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LHC Note 155

**CONSTRUCTION AND TESTS OF A MODEL OF THE
LHC SUPERCONDUCTING CORRECTOR MAGNET MDSBV**

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**Presented at the 12th International Conference on Magnet Technology
Leningrad, 23-28 June 1991**

**Geneva, Switzerland
September 1991**

Construction and Tests of a Model of the LHC Superconducting Corrector Magnet MDSBV

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Abstract - A full-scale model of the 1.25 m long MDSBV (Magnet Decapole Sextupole Bending Vertical) correction magnet for the Large Hadron Collider (LHC) [1] has been constructed and is currently being tested. The model contains the desired dipole and sextupole but not the decapole which was decided upon later. The magnet was built in a very compact way by placing the dipole coil around the sextupole coil. The two coils were vacuum impregnated and prestressed by shrink-fitted aluminium rings. The design took into account the high positional accuracy requirements for the coils and incorporated manufacturing techniques which are compatible with mass production methods, as approximately 800 of these magnets will be required for the LHC. The model is being tested in liquid helium at the temperature of 4.2 K and will be tested later at 2.0 K. The paper describes the construction, the experience gained during assembly, the test conditions and gives the first test results.

I. INTRODUCTION

The LHC lattice foresees two correction magnets in the standard half cell of each of the two rings, a first one called MDSBH (Magnet Decapole Sextupole Bending Horizontal) or MDSBV (*idem* Bending Vertical) is placed close to the quadrupoles and a second one, MDOS (Magnet Decapole Octupole Sextupole) in the centre of the half cell between the dipoles. The MDSBH and the MDSBV contain respectively a horizontal and a vertical 1.5 T dipole coil for orbit correction. In addition, both contain a 4500 T/m² sextupole coil to compensate the sextupole errors from the main dipole magnets and to correct the lattice chromaticity, and a 3.2×10^7 T/m⁴ decapole coil to correct the decapole errors from the main dipole magnets. The other corrector magnet (MDOS) will be a combination of a sextupole of 1600 T/m², an octupole of 1.8×10^5 T/m³ and a decapole of 1.4×10^8 T/m⁴; the design of which is discussed elsewhere [2].

The MDSBV model has been designed with a sextupole of 8000 T/m² and does not yet contain the decapole. Its cross-section is shown in Fig. 1. In addition to the coils and the shrink-fitted rings one sees the system of keys which centres the coil assembly in the solid iron yoke and absorbs the differential contraction between the two components.

II. CONSTRUCTION OF THE COILS

The design parameters of the sextupole and the dipole coils are given in Table 1.

Fig. 1. Cross-section of MDSBV model magnet
1. Sextupole coil, 2. Dipole coil,

The sextupole coil was wound with a superconducting wire of rectangular cross-section, around a copper central island which had previously been insulated with 0.2 mm of G-10. End spacers were put in after every second layer to dilute the end field and to absorb the space taken by the joggles. It was then impregnated with epoxy resin in a mould. From the tests carried out on trial coils it appeared that the PVA insulation on the wire expanded during the heating of the mould thereby blocking the interturn spaces and preventing the resin from fully penetrating

TABLE 1
COIL PARAMETERS OF MDSBV MODEL MAGNET

	Sextupole	Dipole
Wire dimension (metal)	0.58 mm x 1.08 mm	Diam. 0.29 mm
Wire dimension (overall)	0.70 mm x 1.20 mm	Diam. 0.35 mm
Copper/NbTi ratio	1.6	4.5
Insulation (enamel)	0.06 mm PVA	0.03 mm PVA
Nominal current	458 A	47 A
% of short sample	61	83
Number turns/coil	104	1332
Stored energy	6.2 kJ	5 kJ
Inductance	59 mH	5.7 H
Length straight sectn.	1 m	1 m

the coil. The impregnation and curing of the actual coils was therefore carried out at a lower temperature to avoid this problem.

The coil wire resistance was measured and the ground insulation tested, before and after winding the coil and also after impregnating with resin.

The dipole coil was wound with a superconducting wire of round cross-section (diam. 0.29 mm), again around a copper central island. Winding trials showed that it was difficult to wind such a thin wire in a regular pattern. The wire was therefore prefabricated, on a special machine, into a twelve parallel wire ribbon, bonded together with a meniscus of epoxy resin between each wire. To ensure that subsequent turns did not nest in the grooves of the previous turn, the ribbon was flattened between rollers reducing the overall thickness from 0.35 mm to 0.32 mm. This produced flats on the wires and ensured that the turns would stack in a regular manner. As the insulation on the ribbon was very thin, it was important to carry out the work in a clean area to avoid dirt particles getting between the layers and puncturing the insulation.

The coil basically consists of two blocks, separated by a copper spacer. Three other sub-blocks had to be created to allow the coil to follow the curvature of the cylinder. These were created by wedge-shaped longitudinal spacers. The latter and the end spacers were fabricated from filled epoxy resin.

The series connections of the twelve wires in the ribbon were made after the coil had been impregnated with epoxy resin. This had the advantage of being able to carry out inter-wire insulation tests at all stages during the fabrication.

The connections were made by fanning out the ribbon at the ends into individual wires and removing the PVA insulation. Connecting wires were then twisted together and soft-soldered. Each joint was then soldered to a printed circuit board to provide mechanical support and additional heatsink by the soldered tracks. Table 2 gives the resistances of different connection samples, measured at 4.2 K. Fig. 2 show the execution of the series connections of the dipole coil pancakes.

TABLE 2
JOINT RESISTANCES OF PAIRS OF DIPOLE WIRES
Measured results for a joint length of 10 mm. (Only one sample of each combination was measured, therefore can only be used as guideline figures)

Method of bonding	Joint layout		
	Twisted	Twisted and wire-wrapped with Cu wire	Twisted and wire-wrapped with s.c.wire
Pre-tinned wire, soldered	$3.6 \cdot 10^{-7} \Omega$	$2.6 \cdot 10^{-7} \Omega$	$1.0 \cdot 10^{-7} \Omega$
Bare wire, soldered	$1.2 \cdot 10^{-7} \Omega$	$0.5 \cdot 10^{-7} \Omega$	$0.6 \cdot 10^{-7} \Omega$
Bare wire, not soldered	$2.2 \cdot 10^{-4} \Omega$	$2.0 \cdot 10^{-4} \Omega$	$6.6 \cdot 10^{-4} \Omega$

Fig. 2. The soldered joints of the dipole pancakes

III. ASSEMBLY OF THE COILS

The sextupole coils were assembled on a retractable mandrel using dowel pins. The inter spaces between the coils were filled with glass fibre and, at seven places over the length of the coil, bands of pre-impregnated glass fibre were wound around the assembly and cured at room temperature. The bands were clamped in accurately located mould tools such that after curing the outer surface of the bands provided a precise diameter onto which the dipole coils were located concentrically with the sextupole coils within the required tolerance. The bands also guaranteed the angular positions of the sextupole coils such that the dowel pins could be withdrawn. This was necessary to allow the final extraction of the central mandrel. The series connections were then made between the sextupole coils by soldering the connecting pairs of wires into u-shaped copper channels, the latter forming an additional heatsink.

The sextupole coil assembly was finished by filling the spaces between the bands with glass fibre tape which was then filled with resin during the final impregnation of the complete coil assembly.

The dipole coils were assembled on the outside diameter of the sextupole and banded in the same way. Their angular position relative to the sextupole coils was maintained with tooling mounted on the two ends. Once these bands were cured the tooling was removed, the series connections were made, and the interspaces between the bands filled with glass fibre tape. Finally, the whole assembly was impregnated in a mould. The diameter of the mould had been made such that the coil diameter would be precise enough for the fitting of the aluminium shrink rings without any machining of the coil assembly. It appeared to be necessary, however, to polish the outside of the coil assembly as the roughness of the surface was not acceptable for the shrink fitting process. (The precision obtained during assembly is typically ± 1.5 milliradian for the angles of the pole mating faces and ± 0.05 mm on the radii.)

The shrink fit was done after measuring the diameter of the impregnated coil assembly and machining the aluminium shrink rings to the desired interference fit. Table 3 gives the measured fit at room temperature as well as at 77 K and also lists the deduced pre-stress and contraction coefficients at liquid nitrogen temperature.

Finally, the keyways were machined in the aluminium rings to centre the coil assembly in the yoke. The latter was planned to be made of a simple thick-walled iron tube. However, it was not possible to machine the keyways over the one-metre length within the desired precision of 0.05 mm and therefore the yoke had to be subdivided into short lengths. For a series production a laminated yoke made with precise stampings will therefore be more appropriate.

The power connections to the current leads were made on the periphery of the magnet by clamping the lead against the coil wire (Fig. 3).

The input and output wires of the sextupole coil were brought out of the coil assembly up to the clamps on the periphery and were backed up with a copper strip. The input and output wires of the dipole were first soldered to a thicker wire of the type used for the sextupole coil and then brought from the coil to the clamps as in the case of the sextupole. Shunt resistors, to protect the magnet against an accidental open circuit, were mounted on the outside of the yoke and were directly connected to the coil side of the connection clamps.

IV. THE TESTS

A first test has been carried out at Rutherford Laboratory at a temperature of 4.2 K. This test, where the magnet was suspended in a vertical cryostat, included the measurement of the magnetic field (by means of Hall probes), the voltages on each individual sextupole coil and the voltages on each dipole pancake. As can be seen on the load lines (Fig.4 and Fig. 5), the sextupole was expected to reach its nominal field even at this temperature but the dipole was not. The first part of the test consisted of running up the sextupole magnet and the dipole magnet separately. In the

TABLE 3
PRE-STRESS FROM SHRINK FIT AND COOLDOWN

Shrink fit	
O.diam. impregnated coil (R.T.)	82.482 ± 0.009 mm
I.diam. aluminium rings	82.360 ± 0.010 mm
Idem after shrink fit	82.422 ± 0.010 mm
Pressure between ring and coil	9.8 N/mm ²
Cooldown to 77 K	
I.diam. aluminium rings	82.103 mm
I.diam. free aluminium ring	82.066 mm
Thermal contraction aluminium	3.6 x 10 ⁻³ mm/mm
Thermal contraction coil	4.1 x 10 ⁻³ mm/mm
Remaining pressure between ring and coil	6.8 N/mm ²

Fig. 3. The power connections of the magnet

Fig. 4. The load lines of the sextupole. (Conductor parameters given in Table 1)

second part one magnet was powered and the other run up to see the limitations introduced by the coexistence of the two magnetic fields. This second part was repeated after changing the polarity of one of the magnets. In this case the field distribution changes to its mirror image and the peak fields will therefore be found in locations symmetrical to those in the previous condition. The dipole performance is shown in Fig. 6. In stand-alone operation, it trained from 44% to 80% of short sample current (corresponding to a field of 1.44 T) in 32 quenches and was still improving. With an additional sextupolar field, the peak field in the dipole coil increases and occurs in another location. Therefore it trained again but more rapidly. After changing the polarity, it seemed to continue the same training curve. The sextupole performance is shown in Fig. 7. In seven quenches it trained from 52% to 74% of short sample current (corresponding to a gradient of 8500 T/m²). The training was stopped at this point to avoid overstressing

Fig. 5. The load lines of the dipole. (Conductor parameters given in Table 1)

Fig. 6. Training of dipole at 4.2 K

the coil as its design gradient was 8000 T/m². An additional dipole field caused a new training to approach a similar point as compared to short sample current. A second test will follow at CERN and will include the measurement of the field harmonics in the straight section and in both ends. Although this test will finally be done at the LHC operating temperature of 1.8 K, the magnet will first be tested at 4.2 K to see whether it will directly reach the present performance again or whether it will re-train.

VI. CONCLUSIONS

The MDSBV magnet model, built by "nesting" the sextupole coil inside the dipole coil, has been constructed and successfully tested at 4.2 K. The dipole, designed for a field of 1.5 T at a temperature of 1.8 K was brought to 1.44 T in stand-alone mode and to 1.08 T when the sextupole was powered at 80% of nominal field. The sextupole, designed for 8000 T/m² at 1.8 K, was brought

Fig. 7 Training of sextupole at 4.2 K

to 8500 T/m² in stand-alone operation and to 6800 T/m² when the dipole was powered to 67% of its nominal field. The dipole showed more training than the sextupole, maybe due to the large number of turns (1332) per pole. The result seems to confirm that the magnets, after training, may run at 70% of short sample current. However, a second test at 4.2 K is necessary to check whether the magnets will re-train. A final test at the LHC operating temperature of 1.8 K is planned in the near future.

ACKNOWLEDGMENTS

We would like to acknowledge the design effort of M. Parr (Tesla) and R. Mauris and H. Nemoz (CERN), the fabrication by J. Treasure (TESLA), the quench studies by D. Hagedorn and F. Rodriguez-Mateos (CERN), the testing by R. Puffett (RAL) and B. Vullierme (CERN), the preparation of the paper by the DTP-4 Centre (CERN) and last but not least J. Wheatley, D. Willis and T. Kitchen of Tesla Engineering who strongly stimulated and supported this work.

REFERENCES

- [1] A. Ijspeert, R. Perin, E. Baynham, P. Clee, R. Coombs, J. Wheatley, D. Willis, "Development of a superconducting sextupole-dipole corrector magnet," Proc. 11th Int. Conf. on Magn. Techn. (MT-11), Tsukuba, Japan, 1989, London, Elsevier, Vol 1, pp 200-205.
- [2] E. Baynham, R. Coombs, P. Clee, A. Ijspeert, R. Perin, "Design of a superconducting multipole corrector for LHC," unpublished, submitted to this conference.