EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 263

Experience with the Fabrication and Testing of the Sextupole Superconducting Corrector Magnets for the LHC

*J. Salminen, A. Ijspeert, Z. Ang, J. Billan, L. Walckiers
**S. Bapna, M. Karmarkar, A. Puntambekar, A. Thipsay
***L. García-Tabarés

Abstract

The LHC main dipoles will be equipped with sextupole corrector magnets with a field strength of 1700 x^2 (T,m) and a magnetic length of 110 mm to correct sextupole field errors. Within the LHC magnet programme CERN has developed in collaboration with CAT a cosine-θ type of design where much emphasis has been put on the cost reduction. The magnet features a two-layer racetrack coil, without end spacers, wound from a rectangular NbTi-wire. The two layers are wound simultaneously turning in opposite directions. The yoke is made of a scissor-type of lamination, which allows bringing the iron close to the coil for field enhancement. In this paper we review the manufacturing experiences with the first 12 prototypes built at CERN and CAT. The results of the training at 4.2 K and 1.9 K are presented along with the magnetic field quality measured at room temperature and at 1.9 K.

* CERN, Geneva, Switzerland.
** CAT, Indore, India
*** CEDEX, Madrid, Spain

Presented at MT15, Beijing, China, 20-24 October 1997

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 2 February 1999

Experience with the Fabrication and Testing of the Sextupole Superconducting Corrector Magnets for the LHC

J. Salminen, A. Ijspeert, Z. Ang, J. Billan, L. Walckiers
CERN, Geneva, Switzerland

S. Bapna, M. Karmarkar, A. Puntambekar, A. Thipsay
CAT, Indore, India

L. García-Tabarés
CEDEX, Madrid, Spain

Abstract -- **The LHC main dipoles will be equipped with sextupole corrector magnets with a field strength of 1700 x^2 (T,m) and a magnetic length of 110 mm to correct sextupole field errors. Within the LHC magnet programme CERN has developed in collaboration with CAT a cosine-θ type of design where much emphasis has been put on the cost reduction. The magnet features a two-layer racetrack coil, without end spacers, wound from a rectangular NbTi-wire. The two layers are wound simultaneously turning in opposite directions. The yoke is made of a scissor-type of lamination, which allows bringing the iron close to the coil for field enhancement. In this paper we review the manufacturing experiences with the first 12 prototypes built at CERN and CAT. The results of the training at 4.2 K and 1.9 K are presented along with the magnetic field quality measured at room temperature and at 1.9 K.**

I. Introduction

In the LHC ring each bore of the main bending dipole is equipped with a superconducting sextupole (MCS) and decapole (MCD) corrector magnet, so called spool-pieces, to correct systematic sextupole and decapole field errors in the dipole field. There are some 2500 magnets of each type. Half the MCS-magnets will be built by Indian industry under the supervision of CAT. The first prototype spool-pieces, 10 MCD and 12 MCS magnets, have been built and tested. They will be mounted in the end of the dipole models that will be used for the second LHC test string. In this paper we review the manufacturing experiences on the MCS prototypes only, since the design principles are the same for the two magnet types.

II. Manufacturing

A. Coil Winding

1) Principle: The coil features two radial layers each consisting of 13 turns. The winding starts in the middle of the wire and the two layers are wound simultaneously turning in opposite directions around a G11 central island. The epoxy is applied on the wire continuously during the winding. After the winding the end filler pieces are positioned and the coil is clamped in the curing mould [1].
2) Epoxy system: The used epoxy system is Araldite AW106 + Hardener HV953U from Ciba-Geigy. The epoxy system has been chosen due to its short curing time of 10 min. at 100°C. However the coils are kept 1h in the oven, since it takes about 45 mins before the temperature stabilises in the curing mould. According to the manufacturer a shear strenght of 27MPa should be attained with this curing temperature.

TABLE I
MAGNET PARAMETERS

Nominal strength	1700 T/m^2
Overall length with the shield / Magnetic length	160 mm / 111 mm
Nominal current	550 A
Working temperature	1.9 K
Turns per coil	2 × 13
Peak field in the coil in 3D	2 T
Quench current at 1.9 K / 4.2 K	1380 A / 1010 A
Self inductance	0.769 mH
Inner / Outer diameter of the coil	56 mm / 66 mm
Inner / Outer diameter of the yoke	66 mm / 90 mm
Inner / Outer diameter of the shrink ring	89.86 mm / 96 mm
Inner / Outer diameter of the screen	110 mm / 120 mm
Cable dimensions bare	1.13 mm × 0.726 mm
Insulation thickness (PVA)	60 μm
Cu/Sc ratio	1.6
RRR-value	100
Filament diameter	7 μm
Icr (5 T,4.2 K) ⊥ and // to broad side	700 A / 800 A

The major drawback of the used wet winding technique is that a wet wire is not very convenient to work with. We have explored unsuccessfully different pre-preg coatings on the wire and coated tapes to develop a cleaner winding process. However the tested materials had several disadvantages; a too long curing time for series production, low shear strength, or bonding under too high a pressure. Therefore it has been decided stick to the present method and to further develop it.
3) Actual production time and the aim: The aim is to produce a coil in 20 minutes. Presently the whole winding process including the impregnation in an oven, cool down and cleaning of the tooling takes about 5 hrs per coil. The long time is mainly due to the present curing tooling, which has not been designed for mass production. In the future it is foreseen to replace the separate curing fixture by pneumatic clamps integrated on the winding mandrel and to impregnate the coil by passing a current through the windings. It has been noticed that a significant gain cannot be obtained in the coil winding itself, since the actual winding time is only 20-30 mins per coil with the simple hand driven machine.

Manuscript received October 20, 1997
J. Salminen, +41-22-7674305, fax +41-22-7676300, Jukka.Salminen@cern.ch

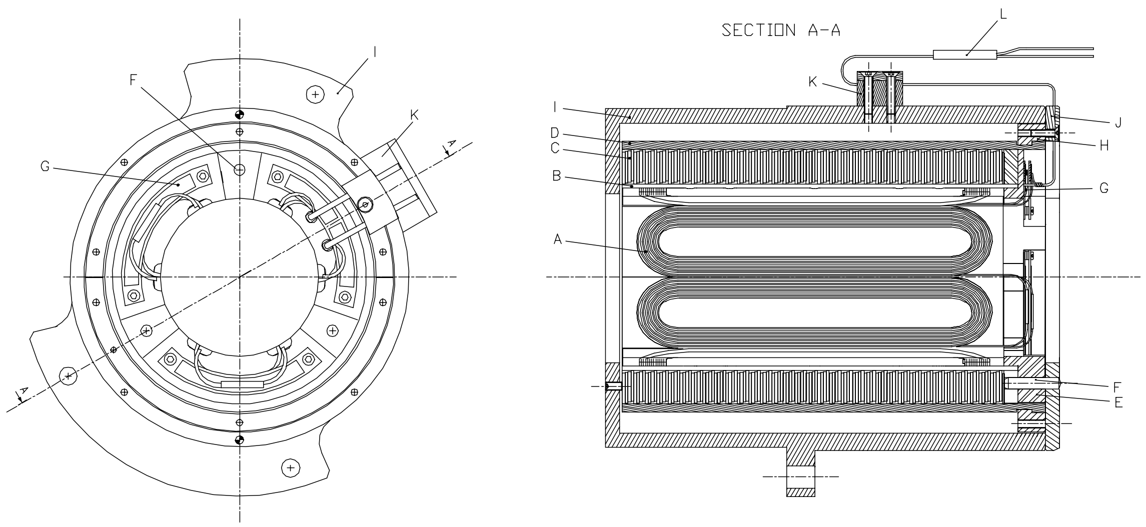


Fig. 1. MCS-magnet in the magnetic shield: A) Sc-coils B) Fibreglass bandage C) Scissor-laminations D) Aluminium shrink ring E) Fibreglass end flange F) Dowel pin G) Inter-coil connections on circuit boards H) Fixation clamps I) Magnetic shield J) End plate of the magnetic shield K) Support of the connections L) Bus-bar connections secured by a copper grip

4) Releasing agent: A semi-permanent Zyvax releasing agent from Zyvax inc. has been applied on the impregnation tooling. The agent is composed of two parts; a mechanical part that hinders the resin from bonding mechanically, and a chemical part that hinders from bonding chemically.

B. Assembly of the magnet

1) Assembly of coils: The coils are mounted around a tubular aluminium assembly mandrel. A 75 µm thick PTFE coated fiberglass foil is put between the coils and the mandrel to facilitate the extraction of the mandrel after the assembly. The coils are pressed on the mandrel, since they are slightly distorted due to the internal winding stresses. The possible voids between adjacent coils are filled with G11 shims and the coils are glued together with a G11 connection plate.
2) Fibreglass bandage around the coils: A fibreglass pre-preg cloth, ISOPREG EP11200 from Isovolta, has been wrapped around the coil assembly. The resin content of the cloth is 45% (weight). A thermo-retractable STTI polyester tape is wrapped around the pre-preg cloth to provide curing pressure. Although the pre-preg requires to be held at 130°C for 10 hours for complete curing, sufficient curing for our purposes is obtained in 6 hours at 120°C. The glass transition temperature of the cured bandage is about 150°C. Finally the outer diameter of the bandage has been turned to the right dimensions and the assembly mandrel has been extracted.
In three magnets built by CAT, the glass fibre bandage has been replaced by gluing a G11 tube on the coils, using the previously described epoxy system. The tube has a slightly larger inner diameter than the outer diameter of the coil assembly. A 3 mm wide longitudinal slit is machined over the length of the tube, so that the tube can be clamped into a contact with the coils and the inner surface of the tube is roughened to improve the bonding of the glue. A possible residual gap, after the clamping, is filled with G11 shims, to avoid resin rich areas in the periphery. The assembly is cured in an oven at 100°C for 1 h. Finally the outer diameter of the G11 tube is turned to the desired dimension. This system allows a faster curing than the pre-preg bandage but has a risk of undesired resin rich areas next to the coils. However there were not observed any differences in training due to this.
3) Connections: The inter-coil connections are soldered with a PbSn-solder on pieces of a printed circuit board. The crossing of the wires, required for the connection in series, are done by sandwiching the circuit boards and screwing them on the end connection flange. The inter-coil connections are secured mechanically by copper grips so that there is never a danger of an open connection, which would stop operation of all the 154 magnets in series and ultimately might leave LHC without the needed controllability. Finally the connections are protected by a G10 plate. The leads for the bus-bars are soldered to a thicker sc-wire, which is clamped on the magnetic screen.
The PVA-insulation on the wire is removed chemically by sulphuric acid. The validity of this method must be further considered, although the wire is afterwards carefully rinsed with purified water there is a risk that the residual acid continues to migrate between the enamel and the copper. This would make the insulation brittle in the course of time and could lead to short circuits.
The heat generation of the magnet is defined by voltage measurements over the magnet. In order to filter out the possible perturbations e.g. due to a ripple of the current, the signal is integrated over five seconds. The measured heat generation at 600 A varies between the magnets from 20 mW to 56 mW. These values are substantially higher than the maximum desired value of 10 mW for the heat generation in to the LHC helium bath. In future the contacts are hoped to be improved by using ultrasonic welding instead of the soldering.
4) Shrinking cylinder and yoke laminations: The pre-stress, needed to avoid any conductor movements during a magnet excitation, is created by mounting an aluminium shrinking cylinder over the yoke laminations. The slightly eccentric scissor-type of laminations transfer the compressive forces from the aluminium cylinder to the coils [2]. At room temperature the radial interference between the yoke and the

cylinder is 0.07 mm, which introduces into the coils a maximum azimuthal compression of 40 MPa. At liquid helium temperature, due to the cool down contraction, the compression further increases to 65 MPa. For mounting the aluminium cylinder is heated up to 200°C, using electric heating collars clamped around it.

The laminations used in the magnets built by CERN were produced by an electro-erosion machining of 1 mm thick ARMCO-plates. A phosphation done on the plates turned out to be insufficient as protection against corrosion. In the magnets built by CAT, the laminations are punched of organically coated non-grain oriented 0.5 mm thick silicon steel as per standard AISI M45. The coercive force of both materials is about 100 A/m at 1 T and saturation starts above 2.1 T. Both steels are perfectly acceptable, since all the magnets behaved similarly irrespective of the yoke material.

5) Magnetic shield: For protecting against fields of bypassing bus-bars and the fringe field from the dipole ends, the spool-pieces are shielded by a low carbon steel screen, which acts also as a support of the magnet. The angular alignment of the magnet is given by three dowel pins, which are attached to the connection flange.

C. Inspection

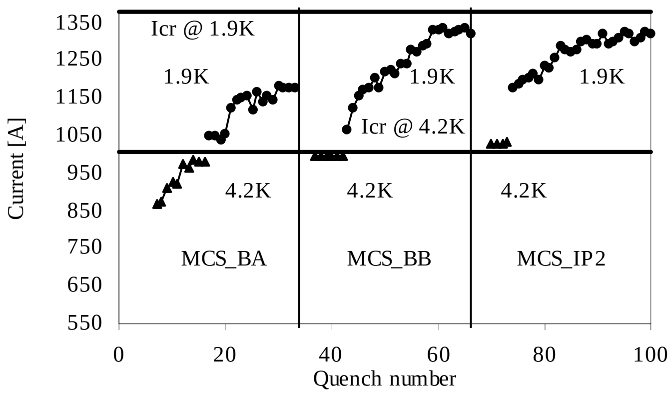
1) Electrical inspection: The individual coils and the complete magnet were tested for ground and inter-turn insulation. The measured resistance of the ground insulation for the 1 kV dc was more than 1 GΩ. The inter-turn insulation of individual coils was checked by discharging a 500 V through a capacitor (an LCR-circuit) and observing the decay of the voltage on a oscilloscope. The decay curve is smooth for an ideal coil. The number of turns can be derived from the measured time period. The measured values of the magnets' self inductance were of the order of 0.73 mH, which is 5% lower than the calculated value.

2) Mechanical inspection: After the assembly of the magnet, the radial displacements of the aluminium shrink ring has been measured, in order to verify that the pre-stress is transferred in to the coils. The increase of the aluminium cylinder outer radius is about 0.035 mm, which corresponds to the above mentioned 40 MPa compression in the coils.

III. Training

CAT has tested all magnets at 4.2 K before shipping them to CERN. The magnets built by CERN were first trained at 4.2 K by CEDEX, since the measuring facilities at CERN were not available. All the magnets are further tested at 4.2 K and 1.9 K in CERN. Fig. 2. presents the measurements done on three magnets at CERN. Altogether the magnets showed very little training at 4.2 K and some of them such as MCS_BB reached the short sample limit at 4.2 K without any training. None of the 12 magnets except MCS_BA showed any retraining at 4.2 K. At 1.9 K all the magnets showed very slow training which started only a few dozens of amperes above the plateau at 4.2 K. The long training is believed to be due to insufficient azimuthal pre-stress in the coils. According to a finite element analysis a part of the coil is subjected to tensile forces, above the operating current of 1050 A. The tensile stresses might cause epoxy cracking and movements of the wire, which initiate the premature quenches. However there is no need for any modifications on the design parameters, since the training starts far above the nominal operation area of ±600 A. The current decay was measured at 4.2 K to calculate the MIIT's and furthermore define the hot spot temperatures, which proved to be at maximum around 250 K. The measured quench voltages were a couple of volts.

Fig. 2. Training of three magnets at CERN. The magnets have been tested earlier at 4.2 K. MCS_BA was the only magnet, which showed retraining. MCS_BB did not have any training quenches at 4.2 K. At 4.2 K and 1.9 K the critical currents are 1010 A and 1380 A respectively.



IV. Magnetic Field Quality

A. General

1) Electromagnetic-design: The 3D em-design is done with the ROXIE-code developed at CERN [3]. The integrated strength of the sextupole component is 0.01887 Tm at the nominal operating current of 550 A. The calculated, measured and maximum allowed multipoles are listed in Table II.

2) Sources of the field errors: In this type of magnet there are three principle sources of the field errors; the winding geometry, the filament magnetization and the iron saturation. Moreover, the sextupole correctors will produce quadrupole and dipole terms if misaligned in respect to the dipoles [4]. The alignment errors should be taken into account when the maximum allowable multipole errors are defined. The alignment is however beyond the scope of this paper.

B. Transfer function

The measured and calculated transfer functions are shown in Fig. 3. The difference between this particular measurement and calculated values is 3.5% and can be explained by the fact that the individual measuring coils did not cover the whole magnet length but were built of consecutive coils with gaps in between. The persistent currents (filaments magnetization) are biggest at low excitation levels [5]. The measured value of persistent currents at 5 A, after a cycle to 1100 A, is 12×10^{-6} Tm, which is negligible. The saturation of the yoke starts beyond the operation range of ±600 A.

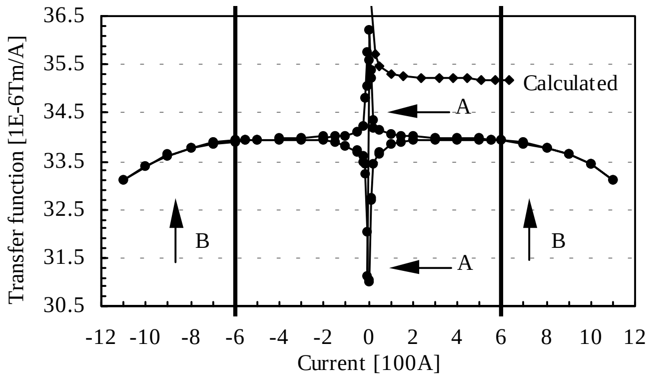


Fig. 3. Transfer function of the MCS_IP5. The operation area is ±600 A. A) Effect caused by persistent currents that flow in the sc-filaments. B) Iron saturation. The difference between the calculated and the measured values is about 3.5% see text.

C. Measured Field Quality

The field quality of the magnets is measured both at room temperature and at 1.9 K, by using a rotating coil. We tried to establish a correlation between the cold and the room temperature magnetic measurements, so that in the future magnets can be measured at room temperature. This would allow magnet manufacturers to check the field quality of the magnets with a simple measuring set-up. The values listed in the Table II show a good correlation between the two measurements. However, the room temperature measurements are relatively error sensitive, since the measuring device is not shielded and the signals are weak. In addition the earth's magnetic field introduces a systematic error in the dipole term, which must be corrected.

Inverse field analyses have been carried out using the error matrices given in the reference [6]. Relatively small coil block movements can explain the measured multipole errors. For example, a radial displacement of a single coil by 0.1 mm produces 8 units dipole and 4 units of octupole error. This type of error is very likely, since the thickness of the glue on the coil surface varies, due to the manufacturing imperfections. An azimuthal error of 0.05 mm in one coil block, much smaller than the manufacturing accuracy, produces 9 units of dipole component.

TABLE II
MEASURED FIELD QUALITY OF MCS_IP6 IN UNITS

	Calculated		Allowed	600 A @ 1.9 K		2 A @ 293 K	
n	$\|b_n\|$	$\|a_n\|$	Modulus	$\|b_n\|$	$\|a_n\|$	$\|b_n\|$	$\|a_n\|$
1	-	-	6500	58.14	41.29	57	15
2	-	-	200	0.844	0.489	0.8	0.5
4	-	-	80	12.14	14.24	5.3	18.12
5	-	-	70	4.92	0.87	4.84	0.328
6	-	-	9	0.91	2.38	1.1	2.34
7	-	-	-	0.18	0.52	0.186	0.4
8	-	-	-	0.05	0.026	0.08	0.057
9	0.011	0.002	-	0.7	0.0003	0.69	0.029
10	-	-	-	0.014	0.004	0.01	0.0054
11	-	-	-	0.0018	0.013	0.0008	0.0149
12	-	-	-	0.0006	0.0006	0.0002	0.0023
13	-	-	-	0.0004	0.0002	0.0004	0.0007
14	-	-	-	0.0003	0.0001	0.0003	0.0002
15	0.004	0	-	0.006	0.0004	0.0056	0.0001

The values are relative to the main component $[10^4 B_n/B_3]$. The calculated skew components are from the connections. The maximum allowed systematic field errors are provisional including misalignment errors [7]. The measured values of all the magnets are same order of magnitude.

V. CONCLUSIONS

Twelve prototype superconducting sextupole corrector magnets have been built and tested. All the magnets were training free within the maximum operation area of ±600 A. Some magnets reached the short sample limit at 4.2 K without any training. All the magnets showed very much training at 1.9 K, probably due to insufficient azimuthal pre-stress in the coils. The magnetic field quality measured at liquid helium temperature and at room temperature showed a good correlation. The measured heat generation of the magnets exceeds the maximum allowed one, due to too high inter-coil contact resistance. In the future the connections might be done by ultrasonic welding instead of soldering.

ACKNOWLEDGMENT

The authors would like to acknowledge J. Mazet, J.-C. Perez at CERN and K. Vaishnav at CAT for building the magnets.

REFERENCES

[1] J. Salminen, A. Ijspeert, A. Puntambekar, “Superconducting sextupole corrector magnet for the LHC main dipoles,” EPAC-96, Sitges, 1996, pp. 2252-2254.

[2] A. Ijspeert, J. Salminen, “Superconducting coil compression by scissor laminations,” EPAC-96, Sitges, 1996, pp. 2237-2239

[3] S. Russenschuck, “A computer program for the design of the superconducting accelerator magnets,” LHC Note 354, CERN 1995.

[4] L. Bottura et al., “Field quality of the main dipole magnets for the LHC accelerator,” EPAC-96, Sitges, 1996, pp. 2228-2230

[5] R. Wolf, “Persistent Currents in the LHC Magnets,” MT-12 Conference, Leningrad, June 1991, pp. 374-377.

[6] F. Sisini, J. Salminen, “Tolerance study of the superconducting sextupole corrector magnet for the LHC main dipoles,” LHC-ICP Technical Note 97-1, CERN 1997.

[7] W. Scandale, CERN, personal communication, 1997.