a symmetric separation/recombination dipole arrangement in the LHC.

As part of the magnet development programme for the LHC insertions, a 1 meter long 88 mm aperture single layer dipole has been constructed in collaboration with HOLEC. The magnet (MBXSM) was completed in August 1997 and cold tested in the beginning of October 1997. In this report we describe the magnetic and mechanical design of the magnet, the preliminary mechanical tests performed on a 100 mm model, and the production and assembly procedures. Finally, we report on the magnet training behaviour.

II. DESIGN

The cross section of the MBXSM magnet is shown in Fig.1. It consist of a single layer three block coil wound using the outer cable of the LHC main dipole. The cable is insulated with an all polyimide tape. The coil is mounted into injection moulded phenolic spacers which hold the coils in position and serve as ground plain insulation, similarly as in RHIC magnets [2]. The use of phenolic spacers has the advantage of replacing the ground plain insulation with a single component, reducing assembly time and possible errors. The magnet is protected with two strip quench heaters, placed between the coil and the spacers. Gaps are left between successive 100 mm long spacers to allow radial venting of helium.

The compressive strength of the cured RX613 phenolic insert at room temperature is 280-320 MPa and at LHe temperature approaches 500 MPa, much higher than the iron yoke. Its room temperature tensile stress at fracture is 70-90 MPa, strongly suggesting that the phenolic spacers should be under compression at all times. The modulus and thermal contraction coefficient of the phenolic are very close to those of the coil (12-14 GPa vs. 9-18 GPa, and 14.4 x 10^{-6} K^{-1} vs. 15.4-18.4 x 10^{-6} K^{-1} , respectively).

The yoke has two functions: it provides coil pre-stress by compressing the phenolic spacers, and serves as the magnetic flux return path. It is assembled from a single lamination. Two such laminations are placed together, one being reversed then fixed with a stainless steel shear pins. After the top and bottom yoke halves have been forced together under a press, four keys are inserted to maintain the stress in the coil. Identical mild steel laminations were use in the end region of the magnet.

A stainless steel two part cylinder is placed around the magnet yoke. The halves are welded together, applying a supporting force to the yoke. This welded skin will also act as the helium vessel for future production magnets. A simple end plate is welded to the outer cylinder to restrain the longitudinal magnetic forces.

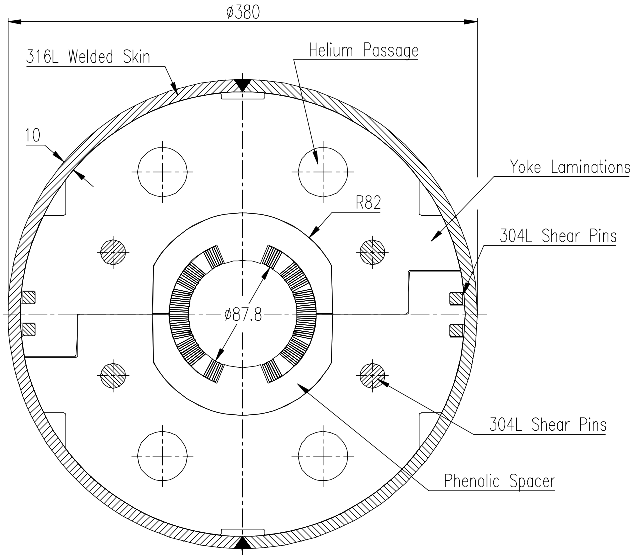

Fig. 1: Cross section of MBXSM type model.

Manuscript received October 22, 1997.

G.A. Kirby, +41-22-7678233, Glyn.Kirby@cern.ch; W. Weterings, +41-22-7674897, Wim.Weterings@cern.ch, http://www.cern.ch/; H. Boschman +31-180-445561, hboschman@hma.nl.

B. Magnetic Design and field optimisation.

The ROXIE program, developed at CERN for the design and optimisation of the coil and yoke geometry for LHC the superconducting magnets [3], was used as an integrated design tool for the MBXSM magnet. The steps in the design process were the following:

- Feature-based geometry creation of the coil cross-section and the coil end region.
- Mathematical optimisation of the coil cross-section including the iron yoke.
- 3d field optimisation in the coil ends using deterministic non-linear programming methods.
- Production of drawings by means of a DXF interface.
- End-spacer design and manufacture using an interface to CAD-CAM and 5-axis milling machines.

Using the ROXIE routines for definition of the coil cross-sections made of Rutherford-type superconducting cables, the geometric position of MBXSM coil blocks was calculated from given input for the LHC main dipole outer layer conductor (specified in a cable data base) and the radius of the outer layer winding mandrel. The exact positions and inclination angles of the blocks were determined in order to optimise the magnet field quality.

The fact that the keystoning (trapezoidal shape) of the cable is not sufficient to allow its edges to be positioned on the curvature of a circle was taken into account. This effect increases with the inclination of the coil blocks versus the radial direction. The keystoning of the cable also results in a grading of the current density in the conductor as the cable is more compacted (less voids between the strands) towards the narrow side. The main parameters of the optimised MBXSM magnet are given in Table 1.

Table 1. Main parameters of the MBXSM magnet

Operating field	4.50 T @ 4.2 K and 9.34 kA
Quenching field	5.96 T @ 4.2 K and 12.65 kA
	7.20 T @ 1.8 K and 15.9 kA
Transfer function	
at 4.5 T	0.482 T/kA
at 7.2 T	0.460 T/kA
Self inductance	1.89 mH/m
Peak field : main field (3d)	1.16
Coil pre-stress at 293K	70 MPa
Turns / beam channel	56
Coil inner / outer diameter	87.8 mm / 118.6 mm
Yoke inner / outer diameter	164 mm / 360 mm
Cable width	15 mm
Coil length	1080 mm
Magnetic length	880 mm
Expected field errors at 4.5 T and 10 mm radius	
b3	1.88
b5	0.096
b7	-0.0007
b9	-0.0007

B. Mechanical Design

The mechanical design of the magnet has been optimised using ANSYS for assembly at room temperature, cool down to 4.3 K and excitation up to nominal current.

For magnet assembly a press is used to deform the laminated yoke so that 4 locking keys can be inserted. A force of 44.1 kN per lamination is required in order to bring the lamination key openings in alignment. The interference between coils and the phenolic spacers was calculated so that sufficient compressive stress in the coils at nominal field could be achieved without damaging the coils during the collaring stage. The finite element model gave a stress of 90 MPa at yoking for a coil compression of 28 MPa at nominal field (Fig 3.).

During yoking, high stress concentration occurs in the contact surface between the upper and lower lamination with local plastification of small areas around the keys and on the contact surface. After insertion of the keys the press is released and shear stresses up to 120 MPa are developed in the keys, while the pre-stress in the coils drops to 70 MPa.

Following cool-down and excitation of the magnet, a further loss of compression in the coils occurs. This loss is due to the different thermal contraction coefficients and the magnetic forces. The estimated coil stress is 40 MPa after cool-down and 28 MPa after excitation.

III. INSTRUMENTATION

Voltage taps for quench detection and localisation were installed as well as capacitive pressure transducers [4] which were fitted on the pole shims to monitor the coil pre-stress during magnet assembly, cooldown and power testing.

Four capacitive pressure transducers (two triple and two single) were placed into the straight part of the magnet. Triple gauges were used to monitor the variation of pre-stress over the width of the cable during the assembly as well as during cooldown and excitation. Single gauges gave the average prestress value in the coil for the individual poles. Additionally, the cable ramp section was equipped with two special gauges on the ramp side and two single capacitive gauges on the opposite side. These special gauges were divided into three parts covering all of the cable ramp area in order to monitor the pre-stress distribution..

IV. FABRICATION

A. Coil fabrication

The coils were made of cable with 36 strands of 0.825 mm. The cable insulation was composed of one layer, 50% overlapped, 50µm polyimide tape and a 70 µm bi-stage polyimide tape, wrapped onto the cable spaced by 2 mm to create a channel for the helium cooling after curing of the coil. Following the 3 block structure of the coil, the coil-ends were divided with 4 spacers for non connection side and 6 spacers for the connection side.

The shape of the end-spacers was determined by the shape and position of the coil blocks as found in the field optimisation process. The surfaces to be machined were described by 9 polygons, which were transferred into a CAM system, CATIA, for the calculation and emulation of the cutter movements for machining the piece. As an interface, ASCII, VDA and DXF files were made available. The spacers were machined by means of a 5-axis CNC machine from woven glass tissue reinforced epoxy resin tubes of quality EPGC3 (G11). Because of the abrasive nature of the glass dust, diamond tools had to be used. After winding a dummy coil it was found that small modifications needed to be made to the shape of the end spacers in order to achieve better support of the cables coil ends.

The copper spacers used for defining the three blocks of the straight part of the coil were cold drawn from Cu-OF oxygen free copper, ASTM C10200, and were insulated following the same procedure as used for the cable. A longitudinal gap of 0.3 mm between the end-spacers and axial spacers was left on both sides of the coil to allow for dilatation during curing. The coils were wound clockwise, with a tensile force of about 40 kg, starting with an extra turn which was to be used for shaping the cable ramp after curing. After winding, the coils were cured in a precise mould which was closed at room temperature, creating a pre-stress in the coils of 80 MPa. The mould was then heated up to 160°C for 20 minutes. The size and elastic module of each half coil were measured to define pole and coil head shimming before impregnating the coilheads with stycast® 2850FT. For coil leads, the inner most turn was ramped in the plane of the conductor to 2.3 mm above the coil head. A strip of cold drawn high conductivity oxygen free annealed and tin-silver coated copper was soldered (Sn96Ag4, T=220° C) to this cable, starting at 30 mm before the ramp, in order to thermally stabilise and mechanically stiffen the ramp in its curved position. This cable lead was then placed in a box which was firmly clamped into the phenolic inserts on the coil heads.

B. Mechanical Model

In order to verify the mechanical design of the magnet, a 100 mm long model was built. In this model, four 100 mm long capacitive strain gauges were placed between the windings and the nose of the inserts for monitoring the behaviour of the structure. One of the gauges was subdivided into 3 parts, measuring the stress on the internal, middle and external radius of the coil. The model was assembled using straight parts of the dummy coil, phenolic inserts, glass-epoxy shims, pieces of quench heaters and yoke laminations, as shown in Fig. 2.

Although the initial shims were calculated on the basis of measured coil sizes, the stress inside the coil after the yoke gap was first closed was only 40 MPa, Fig. 3. To compensate for the deformation of the phenolic spacers, extra shims were added and the compression cycle was repeated. Finally, with 0.50 mm extra shim for each coil-quadrant, the stress levelled at approximately 100 MPa. Then the keys were introduced and the assembly press was released, which resulted in decrease of the coil stress to 76 MPa. Additional 5 MPa were lost after 12 hours. The triple gauge, however, showed that the stress was not distributed regularly over the compression surface of the cable: it was 25 MPa lower on the inside of the coil than on the outside. When cooled to 77 K, the average stress decreased to 38 MPa. Near the tip of the nose, however, only 20 MPa were measured.

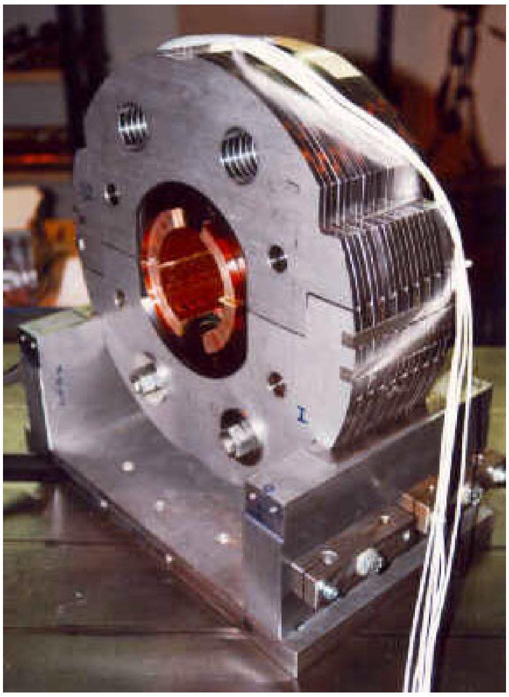

Fig.2: View of the collared mechanical model.

After two months, the stress inside the coil was slightly better redistributed, and on average only 2 MPa was lost. The skin was then welded, and the stress increased by about 2 MPa. However, this slight increase was almost completely lost again after 24 hours. Tests at LN_2 yielded basically the same results as without the skin.

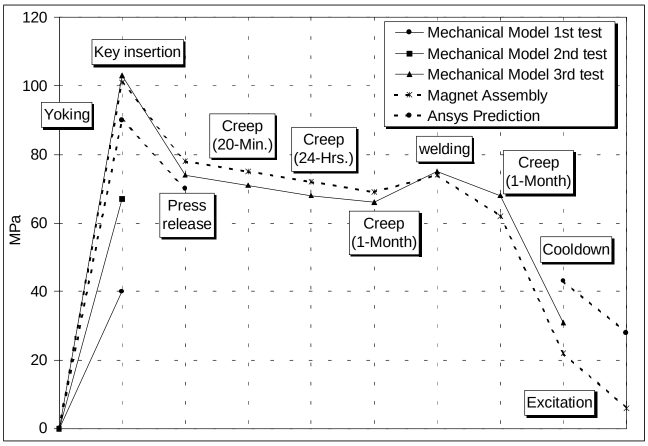

Fig. 3. Average pre-stress distribution in the MBXSM straight section.

It was concluded that on the average the stress measurements matched the finite element calculations quite well. However, the stress on the tip of the spacer nose was dangerously low and was expected to decrease to practically zero when exciting the magnet. It was therefore decided to use tapered shims for the MBXSM magnet so as to increase the stress on the inner radius of the coil and decrease it slightly on the outer radius.

C. *Magnet Assembly*

The two coils, easily and quickly assembled with the quench heaters and phenolic inserts and equipped with a number of capacitive gauges, were placed inside the lower yoke lamination packs. The top laminations where then positioned in order to prepare the magnet for collaring. The behaviour of the stress inside the coils during compression, keying of the structure and welding of the cylinder was in good agreement with the short mechanical model (Fig. 3). The average stress in the straight part of the coil just prior to magnet testing was 60 MPa, identical to the mechanical model. Due to the tapered shims, the peak stress on the inner radii of the coils, contrary to the mechanical model, was 20 MPa higher than the average, while on the outer radii it was lower by 20 MPa.

V. INITIAL COLD TEST RESULTS

The magnet was extensively tested at CERN in October 1997. In this report we present only the training behaviour; the other results will be published in a forthcoming report. The training history of the magnet is shown in Fig. 4. The first quench occurred at 5.15 T, 87 % of short sample limit, and after 5 training quenches the magnet reached the short sample current at 4.35 K. For quench number 13, the energy deposited in the magnet was increased from 20 % to 65 %, which resulted in a reduction in quench field for quench 14. After 16 quenches the magnet was cooled to 1.9 K, and the first quench was at 6 T, 84 % of the estimated short sample.

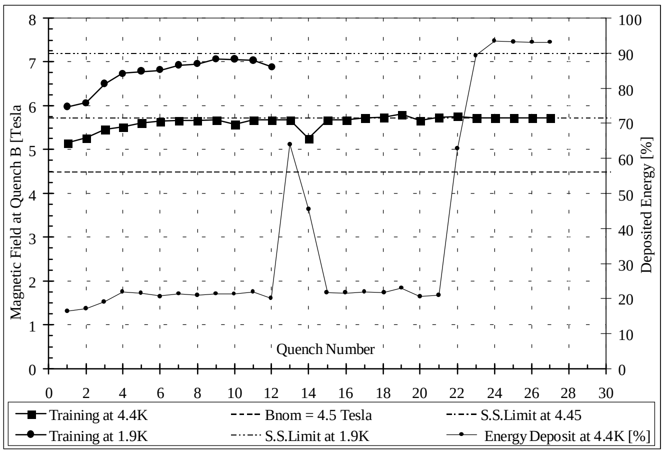

Fig. 4. Training of the magnet at 4.4K and 1.8K.

After 7 quenches the magnet trained to above 7 T, very close to its limit at 1.9 K. The capacitance gauges showed that the average pressure applied to the coil by the spacers unloaded at about 5.2 T, which did not seem to harm the performance of the magnet. All quenches were determined to occur in the transition region between the straight section and coil ends, in the peak field area. After training at 1.9 K, another 11 quenches were performed at 4.35 K, some with over 90 % of the energy deposited in the magnet. In all cases, the magnet quenched at its short sample limit.

VI. DISCUSSION

Using phenolic inserts, which have been fabricated cheaply in large quantities and with good reproducibility, the assembly of the magnet was easy and straightforward. However, in this type of structure the pre-stress in the coils depends fully on the yoke and its deformation. Because of the elastic properties of the phenolic material, the tolerances on the dimensions of the shims are less demanding, but on the other hand, due to the elastic deformation of the inserts the coil blocks may not be sufficiently well defined during operation (especially in the azimuthal direction). This could lead to geometric field errors, to which the tolerances of the inserts also contribute. These aspects of phenolic inserts require further study in LHe conditions. Finally, long-term creep effects still need to be checked.

VII. CONCLUSION

A 1 meter long superconducting dipole featuring a single layer 88 mm aperture coil, fully instrumented with pressure transducers, has been assembled and cold tested. The magnet performance was above expectations, as the magnet trained to its short sample fields of 7.2 T (1.9 K) and 5.6 T (4.35 K) in a small number of quenches. It is planned to assemble and test a second model dipole with identical mechanical structure to further examine this type of dipole made with phenolic spacers.

ACKNOWLEDGEMENTS

The authors wish to thank B. Szeless for his support, D. Tommasini and the LHC model team for their advice and F. Rodriguez-Mateos for the supply of the quench heaters. We also thank the technicians responsible for the model assembly for their excellent work, and the LHC power test team for the quench measurements.

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